Soils Research in Agroforestry

Proceedings of an expert consultation

Editors H.O. MONGI & P.A. HUXLEY
Tech. Editor David Spurgeon

/ICRAF publication/. Collection of /soils research review papers/ on methodologies/ and /strategies/ that can be of value in the/ development/ and /study/ of /agroforestry systems/. Papers indicate the /state-of-the-art/ in /soils research/ relative to the needs of agroforestry by examining research in agriculture and forestry under /monoculture/, mixed- and inter-cropping conditions/, especially those incorporating /trees/, and describe /research methods/ that require further development to meet agroforestry needs. Presents /indications/ for /soils research/ in different /agro-ecological conditions/ and for /fragile ecosystems/. Summarizes the /chemical, biological and physical methods/ proposed for use in monitoring soils under agroforestry and stresses the need for /standardization in methodology/, /reporting styles/ and /research strategy/.
SOILS RESEARCH IN AGROFORESTRY

PROCEEDINGS OF AN EXPERT CONSULTATION
held at the International Council for
Research in Agroforestry in Nairobi,
March 26-30, 1979

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# SOILS RESEARCH IN AGROFORESTRY

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PREFACE

This collection of papers reviews soils research that can be of value in the study of agroforestry systems. The papers summarize relevant work in agronomy and soils under monoculture, mixed and inter-cropping conditions and the research methods used as they relate to soil management under agroforestry conditions.

A common outlook is developed on current soil research problems and some proposals are made as to how best these could be solved.

The papers indicate the "state-of-the-art" in particular subjects relative to needs in agroforestry, and propose appropriate research methods and strategies for monitoring soil conditions and evaluating soils data in agroforestry systems. They also indicate which techniques need further development and emphasize the need for standardization in methodology and reporting styles.

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This working group study, which is the first scientific meeting called by the newly established ICRAF agency, highlighted both the promise and the difficulties of a venture into a scientific border area of multi-disciplinary subjects. Papers had been invited from specialists in physical, chemical and biological aspects of soils from the separate fields of agriculture and forestry. The intention was to select soil science technologies that would serve well in developing countries in the area of overlap of disciplines now termed "agroforestry". The meeting addressed this subject area as the study of techniques of land-use by which farmers derive income from tree products as well as from field crops and livestock.

The opportunities arise from the search for optimum combinations of tree crops with arable crops and livestock in the context of small-scale farming under tropical or semi-arid conditions. Although profitable and productive systems are known in other contexts, as in Israel and Australia, few studies have been undertaken in developing countries. The difficulties arise both from the wide ecological range and from the diversity and complexity of environmental, economic and social factors which interact to determine the success or failure of such systems of land use. Approach to such studies therefore requires most careful preparation.

Relevant scientific evidence can be drawn from both forestry and agricultural studies whose ecological range includes high altitude montane forests, where natural hardwoods, plantation softwoods, tea and coffee plantations are the main tree crops. In the low-altitude forests of the humid tropics, rubber, cocoa, coconuts and robusta coffee plantations are the main cultivated tree crops, while in the drier savanna conditions fruit and nut trees as well as plantations for fuel and poles offer opportunities for income. At the extreme of the range, on the edges of the deserts, trees are an important source of
fodder for livestock and the harvesting of gum arabic provides a cash crop from drought-resistant acacias. Irrigated fruit crops, such as citrus and dates, add to the complexities of land-use patterns.

In total the areas of all such tree crops in the developing countries are vastly exceeded by the more primitive bush-fallows and forest-fallows of traditional systems of shifting cultivation. Problems of the maintenance of soil fertility in these ancient methods of subsistence agriculture have received increasing scientific attention, which has contributed data on the circulation of nutrients and the improvement of food crops in shifting cultivation. Such data are important sources for the study of agroforestry. These ancient traditional systems of shifting cultivation are now being destroyed by rapidly increasing population pressures as invasion of the fallow area reduces them to continuous cultivation. The need to substitute improved land-use patterns increases every year.

This wide ecological range and diversity of economic effort was well illustrated in the papers contributed to this meeting; these included technologies from soil studies conducted over the whole range from montane forests to the edges of hot deserts. Since most of the soil science technologies have been developed in response to the needs of agriculture, it was inevitable that few of the papers dealt with evidence from trees. Six papers did, however, summarize soil studies in recognizable agroforestry situations.

Dr. Tejwani described the use of hardy tree species in India for gully-stopping and erosion control in semi-arid areas that are under severe pressure from cultivation and grazing. The unique aspect of these long-term experiments was their demonstrated economic success, since sales of fodder, poles and firewood amply repaid the costs of establishment. Drs. Okigbo and Lal described soil fertility studies under shifting cultivation in the humid tropics of Nigeria; Dr. Lal described the introduction of zero-tillage techniques, while Professor Ahn summarized soil fertility evidence that defined the necessary duration of bush fallows. Dr. Sanchez assembled valuable South American data from experiments published mainly in Spanish
and Portuguese journals on the nutrient contents of both soils and biomass in humid tropical forests, and of their distribution after felling and burning.

Mr. Ahmed described the customary planting of acacias among foodcrops in the marginal areas of the Sudan and the need for quantitative studies to improve the use of trees to stabilize the present precarious subsistence farming. The writer outlined the evidence from soil physics and hydrology studies of the effects of the "shamba" (taungya) system of establishing seedling pines in vegetable gardens over a complete water-shed, thus converted from montane forest.

The papers on soil technologies included soil taxonomy and survey, soil physical properties, soil fertility and methods of chemical analysis, use of radioactive tracers, soil microbiology and nitrogen fixation, the effects of mycorrhiza and the problems caused by nematodes and by termites. The path charted by Professor Kamprath through the technical maze of soil analysis will be a welcome help to many soil scientists in the tropics. None of the techniques of these many aspects of soil science are specific to agroforestry studies or have need to be, but they must be applicable to the problems of tropical subsistence farming.

Data on fertility of soils under forestry plantations are rather scarce, since the general experience of success without the use of fertilizers has minimized the incentives to study soil fertility changes over the long time-spans involved. However, on the biological side, the dramatic experience in Kenya of the total failure of pine plantations in the coastal littoral until planted with an admixture of soil containing mycorrhiza from the highlands, provided a convincing local background to Professor Redhead's paper. Many of the technologies described were too specialized for critical discussion in a small multi-disciplinary working group but they illustrated the formidable variety of factors that may govern the success or failure of the introduction of new practices of agroforestry, or even the introduction of well-tried methods into an un-studied environment.
This was an interesting and informative explanatory meeting, which emphasized that agroforestry is the zone of interaction between two complex and widely studied human pursuits - agriculture and forestry. It is a major challenge to ICRAF to prepare and to organize future studies so that they will concentrate on the problems and opportunities presented by more specific situations in defined ecological zones. This will be essential if a positive impact is to be achieved on target areas in which successful innovations could raise the living standards of many millions of farmers in many developing countries.

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INTRODUCTION

Most of the world's poor live in the tropics. Many of them eke out a living based on unimproved traditional production systems in areas that are largely "marginal". Because of increasing population pressure, many of these fragile ecosystems have suffered rapid degradation; soil fertility has been reduced and productivity has dropped significantly. The consequence is that food and fuel supplies are dwindling in these areas, while there is an increase in hunger and malnutrition.

In many cases, the improvement of the old and traditional practices of combined food and wood production, or agroforestry as it may now be called, is seen as the most promising land-use system, not only to arrest these detrimental trends but also to provide a continuing system of food, fuel and shelter to the affected people - and in some cases, to reclaim degraded areas.

The International Council for Research in Agroforestry (ICRAF) has been established as an agency that will promote agroforestry systems in order to achieve better land-use in developing countries by encouraging, supporting and coordinating research, training and education efforts in this field.

Research on soils and soils management in agroforestry is scanty. The speedy development of modern agroforestry production systems will hinge not only on the evaluation of traditional practices and analysis of existing agroforestry research and related intercropping investigations, but also on the appraisal of all relevant research data from agriculture, horticulture and forestry. Yet this is very widely dispersed in the literature. In order to ensure that a start be made in documenting this kind of information, this consultation of soils experts was held by ICRAF in Nairobi, Kenya, from March 26-30, 1979.

Agroforestry systems will involve growing different agricultural crops and woody perennials together in various spatial and temporal combinations. Thus, a multi-disciplinary approach is needed and all aspects of soils research in agroforestry must be considered.
Standardization methods must be developed to make best use of the scanty manpower and material resources available, and to facilitate extrapolation of data to similar ecological zones.

The working group spent about one-third of its time considering the concepts on which agroforestry is based. The remainder of its time was spent determining the research methodology and strategy best-suited to agroforestry systems. In some cases contributors had considerable difficulty summarizing and extrapolating existing data so as to make them directly relevant to agroforestry. This is not surprising, for on the one hand, there is a dearth of relevant information in their particular fields and, on the other, there are inherent hazards in trying to relate existing information to conjectural agroforestry situations. The success with which this has been done may well reflect the need for further work in specific areas of soils research.

The consensus of the group was that the focus in soils research in agroforestry should be on:

- studies on marginal lands, including those where both high and low rainfall is a limiting factor, aimed especially at soil improvement and management under low-input farming conditions (among the poor);
- rehabilitation and protection of the production base where degraded, and development of a satisfactory hydrological and ecosystems balance;
- better conservation of both soil and water, utilizing plant species able to provide a more stable biomass in low-fertility conditions compared with most agricultural cropping systems;
- ascertaining the efficiency of traditional agroforestry systems in terms of soil fertility and the maintenance of sustained productivity;
- evaluating efficiencies of biological N2-fixation and mycorrhizal associations in various agroforestry systems and ascertaining the most effective ways in which to exploit these;
- investigating the "nutrient pumping" effect of deep-rooted perennials by monitoring nutrient cycling and studying root
activity at depth so as to obtain more precise data for a range of species and environmental situations;

- determining the optimum fallow lengths and nutrient element needs for optimum plant nutrition under particular agroforestry systems (modified shifting cultivation systems);

- determining possible ways of stabilizing the agricultural cropping plan of shifting or zonal systems by utilizing associated woody perennials.

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THE IMPORTANCE OF WELL-FOCUSED SOILS RESEARCH IN TROPICAL AGROFORESTRY SYSTEMS

OPENING ADDRESS TO THE EXPERT CONSULTATION BY
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The question of providing enough food and better nutrition, clothing, shelter and other material needs to the world's poorest people, the majority of whom are in the tropics, is a very big challenge today, especially when viewed against the very meagre crop yields and the ever-increasing cost of the labour and inputs.

The tropics have about 50% of the world's population and only about 40% of the earth's land surface. It is anticipated that by the year 2010 the tropics will have nearly doubled its population as against a 20 - 30% population increase in the developed countries. With as much as 12% of the land being desert or semi-desert, and another 45 - 50% of the land being wasted lands or lands unsuitable for arable or mixed farming, the prospects for higher food and fibre production are minimal unless more effective production systems are evolved in the very near future. Even in the potentially arable areas better land-use systems that permit better soil conservation in the broad sense are required. Here, too, more wood for fuel and building is needed and it will have to be produced on the farms.

Agricultural production in most of the tropics is still inherently based on shifting cultivation systems, related bush fallows, or combined systems of food, fodder, fibre and wood production modelled on attempts by the local population to improve on shifting cultivation systems. There has been little relevant research done to improve these systems. In the past, research investments have been directed at the needs of plantation agriculture, which accounts for less than 5% of the total agricultural production systems.

Someone may ask, why this soils expert consultation? As we know, the predominant dependence of the majority of people in the developing areas of the tropics on agriculture and forestry as a source of livelihood - food, fuel, fibre, shelter and wood, among other needs necessitates continued relevant research to increase productivity in the various land-use and farming systems and an understanding that the proper management of soils is a fundamental aspect of all such research.
The ever-increasing demographic pressure on the land and the use of inappropriate agricultural and forestry production systems has resulted in population outstripping production in most areas and in alarming land quality deterioration and degradation.

There has been far too little research undertaken to test the efficacy of, and to improve, indigenous agricultural production systems which are seemingly more suitable in the tropical environment. The erosivity of the tropical climate, and vulnerability of the majority of the soils of these areas to erosion hazards and leaching of plant nutrients, are such as to dictate a closer examination of all production systems that emulate the natural closed tropical forest ecosystems. Then we need to develop production systems that are socially acceptable in terms of optimum economic returns off the land on a sustained basis, while at the same time ensuring optimum protection to the land and the ecosystem: that is, permitting the least site deterioration.

In the past, and at present to a very large extent, tropical agricultural and forestry research has tended to be overly influenced by practices and experiences in the temperate countries. Because of the excessive interest in using plantation and estate agriculture in the tropics to produce raw materials needed in industrialized countries, there has been little advance in developing suitable agricultural production systems for the tropical areas. These are, furthermore, now suffering serious demographic pressures and their once-suitable shifting agricultural production systems cannot offer adequate sustenance.

There has been far too much wastage of some of our land and soil resources while we plod on almost blind-fold, indulging in unsuitable production practices that obviously have resulted in a ruination of the invaluable land.

Against this background, we must continue to do our utmost in keeping land productivity at as high a level as possible while we continue to search for new and better agricultural and forestry production systems.

The strong belief that combined food and wood production systems would be better suited to the tropical areas that are "marginal", or are in environmentally fragile ecosystems, is a good one, the reality of which must be very quickly and effectively evaluated. We cannot afford to wait for too long for these results to materialize, as each day thousands of hectares of potentially productive land go to waste (increasing the amount to be reclaimed). We must determine well in advance how to carry out the needed research use approved methods (where these exist) and employ an agreed strategy that will ensure that
we obtain good results that can be extrapolated to similar agro-climatology zones.

The decision to hold this expert consultation for the development of the requisite soils research methodologies and strategies that are likely to be best applicable to soils research in developing agroforestry systems is, therefore, a good one, for which ICRAF should be commended.

Taking stock of what is already known and then determining its probable application to new disciplines (such as agroforestry) is a scientific prerequisite. A very considerable amount of information is available from research already undertaken for the management of soils and agricultural and forest plants under monoculture. Also currently available, but to a very limited extent, is information on some inter-cropping systems, not to mention plantations agriculture.

There is a lot we can learn from those people who have developed successful combined production systems (sequential or continuous and permanent), even though most of it is currently unwritten.

In order to forge ahead with a new and better approach to food, fodder, fibre and wood production in the tropics that will take account of the social, economic political and "cultural" needs of the people, a new research strategy for soils research is needed to combat site deterioration, soil erosion, excessive nutrient losses, soil acidity and salinization.

Research is an expensive undertaking; there are a variety of methods that can be used. In order to facilitate easier interpretation of results, operate at the lowest research costs and ensure a better extrapolation of the results to other situations, the researchers should decide in advance which few methods to use and the research priorities and strategies to be followed.
AGROFORESTRY AND FRAGILE ECOSYSTEMS

OPENING ADDRESS BY DR. K.F.S. KING, DIRECTOR-GENERAL, INTERNATIONAL COUNCIL FOR RESEARCH IN AGROFORESTRY, NAIROBI, KENYA

There have been, during the last twenty years or so, remarkable advances in tropical agriculture. Indeed, according to some (see e.g. Borlaug, 1971; Dalrymple, 1972) the progress made in the development, dissemination and adaptation of new agricultural technology in the tropical world has been unprecedented. This "green revolution" (as it used to be called) has been based primarily on the development of high-yielding crop varieties, mainly of wheat and rice, and on the intensification of the principles of plantation agriculture that have served mankind so well in temperate regions and also, for some crops and on some sites, in the tropics.

Unfortunately, the high-yielding crop varieties that are being promoted for use in the tropics seem to require costly inputs of fertilizers, water, pesticides and energy, which few developing countries are able to afford to the extent necessary. Moreover, the areas that are generally and correctly identified by tropical agronomists as being suitable for the growth and production of these high-yielding cereals do not comprise the bulk of tropical land. For these and other reasons, these types of agriculture have not expanded rapidly enough significantly to reduce the number of people in the developing world who are forced to depend for their very existence on food that is produced: (i) in the arid and semi-arid zones of this world; (ii) in the arid savannas of the tropics; (iii) on the slopes of the mountains of the tropics and sub-tropics; and (iv) by practising shifting cultivation in the forest areas of the developing world.

I have ascribed the term fragile ecosystems to these areas because their equilibrium appears to be easily upset and because they become ecologically degraded if certain forms of land-use, particularly sedentary agriculture, are practised in them. They have also been described, from another point of view, as wasted lands (King and Chandler, 1978) because they represent areas in which natural resources are currently being wasted either through over-exploitation, under-utilization and mismanagement, or through sheer neglect.
We have estimated that 4,900 million hectares, or 65% of the land in the tropical world may be classified as being "wasted" or as occupying fragile ecosystems. These lands are found in the poorest countries in the developing world. The number of people who depend upon these areas for their food and livelihood is 630 million or 35 per cent of the total population of the developing countries (King, 1978). The people who live in these areas are, on average, poorer than those who live in other parts of their already poor countries. They are thus the poorest of the world's poor.

They cannot afford to purchase food from other less brittle and fragile ecological zones. Accordingly, if they must eat they must either be given "food aid", or be made to settle in areas that are better suited to permanent arable agriculture, or be given alternative occupations so that they might earn money to buy food, or produce food for their sustenance in these fragile ecosystems.

Although food aid is not to be rejected out-of-hand, it must be regarded as essentially an emergency measure. A nation or part of a nation should not be forced to depend upon such assistance for one of the basic necessities of life.

The resettlement of large populations is not only costly, it is beset by a number of social problems that have led to the failure of most of the land settlement schemes that have been attempted in the Third World.

The developing countries find it increasingly difficult to create job opportunities for their citizens. Indeed, the average rate of unemployment in the developing world is over 25 per cent. Moreover, the rate of job creation is lowest among those who inhabit the fragile ecosystems of the tropics, partly because of the dearth of industrial skills in these areas, partly because of the paucity and inadequacy of training and educational facilities, and partly because the natural resources that are to be found in these zones do not readily permit the transference of modern techniques. It is therefore not surprising that the third possibility, that of creating new jobs in critical areas, has also not been tried extensively, and when tried has not significantly affected the purchasing power of the communities.

The consequence of this failure to offer alternative sources of income or food is that most of the inhabitants of fragile ecosystems must perforce, now and in the foreseeable future, themselves provide their own food.
However, studies of the arid and semi-arid zones reveal a history of degradation of vegetation and soils, and a reduced productivity of both natural and "managed" ecosystems. Traditionally, the populations of these areas have coped with the extreme environment by practising forms of land-use that were extensive or by being mobile, or by being a part of a social system that was based on economic inter-dependence. Today, the rapid increase of populations and the introduction of inappropriate technologies have resulted in the removal of protective trees and shrubs for fuel and shelter, and the cultivation of soils that are ill-suited to arable agriculture. Moreover, many of the intensive farming practices that have been attempted, although increasing yields in the short-run, have made the soils more vulnerable to erosion and have indeed led to desertification. In addition, in areas where there is a close connection between dryland cultivation and grazing, the collapse of the crop-based system tends to lead to the failure of the pastoral (King and Chandler, 1978).

The situation in the arid savannas, which are to be found mainly in South America, is no less reprehensible. Here again, an extensive resource is not only being under-utilized, it is also being degraded. The savannas in this fragile ecosystem have soils that are acid and toxic. Even though the land is generally level, extremely poor soil strength in terms of cohesion and friction make the soils susceptible to erosion if the plant cover is disturbed. And yet, crop farmers in these areas customarily practise rotational burning of the mature forage during the dry season to obtain tender forage for cattle feeding. Despite the practice, however, the savannas have a low grazing capacity, much of the area being capable of supporting only one head for every eight to sixteen hectares. The returns to the society for the ecological degradation that is caused on these sites are, therefore, low.

Forests in tropical and sub-tropical mountain ecosystems are being razed to the ground at alarming rates to provide wood for fuel and shelter to rapidly growing populations, and to yield land for farming for food for the inhabitants of these areas. The improper land-use of upland areas obviously affects the development of those who live there. What is perhaps more important, is that malpractices in the utilization of the slopes of these hills and mountains often lead to erosion, increased run-off, siltation of the rivers, flooding and droughts.
Agricultural productivity in the often more fertile and higher-yielding valleys is therefore adversely affected; irrigation works are rendered ineffective and the rate of both agricultural and industrial development is reduced. The ravages of the forests in mountain ecosystems are to be observed mainly on the foothills of the Himalayas, and it is perhaps no coincidence that the highest incidence of recurring floods and droughts are to be found in the Indian sub-continent.

Shifting cultivation is practised on every continent that is occupied by developing countries. In general, the systems described by the term 'shifting cultivation' are characterized by the felling and burning of woody vegetation, followed by one to several years of cultivation, and then by a period of forest or bush fallow. After fallow, the cycle is repeated. Shifting cultivators produce food for more than 250 million people, but in recent times they have had to reduce the fallow periods to accommodate increasing populations. As a result, soils have become degraded, indeed often to the point of making the land incapable of supporting further crops. In addition, only about 15 per cent of the timber cut is utilized, the wastage being estimated at US $ 50 per hectare per annum. The practice of shifting cultivation has destroyed thousands of hectares of forests, valuable timber resources have been depleted and the protective cover removed from vast watershed areas.

It is evident in all these areas (which I have described as being "fragile ecosystems"), the necessity for food has forced the occupants to employ land-utilization practices that have led to the degradation of the ecosystems.

Now, the conventional scientific wisdom would prescribe forestry as the "best" type of land-use for these areas. The foresters and the conservationists would point out with truth that there are many species of tree that can be grown on poor soils; that trees exist in a closed self-sustaining nutrient cycle; that forests maintain and improve the fertility of the soils beneath them; that natural and well-managed tropical forests tend to have a multi-storeyed structure that together with the litter and humic layers, provides several lines of defence against rain, reduces soil compaction and increases infiltration, and thus minimizes the incidence of floods and droughts. "Unfortunately, the people who live in those areas for which
the conventional land-utilization wisdom prescribes that only protection forests be established, find it difficult to subsist on the forests alone. In addition to their need for wood for cooking and heating they require food. Indeed, the demand for food is often the dominant imperative in these societies. It therefore seems necessary to attempt to devise and perfect a system of land management which eschews the false dichotomy of agriculture and forestry, which conserves the ecosystem and which, at one and the same time, provides food and wood. Such a system is agroforestry". (King, 1978).

Agroforestry has been defined as a "sustainable land management system which increases the yield of the land, combines the production of crops (including tree crops) and forest plants and/or animals simultaneously or sequentially on the same unit of land, and applies management practices that are compatible with the cultural practices of the local population" (see King and Chandler, 1978; Bene et al., 1977).

What is the evidence that suggests that forest trees and agricultural crops can be grown together without a deterioration of the site? It comes from several sources.

First, there is the evidence gained from the practice of the taungya system. Blanford (1958) has described how the taungya system was begun in Burma in 1856. Since then the system, though called by various names (see King, 1968), has spread throughout Asia, and to Africa and Latin America. Many of the forest plantations that have been established in the tropical world, particularly in Asia and Africa, owe their origin to the system. There is little doubt, therefore, that in the initial stages of a forest plantation's existence trees can be grown together with annual agricultural crops (see King, 1968 and Hesmer, 1977 for lists of the tree and agricultural crops that are generally grown together). There is also evidence that generally most agricultural crops have no adverse effects on forest crops and vice versa. Indeed, some workers have reported higher yields from both types of crops in certain circumstances and under certain conditions (see e.g. Fishwick, 1961; Griffith and Howland, 1958; Mackay, 1952; Ogbe, 1967; SHEBBEARE, 1921).
Secondly, there is the evidence from the traditional farming practices of the tropics. One example will suffice. Wilken (1977) had pointed out that some societies simulate forest conditions on their farms in order to obtain the beneficial effects of forest structures. For instance, farmers in Central America imitate the structure and species diversity of tropical forests by planting a variety of crops with different growth habits. Plots of no more than one-tenth of a hectare contain two dozen different species of plant each with a different form, and together corresponding to the layered configuration of mixed forests; coconut or papaya with a lower layer of bananas or citrus, a shrub layer of coffee or cocoa, tall and low annuals such as maize and beans, and finally a spreading ground cover of plants such as squash.

And third, there is the evidence that is emerging from the mixed cropping of annual crops. Most authorities now appear to agree that the mixed cropping of annual crops is often a more efficient means of utilizing land area than are pure stands (Fisher, 1976).

It would appear, therefore, that there are sufficient grounds for assuming that agri-silvicultural systems might provide one of the answers to the utilization of fragile ecosystems.

There is, however, a great need for further research. The shade tolerance of various agricultural species must be tested. Forest species that protect the soil but do not significantly reduce energy levels on the forest floor must be identified. Optimum spacings for both types of crop must be ascertained. Thinning regimes designed to optimize the yields of both the tree and agricultural crop must be established. Optimum species combinations must be investigated.

In addition, fundamental studies must be undertaken to underpin the field work and to provide, eventually, a body of basic principles as follows:

(i) the dynamics of the various nutrient cycles that occur when the forest is cleared, during the cropping period and during fallow;
(ii) the allelopathy and complementarity of various species;
(iii) the competition for solar energy among trees and between trees and agricultural crops;
(iv) the morphology and physiology of various tree species;
(v) leaf production and leaf fall of particular species and the influence of their occurrence on competition for solar energy and the nutrient cycle, respectively.

Moreover, new breeding schemes should be designed to obtain in both forest and tree species those characteristics that are considered necessary for successful and efficient intercropping.

It was because of the potential importance of agroforestry, the need for research and the difficulty of conducting such research that the International Council for Research in Agroforestry (ICRAF) was established.

ICRAF’s initial agroforestry programme entails:
(a) the investigation of agroforestry methods on which to base improved farming systems to replace shifting cultivation on tropical soils;
(b) the development of agroforestry pastoral and cropping systems for the prevention of desertification and the rehabilitation of arid and semi-arid ecosystems;
(c) the application of agroforestry systems to the maintenance and improvement of the quality of tropical pasture land; and
(d) the investigation of agroforestry systems for rehabilitating vegetative cover to ameliorate degraded mountain ecosystems.

This programme will, inevitably, be very much concerned with the effects of various soil types on the yields that are obtainable under different agroforestry systems and with the ability of the systems themselves to maintain and improve the fertility of soils. The ICRAF soils research programme will therefore endeavour to ascertain what happens to soil productivity under particular agroforestry systems, in differing climatic zones and under different management practices.

It seemed obvious to us, at the outset, that if we were to obtain useful results, we ought to devise a suitable research strategy. It was also evident that there should be agreed methodologies for monitoring and assessing soil changes under the various agroforestry systems. We soon realized, however, that because of the plethora of methods for testing the
physical, chemical and biological characteristics of the soil, and because publications that were deliberately geared to the problems we wished to solve were, perhaps not surprisingly, not readily available, we faced the danger of dilly-dallying, of wasting our efforts and of employing methods that might not have yielded the desired results.

Accordingly, we decided to hold this expert consultation. We realized that, at this stage, it would be necessary for us to utilize the knowledge that is already available in agriculture and in forestry in general, and in multiple-cropping systems and agri-silvicultural systems in particular. In other words, we felt that it was desirable to begin with "a survey of the available and potential resources for soils research in agroforestry" (Lundgren 1979). We do not seek the mere amalgamation of the disciplines of agriculture and forestry. What we look forward to, in the years ahead, is the evolution of a body of principles that will support and under-pin a new discipline of agroforestry.

Our hope is that by the end of this workshop we will have been advised (i) on the methodologies that should be pursued in those aspects of our work that are concerned with soils, (ii) on the priorities in soils' research that we should follow, and (iii) on the research strategy that we should implement.
LITERATURE CITED


Mackay, J.H. 1952. Notes on the establishment of Neem plantations in Bornu province in Nigeria. Farm and Forest, Vol. II.


NOTE

Tables 1, 2 and 3 for the article "Effects of Land Use on Soil Characteristics in the Sudan", by A. El Houri Ahmed (pp 1-13) appear at the rear of the book.
EFFECTS OF LAND USE ON SOIL CHARACTERISTICS IN THE SUDAN

A. El-Houri Ahmed

ABSTRACT

The agricultural situation, the soils and traditional rotational farming systems in the Sudan are described and the effects of land use on soil productivity under pressures of human and livestock population indicated. Short rotations on the sandy and heavy clay soils of the Western and Eastern Sudan, respectively, result in a rapid deterioration of both soil fertility and productivity, and a build-up of pernicious weeds which eventually give way to desertification as the rotations become shorter and cultivation continuous. Attempts at increasing soil productivity through the application of fertilizers have met with variable results. The use of both Acacia senegal and A. albida was found most beneficial for: (1) the improvement of soil characteristics and arresting ecosystems degradation, (2) increasing soil N fertility and a more favourable C/N ratio, (3) supplying considerable amounts of fodder for livestock, and (4) the production of fuelwood and gum arabic. The use of Acacias and other multipurpose trees in the search for more appropriate land-use systems for the Sudan and similar areas is advocated.

Sustained, optimum yields off the land can be assured only in situations where the land-use system adopted is appropriate both in terms of yield of selected crops and in conserving the soil and the ecosystem. Agroforestry systems are considered as satisfying that need (King and Chandler, 1978; Bene, Beall and Cote, 1977). The development of viable agroforestry systems for the Sudan is contemplated. These will involve making improvements to existing traditional farming systems and the introduction of new intercropping systems based on multipurpose trees. The purpose of this paper is to present the situation in the Sudan with special relation to land use and its effects on soils as an aid to the planning and development of suitable agroforestry research programmes for the Sudan and similar areas.

GENERAL AGRICULTURAL SITUATION

The Sudan is one of the largest countries in Africa. Covering
about 2.5m km², it has a population of 16 million people, increasing at 2.2% per annum. The natural vegetation is very varied, ranging from desert, to semi-desert, short and long-grass savanna, and montane vegetation (Harrison and Jackson, 1958). About 30% of the country, mainly in the north, is largely desert. About 35 m ha of land are considered arable and of this only about 10.4 ha, or 30% is under cultivation. There are an estimated 96 m ha of grazing land and 24 m ha of natural forest. Of the cultivated land, 1.6 m ha are under irrigation, 2.2 m under rain-fed mechanized farming, while another 6.6 m ha are under traditional shifting cultivation or are still unused due to lack of water, for irrigation or domestic consumption, or due to the heavy nature of the soil.

AGRICULTURAL ACTIVITIES

THE TRADITIONAL AGRICULTURAL SECTOR

The traditional sector of agricultural production is characterized by the raising of crops on small farms, with little or no mechanization. The main crops of the sector are sorghum, millets, groundnuts, sesame, and gum arabic. Livestock (cattle and goats) are also raised under extensive nomadic grazing conditions. Shifting cultivation is the dominant land-use practice, with nomadic grazing confined mainly to the semi-arid and dry savanna zone.

THE MODERN AGRICULTURAL SECTOR

The characteristics of the modern agricultural sector are: (1) irrigated agricultural schemes where crop rotations, fertilizer application and plant protection measures are standard practices. The main crops grown are cotton, groundnuts, wheat, paddy (rice), fodder crops and, more recently, sugar cane and kenaf (Mamoun, 1978) and (2) rainfed agricultural schemes which are concentrated in the clay plains of the Central and Eastern Sudan where ploughing and weeding and harvesting are partly mechanized. Sorghum (Durra) and sesame safflower and sunflower are minor crops.
SOILS

Smith (1949) gives a simplified account of the soils of the Sudan.

VARIOUS DESERT SOILS

These occur mainly in the desert and semi-desert northern regions of the Sudan under conditions of less than 200 mm of rainfall. These include (1) skeletal soils of eroded desert mountains, (2) gravel "pavements" where the topsoil has been blown away leaving a layer of flat, polished gravel, and (3) hard non-cracking clay flats and (4) wind-blown sands.

STABILIZED SAND DUNES

Large areas of the West and Central Sudan are covered by stabilized sand dunes. These dunes were originally formed during dry periods in the Quarternary era but, when moisture conditions returned, they became stabilized. The dunes are still stable except in the vicinity of cities, towns and villages where overgrazing or over-cultivation has destroyed the vegetative cover. The coarse and fine sand fractions of the soils usually cover 90-95% of the soil separates while the pH range is 5-9. The soils' contents of organic matter and plant nutrient elements is thus very low, however the permeability is very high.

DARK CRACKING CLAYS

These soils, commonly termed "black cotton soils", occur in wide, uniformly flat plains in Central and Eastern Sudan. Most of them appear to be alluvium transported by the Blue and White Nile, but some may have been formed in situ from basalt rocks. The soils generally have more than 60% clay and are alkaline with a pH of about 9. Gypsum and calcium carbonate crystals and concretions are found, particularly in the lower horizons. They shrink considerably upon drying when a network of wide, deep cracks are formed. At the onset of the rains, the cracks are wetted and close up and these soils then remain practically impermeable. Thus, flooding occurs under high rainfall conditions and during the dry season the little
moisture available to plants in these soils is soon lost in evaporation when the cracks are formed, leaving the soils physiologically dry (Maggar, 1965; Rai, 1965).

RED LOAM AND IRONSTONE SOILS

These occur in areas with over 800 mm rainfall outside the flood plains. They are typically reddish sandy loams overlying a layer of pea-iron nodules or more consolidated vesicular ironstone which is often a few centimetres to a metre or more thick. Sometimes the upper layers are completely eroded to form a flat ironstone pavement. In general these soils range from acid to neutral reaction (pH 5-7). Catenas developed on these ironstone soils are quite variable (Morison et al., 1948).

VARIABLE HILL SOILS

This group comprises all the different and variable soils that owe their origin to hill and mountain topography. They also include the silts that form the Naraz (Acacia albida) lands that characterize the innumerable valleys whose source is the Jebel Marra. The silts are largely derived from erosion of the tuffs occupying the bad lands of Jebel Marra (Tothill, 1944).

LAND USE PRACTICES AND EFFECTS ON SOIL CHARACTERISTICS

The relationship between soil quality and productivity and land use under shifting cultivation, with or without bush-fallow based on Acacia senegal, have received considerable study in the Sudan. Jackson and Shawki (1950) described typical types of shifting cultivation in the Sudan, listing, among others, the gum arabic "gardens".

GUM ARABIC "GARDENS"

Gum arabic "gardens" illustrate a typical cycle of crop production on the sand dunes in the gum arabic production areas (Bond, 1918). The cycle consists of a cultivation period that begins with the clearing of the Acacia scrub. The dunes are
cropped with bullrush millet (*Pennisetum typhoideum*) and sorghum (*Sorghum vulgare*) for 4-10 years, at which time the area is abandoned, generally because of a decline in fertility and infestation with *Striga hermonthica*, a root parasite of these cereals, and the land passed onto the "re-colonization" stage.

The first colonizers of the land are *Cenchrus biflorus* and *Acacia senegal*, all of which regenerate best on formerly cleared and worked soils. The acacia reaches a height of about 1 m after three years, and it is ready for gum tapping at eight years. This is the acacias' "dominance period" and it lasts for about 6-10 years.

The end of the gum-tapping period passes into the next cycle, called the "deterioration phase", whereby, as a result of heavy tapping, the gum trees start dying gradually. The tree does not regenerate except, occasionally, from a stump. The *C. biflorus* is also slowly replaced by denser-growing grasses which become protected from grazing by fallen *Acacia* trees. Eventually the sub-climax vegetation is burned and the cycle is resumed. This rotation system is upset and the balance is made unfavourable under cultivation pressure. Seif el Din (1973) ascribed the decline of forests in the sandy areas of West Sudan to: (1) shifting cultivation, (2) repeated cutting of trees in short rotations, and (3) changes in micro-climate which make it difficult for trees to regenerate naturally. He estimated that a family of 5 working individuals can clear 6 ha, or about 1.2 ha per person. But the cultivation period only averages 5 years (Doxiades Associates, 1964; Seif el Din, 1969) and one person clears only about 0.24 ha per annum under these circumstances. Under this cultivation pressure only pioneer species such as *Calotropis procera*, *Acacia nubica* and *Guiera senegalensis* can colonize the repeatedly-cultivated, low soil fertility areas (Obeid and Seif el Din, 1970).

In addition to the above-mentioned pressures, there is also the need for fuel wood, estimated at 2 m³ per annum (Seif el Din, 1973; quoting Saini, 1964). Assuming that the forests in these areas produce 4.8-5.6 m³ per ha (Weck, 1957), and assuming that one person gets his needs from the land cleared for shifting
cultivation, then the other half must be obtained from other areas. Seif el Din (1973) argued that about 0.25 ha of natural gum arabic forest is cut to provide the additional fuelwood and that this has turned into bare lands, particularly around permanent water sources with a high population density.

DECLINE IN CROP YIELDS

Tables 1 and 2 illustrate trends in the production of ground-nuts, sesame and gum arabic in Northern Kordofan and Darfur. The decrease in yields indicated by the data was ascribed to: (1) the expansion of agricultural production at the expense of traditional rotations, (2) drought and the resultant migration to urban and irrigated areas (Awouda, 1973), and (3) poor farm management and inadequate extension services (Khogali, 1973). The trend can best be arrested through judicious land use based on improved traditional shifting cultivation systems, or the introduction of appropriate agroforestry systems such as those proposed for investigation by ICRAF (King and Chandler, 1978). This is considered important in view of the high levels of expensive fertilizers deemed necessary for only small yield increases with normal agricultural crops (Doxiades Associates, 1964 and 1965).

INFLUENCE OF ACACIA SENEGAL ON SOIL FERTILITY AND PRODUCTIVITY

Preliminary results of trials with sorghum on Qoz sands of Kordofan (Doxiades Associates, 1964) have shown that first-year yields on soils cultivated after 12 years of fallow under Acacia senegal were much better on the spots of the land where A. senegal trees were actually uprooted than at distances away from them. Composite soil samples taken from around recently uprooted 12-year-old A. senegal trees every 0.5 m at radii of 0.25 m, and from the A, B, and C horizons of different trees, showed that percent N and C was higher around the tree, with percent N seemingly highest at about 1.75 m away from the tree. The clay content was also slightly higher around the tree base, but soil pH and available P and K were unaffected. The higher soil fertility around the trees was considered to be due to
N₂ fixation and the contribution of falling leaves and pods and to roots decaying from soil organic matter, all leading to more available soil N and higher C/N ratio (Doxiades Associates, 1964; Gerakis and Tsangerakis, 1970; Habish, 1970).

It became evident that *Acacia senegal* plays an important role in the build-up of both better soil physical conditions and higher soil fertility in the traditional agricultural rotations, as well as its function in yielding gum. The part played by different processes, however, has not been fully investigated. In addition to the fertility build-up through N₂ fixation and decaying litter and old roots, it is believed that considerable "nutrient pumping" from the subsoil also occurs.

**THE ROLE OF ACACIA ALBIDA IN SOIL IMPROVEMENT**

*A. albida*, commonly known as "Haraz", occurs widely and is particularly successful along the "wadis" (seasonal water courses) of Western Sudan (see El Amin, 1973; Aloni, 1973; Carr, 1975; Vassal and Lescanne, 1976). Its growth pattern varies widely as it is sometimes found growing singly and sometimes in clumps forming a continuous canopy. It bears its leaves during the dry season and sheds them at the start of the wet season (NAS, 1975).

*A. albida* seemingly increases the fertility of the soil in its immediate vicinity. In some areas sorghum has been continuously grown year after year under *A. albida* stands for as long as 30 years (Ferguson, 1949). Radwanski and Wickens (1970) quote the work of Blair (1963) who observed that irrigated wheat plants attained a height of 80 cm and had eight ears per plant, each with about 32 grains, whereas the plants away from the tree were only 30 cm tall, with three ears per plant each averaging only 22 grains. Yields of millet in Senegal, where plants were growing under *A. albida* trees, were 250% higher in grain yield and 350% higher in protein content than those of millet plants growing much further away from these trees (Charreau and Vidal, 1969).

Adverse conditions on mantle soils of Zalingi have been shown to be alleviated by *A. albida*. These soils have very
free internal drainage and low-water-holding capacity because of the presence of gravel and a relatively small clay content. The clay fraction itself appears to be largely of the 1:1 lattice type (mainly kaolinite) and the structural aggregates have little stability. Thus, when wet, the surface of such soil is structureless and loose, and has little resistance to sheet and gully erosion. In rainless periods the surface horizons become extremely dry and compacted. However, under A. albida, the soils contain more organic matter, which makes the structural aggregates more stable. There is also much leaf-litter on the surface, which forms mulch and which decreases the rate at which water is lost in the dry season, when, in addition, the soil surface is shaded by the fallen leaves.

In a comparison of mantle soils under A. albida and without, the contents of organic carbon, nitrogen and phosphorus differed significantly: the uppermost horizons under A. albida contained more organic carbon, nitrogen and phosphorus but less potassium. Furthermore, the C/N ratios of the topsoil under A. albida was unusually low, mainly because the nitrogen content was high. The more vigorous growth of sorghum under the tree in these conditions suggested that more nitrogen was available to plants there.

More dung can be found near trees, which results from livestock seeking shade and pods under them. This in part accounts for the higher soil N and P found (Radwanski and Wickens, 1967).

A. albida helps bind soils, especially along the "wadis" where this effect may keep the stream beds to their boundaries. Where A. albida has been cleared, erosion and widening of stream beds occur. As yet there is no evidence of N₂ fixation under A. albida (NAS, 1975).

MECHANIZED, RAINFED AGRICULTURE IN THE CLAY PLAINS OF CENTRAL AND EASTERN SUDAN

The soils of the clay plains are described by Smith (1949) and Babiker (1965). They are low in available N but they
displayed a variable response when fertilizer N was applied to sesame, sorghum and groundnuts grown on virgin land (Babiker, 1965). The response to other crops was, however, more even (Rai, 1965). Response to N by these crops, including cotton, was significant however, if these crops were raised after some others (Rai, 1965; quoting Bunting et al. (unpub)).

In the area of mechanized agriculture only sorghum grain is removed from the field. Straw disposal by burning or by discing showed that burning resulted in the lowest yield while discing—temporarily tied-up available N, and the immediate following crop needed additional N fertilization (Rai, 1965). In a follow-up study Rai (1965) showed that green manures of sorghum, sunnhemp and Dolichos lablab, following a grain sorghum crop, were beneficial in building up soil physical properties.

Table 3 shows data for a crops-bush fallow rotation (4 years' fallow) initiated with sorghum and sesame as the main crops at El Dali. The rotation was subsequently abandoned and the land continuously cultivated. The decline and variability in yields after 1964 was so serious by 1970 that some 8330 ha were handed over to the forest department for reforestation with A. senegal.

NOMADIC AND SEDENTARY GRAZING

Nomadism is common among the people living in Northern Sudan, especially those living away from river valleys. The population of livestock in the Sudan has increased from 3 million in 1917 to 35 million head of cattle, camels, sheep and goats in 1970 (Seif el Din, 1973), mainly as a result of increased veterinary services.

Because of uncontrolled grazing, much damage has been caused to the vegetation, especially as a result of the browsing habit of goats, which frequently eat the coppice shoots. The effect of the goats has been especially marked in Kheiran in Northern Kordofan, where the land is now devoid of vegetation.
The northern part of the country north of latitude 12°N has no permanent underground water sources as it lies on basement complex rocks. In the Nubian sandstones and the Um Ruaba series, water is obtained from deep artesian wells. Because of the scarcity of water, the areas around these artesian wells, and the shallow surface "shells" of the basement complex areas, are generally denuded of vegetation due to overgrazing and browsing by animals during their search for water. A single cow treads over 400 m² daily in search of its feed, so considerable damage to soil occurs when many animals are kept in any one area for long periods (Sarlin, 1963). Desertification soon creeps in (Sourman, 1964). Controlled grazing can arrest desertification (Darrag, 1969).

SUMMARY AND CONCLUSIONS

Problems of raising agricultural crops and livestock with inadequate control of factors that adversely reduce vegetative cover on the sandy and heavy clay soils of Sudan have been considered. Both Acacia senegal and A. albida have been shown to be important tree species which, besides producing gum arabic and fuelwood, are very important in the sustainable system of traditional agricultural crop rotations.

Pressure of cultivation and resultant short fallow periods have been shown to result rather quickly in decreased yields on the sandy soils. In these areas, as well as on the clay plains, Acacia trees have been shown to be vital to a viable agriculture, especially in supplying N and P, and in holding the soil against erosion and improving soil physical properties.

The benefits of leguminous trees in agricultural production in the dry climate of the Sudan have not yet been fully demonstrated. Their use in land restoration, especially in shelter belts to combat erosion and in improving microclimates, shows much promise. The search for multipurpose trees for fodder and other economic benefits, as well as for their role
in the stabilization of fragile ecosystems, especially for arid lands, is an important matter that should be actively pursued in the development of viable agroforestry systems for the Sudan and similar areas.

DISCUSSION

Redhead: Has gum arabic production gone up since 1973?

Ahmed: Yes.

Dommergues: In N₂ fixation studies with gum arabic in Senegal we found no N₂ fixation because of low soil moisture and flushes of inorganic N (about 40 kg N/ha), both of which inhibit N fixation.

Poulsen: The gum arabic tree does not have a negative influence on grass vegetation. This tree is remarkable at nutrient re-cycling.

Pratt: How deep do the roots go?

Ahmed: About 80 cm. The soil is generally rocky below.

Keya: There are nodules on young plants of Acacia senegal. They may have a role in N₂ fixation at early stages.

Dommergues: This is limited to the nursery stage.

Nyandat: Does the decline in crop productivity show that there is something wrong with the soil?

Ahmed: The work of the few soil scientists in the Sudan has been concentrated on the irrigated areas.

King: Sorghum-after-sorghum has adverse soil effects as shown by Dommergues. This could contribute to the yield declines in the Sudan.
LITERATURE CITED


Darrag, A. 1969. Letter No. MAR/PMS/4-B-6/5 of pasture department, Kordofan, Sudan.


THE OPTIMUM LENGTH OF PLANNED FALLOWS

Peter M. Ahn*

ABSTRACT

A planned fallow is either a planted fallow or a natural regrowth vegetation that is allowed to grow and occupy the ground for a period, with the deliberate aim of regenerating the soil. Natural fallows are a feature of shifting cultivation, a varied but widespread and extensive system of agriculture in the tropics and subtropics that has worked satisfactorily as long as fallow periods have not been reduced to inadequate lengths by increased pressure on the land. The optimum length of fallow depends on a variety of factors, partly social and economic. In the case of planted tree fallows expected to give some economic return in addition to acting as soil improvers, the time taken to yield timber or other products influences the desirable length of fallow. The main factors, however, are usually those that influence the rate at which the fallow brings about soil changes — including soil, vegetation and climate. To the soil scientist, agronomist and agroforester, the scientific challenge is to investigate the functions of the fallow, and to elucidate and quantify the exact mechanisms by which it improves soil productivity. It is then possible to recommend, in relation to the rate at which these mechanisms work in a given situation, an optimum length. The optimum point at which to clear a fallow is related to the flattening out of the curve showing organic matter levels, i.e. to the time when the annual increment of improvement falls to a level where it no longer justifies keeping the land out of production any further. This point is influenced by economic factors, but cannot be discussed scientifically without a knowledge of both the physical, chemical and other changes taking place, and their effects on the growth and yields of the crops grown when the fallow is cleared.

Fallow are of many types, but are broadly governed by the nature of the environment, particularly soil and climate. In studying fallows and soils and their influence on each other, it is as well, therefore, to adopt an ecological approach, as advocated by Nye and Greenland (1960) in their now classical and still outstandingly useful treatment of the subject.

A fallow, in the sense in which the word is used in connection with shifting cultivation, is almost always a natural fallow, i.e. natural re-growth vegetation which springs up more

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or less spontaneously when a farm is abandoned and no longer weeded. A planted fallow, in contrast, is a fallow deliberately planted, usually a shrub or tree fallow, though in the tropics as a whole planted fallows are unimportant, even though receiving increasing attention by agronomists and agroforesters. A planned fallow, as understood in this paper, is any fallow, whether natural or planted, that is allowed to grow and occupy the ground for a period with the deliberate aim of regenerating the soil. The implication is that the planned fallow is cut down when it has achieved its task as much as circumstances will allow. In practice, however, the extent to which fallows are cleared because the farmer is conscious that they have regenerated the soil sufficiently is doubtful: as pressure on the land increases it is cleared more because it is needed than because the fallow is judged to have fulfilled its task. Nevertheless, it is essential to consider what would be an optimum length of a planned fallow in relation to soil and other conditions, including economic ones. This paper attempts to draw attention to some relevant aspects of this question.

NATURAL FALLOWS

Natural fallows in the tropics are of two broad types, those occurring in forest environments and those in various savanna and savanna woodland areas. The former may be referred to, from the vegetation point of view, as forest re-growth vegetation and the latter as savanna re-growth vegetation.

Broadly speaking the distribution of forest and savanna vegetation types is influenced mainly by climate, particularly rainfall amount and distribution, but it is also modified by soil (edaphic) factors and by the activities of man, particularly by annual grass burning in savanna areas.

Forest climax vegetation is found where there is adequate total rainfall but where there are no long, severe dry seasons. In West Africa, for example, semi-deciduous high forest is found where rainfall is as little as 1000-1150 mm (40-45 inches) (Ahn, 1959a). But elsewhere, such as the coastal areas of the Republic of Guinea, rainfall of over 2500 mm (100 inches) is associated with savanna vegetation because of the long (six months) dry
season which most forest trees cannot survive. Forest re-growth vegetation as a fallow has the advantage that the climate allows a fairly rapid growth once the farm patch is abandoned. This is in contrast to savanna re-growth vegetation of areas with a single wet season, where a farm is abandoned at the end of the rains. There, little or no re-growth will occur until the main rains of the following year, so that there is a delay before the vegetation takes over and begins to function as a soil improver.

Forest re-growth vegetation in the tropics often consists of a mixture of many species. It is only in certain areas of impoverished soils and vegetation that the usual wide range of species is reduced. In an investigation on the successive stages of forest re-growth vegetation in the forest areas of Ghana, Ahn (1958) found that species did not change very much between areas, nor were they greatly influenced by soil factors, apart from very poor drainage. As long as seed sources had not been diminished by overcultivation in large areas, the various stages of the forest re-growth exhibited a wide floristic composition. It has been argued that natural selection of the most competitive species, plus the presence of a wide variety of species with different root systems and nutritive demands, ensures that a natural fallow, as provided by a forest re-growth vegetation, is likely to be as efficient as all or most planted fallows.

The successive stages of a forest re-growth fallow are fairly well defined. When a farmer stops weeding, a large variety of soft-stemmed, leafy forbs springs up. This stage may last about 18 months and is appropriately referred to as "forb re-growth". Among the forbs may be coppice shoots from the stumps and root systems of trees cut down during the earlier clearing of the forest or forest re-growth vegetation. The advantage of the forb re-growth is that it springs up quickly and adds large quantities of leafy material to the soil, so that organic matter build-up at this early stage of the fallow may be relatively rapid. In practice the cropping period and the fallow period may not be sharply defined, since the former merges into the latter, giving an overlap. This overlap is useful in contributing to the rapid getaway of the fallow and in protecting the
soil during and immediately after the harvest period, which may itself be prolonged into the fallow.

After about 18 months, depending on soil conditions, climate, vegetation and cropping history, the forb re-growth becomes a tangle of shrubs and climbers, and this stage, which lasts a further 6-8 years or more, again depending on local conditions, is known as re-growth thicket. At this stage the vegetation is relatively dense and difficult to clear. Eventually however the re-growth thicket is usually taken over or dominated by quick-growing, light-demanding trees, as well as coppices from previous slower-growing trees, which suppress the thicket: the re-growth is now at the secondary forest stage. This stage is usually characterized by frequent fast-growing trees of various species, but the secondary forest, if left long enough, will itself slowly change in composition as the slower-growing, shade-tolerant species get the upper hand and drive out the fast-growing colonizing trees. The type of re-growth vegetation, its weight and floristic composition are relevant to considerations of its function as a fallow and as a soil improver.

In savanna areas there is a gradual variation of vegetation from the wetter areas to the drier ones, depending on rainfall amounts and the relative lengths of wet and dry seasons, but the vegetation is also modified by soil factors and by man. "Savanna" is originally a West Indian Carib term applied to areas not covered by forest. Now it is used somewhat differently in different areas. The "savannas" of the West Indies and parts of South America are often edaphic ones modified by soil factors such as an impermeable horizon and seasonally poor drainage (De Ovin, 1973; Pietri, 1973; Samuels, 1973). The savannas of Africa, which cover vast areas on either side of the Equator, are not edaphic even though these too may occur quite locally, as behind the West African littoral (Ahn, 1959b). They are primarily climatic, but are also much influenced by man.

Kimble (1960) describes savanna vegetation as consisting of "grasses, bushes and trees adapted to conditions of alternating wetness and dryness" and emphasizes that in Africa there is an imperceptible grading of one savanna subgroup with another without
clear distinctions of either species or structure, though the general gradient is obviously related mainly to rainfall. In West Africa botanists and ecologists distinguish between the moister Guinea savanna, the intermediate Sudan savanna and the relatively dry Sahel savanna, which succeed each other as one goes from the forest to the south to the desert to the north. Although broad-leaved trees become sparser as the rainfall and duration of wet season diminish, and the grass species change to some extent, the lack of clear boundaries has led to somewhat different subdivisions being described and mapped by different investigators. The different approaches of Keay et al., (1959), Schantz and Marbut (1923), Molard (1956), Harrison Church (1974), Rattray (1960) and Phillips (1959) have been usefully synthesized by Swami (1973) to arrive at a composite map with a savanna core zone and transitional areas to the north and south.

It appears that the African savanna areas in particular have been much modified by annual burning of the dead grass in the dry season by man over a long period. Fire protection results in a thickening of the vegetation, sometimes to a savanna woodland, and the grass species change. The evidence from protection plots in West Africa has been convincingly summarized by Ramsay and Rose-Innes (1963), who concluded that the present formations are a man-modified fire sub-climax.

The efficiency of savanna re-growth vegetation as a fallow and soil improver is related, as in the case of forest re-growth vegetation, to such characteristics as the total weight of vegetation, its composition, and the extent of the root system. The weight of savanna vegetation varies considerably according to type and the density of woody vegetation it contains, and is related to rainfall, but is generally much lower than that of forest. Nye and Greenland (1960) quote figures of about 42-300 tons/ha for various forest and forest re-growth formations, excluding roots, as compared with about 11 tons/ha for an Imperata cylindrica fallow including roots, and 2.2 tons/ha for a natural grassland. Colley and Leith (1972) in a study of world net primary productivity (annual biomass increases together with litter production) give annual increases of 20, 15 and 7 tons/ha for
tropical rainforests, tropical deciduous forests and tropical savannas respectively, but the range given for the latter goes down to 2 tons/ha.

**NATURAL FALLOWS IN RELATION TO SHIFTING CULTIVATION**

Natural fallows are associated with shifting cultivation in the tropics, a system defined as one in which temporary clearings are cropped for fewer years than they are allowed to remain in fallow (Sánchez, 1976), so that the land-use factor of Allan (1965), defined as years of cultivation plus years of fallow divided by years of cultivation, is above 2. Shifting cultivation in one or other of its many forms is very widespread in the tropics, being the predominant practice in about 30% of the exploitable soils of the world (Hauck, 1974). It is particularly important in tropical Africa and South America, but even in Asia about one-third of farmland is farmed in this way (Dobby, 1950).

Although originally criticized as primitive and wasteful, shifting cultivation, it is now increasingly realized, works satisfactorily as a system able to maintain production at moderate levels, provided that population densities are moderate in relation to the land available and fallow periods do not become progressively shorter. (If the latter conditions are not met, a downward spiral of reduced yields, shorter fallows and progressively lower productivity will follow.)

The system has been criticized because of the generally low proportion of land under cultivation at any one time and the generally low yields during the cropping period itself. Improvements in agronomic practices and greater inputs, however, do result in yield improvements during the cropping period. The general strategy to improve shifting cultivation lies in a combination of increasing yields during cropping and increasing the ratio of length of cropping to length of fallow. This is done by lengthening the cropping period, using fertilizers and other inputs, and by shortening the fallow period. In this connection, the optimum or practical length of fallow in relation to the restoration of soil productivity, which forms the subject of this paper, is particularly relevant.
PLANTED FALLOWS

In shifting cultivation, the farmer relies on a natural fallow to spring up with little or no assistance from him. One of the relatively early suggestions for the improvement of shifting cultivation was to replace the natural fallow by an artificial, planted fallow. This, it was hoped, would improve soil productivity at a faster rate than natural fallows and at the same time allow a mechanized system of clearing because of its relative uniformity and other characteristics.

It was thought that legumes in particular, for example relatively fast-growing species of *Glyricidia*, might restore soil organic matter levels faster than natural re-growth vegetation and perhaps add more nitrogen to the system. In practice, because of the natural selection of the most efficient species and the great variety of species commonly found in forest re-growth vegetation, it has proved difficult to find a planted fallow that acts more quickly than the natural vegetation in forest areas, while the latter has the big advantage from the farmer's point of view that it comes of its own accord. Savanna re-growth vegetation acts more slowly than forest fallow vegetation, and is less efficient as a soil improver, so in this case it might be easier to obtain a better effect from planted fallows if the limitations of the lower rainfall and longer length of dry season can be overcome.

One of the more promising and obvious applications of agroforestry would be to select species and methods that would make it economically attractive and technically feasible to replace natural fallows with planted tree fallows. To be acceptable, such a fallow should: (a) restore soil productivity in a way comparable to, or better than, the natural re-growth vegetation, and (b) provide the farmer with some sort of economic return, such as timber or firewood for sale, or forage for his animals, which would compensate him for the extra work of planting a fallow.

At present there is still very little use in the tropics of planted tree fallows, and little practical knowledge of what
might be recommended in particular areas. To fill this gap, a number of research projects have been carried out, or are now being carried out, in which the effect on the soil of tree species of known economic value is examined to assess their potential value as planted fallow species, fulfilling both objectives (a) and (b) described above. These investigations are of two broad types: (1) those that start at the beginning and plant a stand of the tree species in question on a soil that has been previously examined and characterized (preferably one that has already gone through a cycle of cropping), and (2) those that examine existing stands of trees and the soil under them in order to assess the effect of the trees on the associated soil. The latter method implies making certain assumptions about the soil when the tree stand was originally established, but quicker results are obtained than with the first method.

In the Cameroons, for example, agroforestry investigations currently under way at Edea, in the wet Littoral Province, include the screening of a number of local and imported leguminous trees, including *Leucaena leucocephala*, for their adaptability to the local conditions of high rainfall and acid soils. They also include the subsequent investigation, over a period, of the effects of stands of selected species established on newly-cleared soil that has been carefully characterized as to its initial chemical and physical properties by taking bulk samples of the 0-15-inch soil layer.

In somewhat related agroforestry investigations in the less wet Ibadan areas of Nigeria, the value of different tree species as possible planted fallows is being assessed by examining existing stands of teak (*Tectona grandis*), *Cassia siamea* and *Gmelina arborea* in particular, either singly or mixed. The soils are analyzed before coppicing in order to elucidate the effects of the tree stand on the soil, the trees are coppiced and the biomass weighed and analyzed, and an agricultural crop is grown on the soil to test the relative effects of the different stands examined as soil-improvers. Preliminary results indicate that *Cassia siamea* is the most efficient as a soil improver, but the least attractive in terms of economic yield, and that teak gives the most attractive returns economically but is a relatively
poor soil improver. Plots under tea.k are often relatively eroded, and crops planted after clearing do less well than those planted on soil cleared from Caspia and other species. This example serves to illustrate the aims of planted fallows and some of the difficulties encountered by current investigations.

In the more densely populated parts of south-eastern Nigeria, farmers practise a planted shrub fallow system based mainly on the planting of Acioa barteri, a shrub or small tree belonging to the Rosaceae, often associated with Anthonotha macrophylla, an introduced species that has spread widely. This is an area where population pressure on the land, resulting in very short fallows sometimes of only a year or two, has forced farmers to modify the traditional systems based on natural re-growth vegetation alone. It suggests that it is perhaps in areas of highest pressure on the land that agroforestry systems based on planted fallows might first find acceptance.

CONSIDERATIONS AFFECTING THE OPTIMUM LENGTHS OF FALLOW

The "optimum" length of fallow depends on a very great variety of factors that must vary according to local circumstances as well as to what is meant by "optimum". An optimum fallow in terms of cash returns over a short period might not be the same as an optimum fallow viewed in relation to maintaining the long-term productivity of the soil. Since agriculture is not the art (or science) of growing crops, but the art (or science) of growing crops for a profit, the factors governing optimum fallow lengths must include economic and social ones. In the case of planted tree fallows expected to give an economic return in addition to acting as soil improvers, the length of time the tree fallow takes to produce that return (such as marketable timber of a certain size) will influence the desirable length of that fallow.

Nevertheless the main factors affecting the optimum length of fallow are those environmental ones of soil, vegetation and climate that influence the rate and efficiency with which the fallow brings about desirable soil changes.

To the agronomist, agroforester and soil scientist, the scientific challenge is to investigate the various functions of
the fallow and to elucidate and quantify the exact mechanisms by which it restores the productivity of a soil. When we know what changes occur during the fallow periods, then we are in a position to compare scientifically the efficiency of different types of fallow and their optimum lengths and to consider the practicability of bringing about those changes more quickly and efficiently by other means.

THE FUNCTIONS OF A FALLOW

An obvious function of the fallow is protective: it shades the soil and thus lowers soil temperatures, which in turn serves to reduce soil organic matter mineralization rates, and it protects the soil from the full force of the rain. Tropical rains are known for their relatively high erosivity, due to high intensities and large drop sizes resulting in high kinetic energy levels. Probably no topsoil structure is sufficiently stable to withstand this high erosivity for long unless protected by a vegetation cover.

A second important function of the fallow is that it serves as a break in cropping that checks pest, disease and weed build-ups. This function might, at least to some extent, be performed by a rotation of crops of by a grass ley, but in shifting cultivation a frequent reason for a farmer to abandon his land is that he is induced to do so by the weeds of cultivation which he finds difficult to control. In such cases the land may not be exhausted and he may, as pointed out by Coulter (1972), actually move to another site where the soil nutrient level is much lower than that of the plot just abandoned because of weeds. To the extent that a fallow functions as a pest, disease and weed break, it is necessary, if an optimum length of fallow in a particular situation is to be arrived at, to consider how long it takes a fallow to check pests and diseases and to smother the weeds of cultivation. Social factors play a part here, because weeding is often done by women, whereas the clearing and burning of new land is the work mainly of men. While weeding is particularly onerous in the rains, clearing and burning is a dry season activity.
In forest re-growth in particular, many of the weeds of cultivation persist into, and contribute to, the initial forb re-growth stage. When this stage gives way to the thicket stage, shrubs, climbers, coppice shoots and young trees progressively suppress the forbs and the weeds of cultivation are suppressed with them. This suggests that to be efficient as a weed break, a forest re-growth vegetation has to be kept growing long enough to reach at least the later thicket stage at which woody species have driven out the forbs. In many tropical situations this takes 4-6 years. *Imperata cylindrica* (often known as 'lalang' or 'spear grass' in Africa and 'cogon' in Asia) is a particularly troublesome and persistent weed of some areas. Pendleton (FAO, 1958), writing of south-east Asia, said that the length of time the land is allowed to remain under forest re-growth fallow "depends on how soon the forest can choke out the 'cogon' and other weeds". Freeman (1975) also discusses fallow periods in relation to 'cogon' (*Imperata cylindrica*) invasion following rice cultivation, and states that in Sarawak 12-15 years may be needed, depending on whether the cropping period included one or two clearings and burnings. *Imperata* is particularly aggressive in south-east Asia; in Africa it is often less so, but may be locally important in the forest-savanna fringe areas.

The main function of the fallow in most cases, however, and the function of particular concern to the soil scientist, is that of improving the physical, chemical and biological properties of the soil so as to make it a more suitable medium for crop growth than it was when it was abandoned at the end of the previous cropping period. The changes in the soil during the fallow period are very complex, and their exact nature will vary with the type of soil and its properties, the structure, floristic composition, weight and rate of growth of the vegetation and with the climate, as well as with the previous history of the soil, including the extent to which clearing and burning destroyed or spared the previous perennial grasses and trees. These changes might be considered in a general way to be related to two distinct but related functions of the vegetation:

(a) the ability of the fallow vegetation to raise soil organic matter levels, and
the nutrient trapping and cycling effect of the vegetation, which results in the net movement of nutrient ions from the lower soil layers to the topsoil, via litter fall, thus resulting in topsoil enrichment.

Soil organic matter levels depend on the balance between additions of new humus from the decomposition of raw residues and humus losses due to mineralization. Additions and losses are conveniently considered separately, since they are affected by different factors. The rate of addition of new humus to the soil depends mainly on the rate at which the vegetation supplies raw organic residues, including both the litter derived from the above-ground parts of the vegetation and dead roots and root exudates. These residues from the vegetation are supplemented by the bodies of soil micro- and macro-fauna. The rate at which the vegetation supplies the raw organic residues that form the raw material for the soil organic matter, and the nature of those residues, depends on the type and weight of the vegetation. In the early stages of forest forb re-growth, the vegetation supplies relatively large amounts of leafy material, and organic matter levels might rise relatively rapidly, but as the re-growth gets older, so might new growth be more in the form of wood and additions of raw residues to the soil will change in amount and composition. The C/N ratio of the organic matter will reflect the composition of the residues from which it is derived as well as the nature of the microbial activity converting them to humus.

It is instructive to compare the amounts and distribution of organic matter under tree and grass communities. In temperate areas of the world, higher organic matter contents are often found under steppes (as in the case of Chernozem and related soils) than under forest. In the tropics this situation is usually reversed. Tropical forest soils receive greater weights of raw organic residues than do savanna soils and, because of lower soil surface temperatures, mineralization rates may be lower. Thus, these soils usually contain considerably more organic matter than do savanna soils, where the total weight of vegetation is less and the amount of raw organic material received by the soil is often further reduced by the annual dry season grass burning, during which the dead grass is ashed. Not only do amounts of organic matter differ between tropical forest and savanna soils,
but the distribution is markedly different (Ahn, 1970). In forest soils large quantities of litter are received at the soil surface and decompose at or near it. The contribution of tree roots may be relatively small and many of these are, in any case, concentrated in the top few inches of the soil. The result is that in forest soils there is a marked concentration of organic matter in the topsoil, particularly in the top 2-3 inches, and then a rapid fall below this to a subsoil in which organic matter levels are typically relatively low (Figure 1 and Table 1). In savanna soils, in contrast, there is much less organic matter in the topsoil, but the transition to the subsoil is more gradual and, in the subsoil, there may be as much organic matter as in forest soils. This more diffuse distribution is due to the lower contribution of surface litter compared with forest soils and the relatively greater contribution of the diffuse grass root system.

The nutrient cycling function of the fallow vegetation depends very much on the density and extent of its root system, which may also differ markedly between forest and savanna re-growth vegetation communities. A deep rooting system has the double function of bringing up nutrient ions released at depth, i.e. from decomposing rock, and of trapping downward-moving ions when an excess of water leads to leaching. In agroforestry systems combining deep-rooted trees with shallow-rooted crops, the trees may be credited with bringing up nutrient ions from deeper layers and thus benefiting the crop. In fallow, the effect may be similar except that the trees precede the crop rather than growing side-by-side with it. Trees and shrubs are often regarded as being particularly efficient at concentrating divalent bases in the topsoil, but savanna grasses and associated savanna trees may have deep root systems and not enough is known quantitatively about the relative efficiencies of the two systems in bringing up nutrients from depth. Savanna soils are, in any case, often shallower and less leached than forest soils, so they are often better supplied with nutrient cations but more likely to be deficient in nitrogen and sulphur. This is due to their lower organic matter contents and, perhaps, the influence of the annual burning referred to above, in which these two elements "go up in smoke" to a considerable extent. In both forest and savanna
Fig. 1: Organic matter distribution in typical West African forest and savanna soil profiles (Ahn, 1970)
Table 1: Typical organic matter contents of West African forest and savanna soils in relation to cropping and fallow (Ahn, 1970)

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Virgin</th>
<th>Cultivated</th>
<th>3 years fallow</th>
<th>10 years fallow</th>
<th>Cultivated</th>
<th>Fallow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper topsoil</td>
<td>5.0-12.0</td>
<td>2.0-4.0</td>
<td>3.0-5.0</td>
<td>3.0-7.0</td>
<td>1.0-1.5</td>
<td>1.0-3.0</td>
</tr>
<tr>
<td>Lower topsoil</td>
<td>1.0-3.0</td>
<td>1.0</td>
<td>1.0-1.5</td>
<td>1.0-2.0</td>
<td>1.0</td>
<td>1.0-2.0</td>
</tr>
<tr>
<td>Subsoil</td>
<td>0.5-1.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5-10</td>
<td>0.5</td>
<td>0.5-1.0</td>
</tr>
<tr>
<td>Weathered substratum</td>
<td>0.1-0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

soils, however, phosphorus is frequently deficient, and one of the more important functions of a fallow, in both cases, might be the increase in the supply of organic phosphorus in the top soil which can improve the supply of available phosphorus to the succeeding crop.

SOIL CHANGES UNDER FALLOW

The nutrient enrichment effects of fallow vegetation can be associated with chemical changes in the soil under fallow, but the effects of fallow vegetation in building up organic matter levels are associated with both chemical and physical changes. Since chemical and physical soil changes are so intimately linked, it is difficult to assess their relative importance. This will, in any case, vary according to local soil and other circumstances. However, to the extent that declining yields during the latter part of a cropping period cannot be maintained by applications of chemical fertilizer alone, as sometimes appears to be the case, the decline and subsequent improvement of soil physical factors under cropping and fallow may be particularly important.

During cropping, organic matter levels in the soil decline. The decline is usually thought to be relatively rapid at first and then to become more gradual. The decline is due to a combination of factors that together (a) reduce the rate of additions of new
humus to the soil and (b) increase the rate of mineralization loss, as compared with conditions under previous fallow or original vegetation. The lower rate of addition of new organic material is related to the reduced rate of residue addition under cropping. The increase in the rate of mineralization loss is associated with increased microbial activity related to cultivation and, often, ash additions during clearing and burning, followed by higher soil temperatures as the soil is more exposed to the sun. Exposure to rain may also result in some actual soil loss due to erosion.

The rise in organic matter levels during fallow results from a virtual reversal of the trends that caused its decline under cropping. Once a forest re-growth vegetation is established, the production of litter quickly reaches a high level and is supplemented by dead roots, root slough and exudates, though under a savanna re-growth both litter and root additions are less and are often further reduced by annual burning. Of the raw organic material added to the soil, only a proportion will contribute to the soil humus, the remainder being lost through oxidation. Nye and Greenland (1960) estimate that the proportion finding its way into the soil humus is 10-20% of that added, so that with an addition of the 15,000 kg/ha of raw material they consider might be typical of forest regions, net additions might be between 1 and 2.25 tons/ha of humus a year. Typical corresponding figures for savanna areas would be much lower, perhaps 2,700 kg/ha of raw residues and net humus additions of only 0.27 to 0.67 tons/ha a year. These ranges may be very approximate but they draw attention to factors responsible for the fact that forest fallow is generally much more efficient as a soil improver than savanna re-growth vegetation.

These additions of humus are to varying extents offset by humus losses as mineralization at the same time, any net increase representing the balance between these gains and losses. However, the rate of mineralization loss itself changes and it is thought that this rate is proportional to the amount of humus carbon present (Jenny, 1941). The rate of increase can thus be represented as

\[ A - kC \]
where \( A \) is the annual addition of humus, \( k \) is the decomposition constant and \( C \) is the amount of humus presently in the soil.

In a soil at equilibrium, when gains balance losses,

\[
A = kCE \tag{2}
\]

where \( CE \) is the amount of humus carbon at that equilibrium level. At any particular fraction, \( p \), of the final equilibrium level,

\[
I = A - pkCE \tag{3}
\]

since we have now substituted \( pCE \) for \( C \) in equation \([1]\), above. According to equation \([2]\), however, \( kCE \) at equilibrium is equal to \( A \), the annual humus addition, so that, by substituting, we get

\[
I = A(1-p) \tag{4}
\]

The practical importance of these considerations can be brought out by considering a few examples. First, if humus carbon is at 50% of equilibrium level, then \( p = 0.5 \), and \( I = A(1-0.5) = 0.5 \, A \). The annual increment is therefore half the annual addition. Second, if humus carbon is at 75% of the equilibrium level, so that \( p = 0.75 \), then \( I = 0.25 \, A \) and the annual increment is down to one-quarter of the annual addition. Finally, if humus carbon is at 90% of the equilibrium level, so that \( p = 0.9 \), then \( I = 0.1 \, A \), and the annual increment is down to only one-tenth of the annual addition.

Examples of calculation based on this reasoning are given in Table 2, which shows the net annual gains (expressed as a percentage of the final equilibrium level) when humus carbon levels are initially at 50% of the equilibrium level and annual additions are equivalent to 10% of the equilibrium level, and also when the initial humus carbon levels are only at 25% of equilibrium levels and additions are 10% and 5% of the equilibrium level.

The calculations given in Table 2 are shown graphically in Figure 2 which gives curves of humus addition for soils initially at 25% and at 50% of equilibrium levels. These curves show clearly that the net annual humus increment becomes progressively less as the fallow gets longer.
Table 2: Calculations showing annual humus additions, expressed as percentages of the final equilibrium level (a) for a soil initially at 50% of equilibrium level with annual additions of 10% of equilibrium level, (b) for a soil initially at 25% of equilibrium level with 10% additions, and (c) for the same soil with 5% additions. Assumptions include: (i) that annual humus additions are constant, and (ii) that the annual decomposition rate (k) is the same during the various stages of the fallow as at equilibrium.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>% CE at beginning of year</th>
<th>Net gain (I=Al-p))</th>
<th>% CE at end of year</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>50.0</td>
<td>5.0</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>55.0</td>
<td>4.5</td>
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<td>3</td>
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<td>4.0</td>
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</tr>
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<td>4</td>
<td>63.6</td>
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<td>3.3</td>
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<td>76.1</td>
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(a) Increase with an initial humus content of 50% of equilibrium and annual additions of 10% of equilibrium

<table>
<thead>
<tr>
<th>YEAR</th>
<th>% CE at beginning of year</th>
<th>Net gain (I=Al-p))</th>
<th>% CE at end of year</th>
</tr>
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<tr>
<td>1</td>
<td>25.0</td>
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<td>2</td>
<td>32.5</td>
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<td>39.2</td>
<td>6.1</td>
<td>45.3</td>
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<td>4</td>
<td>45.3</td>
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<td>50.8</td>
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<td>5</td>
<td>50.8</td>
<td>4.9</td>
<td>55.7</td>
</tr>
</tbody>
</table>

(b) Increase with an initial humus content of 25% of equilibrium and annual additions of 10% of equilibrium

<table>
<thead>
<tr>
<th>YEAR</th>
<th>% CE at beginning of year</th>
<th>Net gain (I=Al-p))</th>
<th>% CE at end of year</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>25.0</td>
<td>3.9</td>
<td>28.3</td>
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<td>8</td>
<td>47.6</td>
<td>2.6</td>
<td>50.2</td>
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(c) Increase with an initial humus content of 25% of equilibrium and annual additions of 5% of equilibrium
Fig. 2: Graphs showing calculated humus contents during fallow periods for soils with initial humus contents at 25% and at 50% of equilibrium level, receiving annual additions of humus carbon equivalent to 5% and 10% of humus carbon at equilibrium level.
As pointed out by Nye and Greenland, the rate of humus increase thus depends very much on how far present levels are below the humus equilibrium level appropriate to local circumstances, *i.e.* that level at which gains balance losses and there is no further net change. If a soil is at 50% of its equilibrium level, the rate of humus increase will be twice what it would be if the soil were already at 75% of its equilibrium level. This important concept helps to explain: (a) why raw organic matter additions to different soils might have very different effects on organic matter content increases depending on whether the soil is well below its equilibrium level or already near it, and (b) that during a fallow period, the initial rate of organic matter increase is relatively high, but that subsequent annual additions become progressively lower, so that the curve flattens out progressively as equilibrium levels are approached. This curve of organic matter conditions can in turn be used as a guide to what the optimum length of fallow might be, since it indicates that each annual increment of net humus carbon increase is smaller than that of the preceding year.

The effects of an increase in organic matter levels during fallow are fundamental to the agricultural productivity of the soil. Chemically the increased humus content increases the cation exchange capacity of the soil and, during subsequent cultivation, mineralization of the increased humus content will result in the release of higher amounts of a range of major and minor elements. To the extent that pH levels and percentage saturation do not change during the fallow, it appears that the increased cation exchange capacity is matched by an increase in the supply of exchangeable cations in the topsoil, presumably those brought up from the lower soil layers by the vegetation. If the C/N ratio of the humus does not change appreciably during the fallow period as humus levels increase, it means that the total nitrogen content of the soil organic matter has also increased in the same proportion as has organic matter as a whole. Similar considerations apply to the C:S and C:P ratios and the totals of organic sulphur and phosphorus in the soil.
The physical changes brought about by increases in humus levels during the fallow, assisted by the protective action of the fallow vegetation, might be even more important than the chemical changes in many situations. An increase in humus carbon is associated with an improvement in soil structure, as shown by an increase in the size and grade of crumbs in the topsoil. This structural improvement, in turn, leads to a lower bulk density and to better aeration, rainfall acceptance and permeability. Most investigators would also agree that an increase in soil organic matter leads to an increase in the available water-holding capacity of the soil.

SOIL CHANGES UNDER FALLOW IN RELATION TO OPTIMUM LENGTHS OF FALLOW

Physical, chemical and biological changes under fallow are very complex and vary according to local conditions, but to the extent that they are related to increases in the levels of humus carbon during the fallow, those increases might usefully be taken as a parameter reflecting the various soil changes that together increase soil productivity. It will be noted that these changes affect the topsoil more than the subsoil, and might best be followed by monitoring changes in the 0-15 cm topsoil layer.

To the extent therefore that organic matter increases in the soil are felt to be of importance to the restoration of its overall productivity, an optimum length of fallow would be related to the point in the organic matter increase curve where it flattens out. Flattening out of the curve reflects the progressive reduction in the size of the annual increment of humus addition referred to in the previous section. As this increment gets smaller, the justification for keeping the land out of production for a further season becomes less. Economic factors, and the opportunity cost of keeping the land idle, plus the local pressure on the land in relation to population/land ratios, will all influence the farmer's decision as to when to clear afresh. Under forest conditions, both soil organic matter changes and the transition from thicket to young secondary forest re-growth suggest that, in many areas, a fallow of 6-8 years
is a desirable practical minimum: below this the soil will be maintained by successive fallows at a lower organic matter level and level of productivity. In savanna areas, changes under fallow are slower, and organic matter levels are generally much lower than in forest areas.

Since, as fallow periods become shorter, soil organic matter levels are progressively falling in many tropical shifting cultivation areas, it becomes urgent to examine the extent to which organic matter levels are really as important as they are generally assumed to be. In many highly-weathered tropical soils physical properties are relatively good, due to a stable microaggregation (Ahn, 1974) and in these soils at least, the physical deterioration associated with a fall in the organic matter level can be expected to be less than that of inherently less-well-structured soils.

To the extent that farmers and modern science are able to maintain yields on soils as organic matter contents decline, the optimum lengths of fallow will shorten. The ultimate aim of agronomic research in the tropics is to reduce fallow to zero. Population pressures in some areas have already reduced fallows to lengths equal to, or only a little longer than the cropping periods. In those circumstances considerations of the optimum lengths of fallow have to be revised if they are not to seem merely academic. Nevertheless, any fundamental rational consideration of fallow periods in relation to cropping must be based on a scientific understanding of the soil changes that occur under fallow and their relevance in a particular area to the subsequent performance of crops grown when that fallow is cleared again.

**DISCUSSION**

**Lal:** Continuous farming with sustained production is indeed possible and feasible in soils of the tropics, provided soil physical conditions are maintained at an optimum level, and nutrient balance is provided by adequate fertilization. The use of commercial fertilizer is inevitable for sustained high yields. However, fertilizer requirements can and should be minimized by suitable agronomic practices and appropriate soil management techniques.

**Ahn:** I entirely agree, particularly with your suggestion that soil physical conditions are maintained. The difficulty of maintaining both physical conditions and adequate plant nutrient amounts and balances obviously varies very much from soil to soil.
Tejwani: While discussing the length of planned fallows, it is presumed that the people who practise it will continue to live there. This would increase population pressure, and hence warrant a decrease in the length of fallow; and production may decrease. While planning farming systems for shifting cultivation, it will be desirable to carry out work on a watershed basis and also to plan for conservation of the production base by providing for forest trees, horticultural lands and encouraging permanent locations.

Ahn: I agree with this. Two obvious ways that already exist for doing away with shifting cultivation are: (1) planting permanent crops, e.g. tea, coffee, rubber, oil palm, etc., and (ii) planting rice in swamps. Sugarcane has been grown for quite long periods in some tropical areas, and soil structure has improved. The main difficulties appear to be associated with the production of arable annual crops in the lowland tropics, without the use of a fallow, a ley or impractically high inputs. The problem obviously varies from soil to soil; if the soil has an inherently good structure (due, for example, to water-stable micro-aggregation) then the possibility of improving shifting cultivation by lengthening the cropping period and shortening the fallow are increased. We should not necessarily equate shifting cultivation with low inputs or the non-use of improved seed, fertilizers, etc.

Sánchez: Is the organic C level in the top 1 metre really different between forest and savanna soils?

Ahn: It is. At least the experiences in Africa confirm this.

Fried: I do not think we should accept from a research standpoint that we must have fallow.

Ahn: Eventually the fallow has to be gradually reduced or eliminated.

King: Peter Ahn and, earlier, Rattan Lal stated that planted fallows are not as efficient as natural fallows. They have based their opinions on rather scattered bits of research in some parts of the tropics. The experiments that have been conducted, in respect to planted fallows, have not attempted to simulate the physiognomy, the structure, of natural tropical forests. They have not attempted to reproduce the stages of succession that occur in tropical forests. What we should try to do is to select tree species that simulate these conditions. I should not like a principle to be enunciated that planted fallows are inefficient before adequate research has been conducted.

Ahn: I fully agree with Dr. King that we cannot expect a stand of a single tree species (such as teak or Gmelina) to do what it takes a succession of different plant communities in nature to achieve. I tried to show that in forest re-growth, in particular, we are dealing not only with a great variety of species, selected by natural competition, but with a succession of plant communities (first dominantly forbs; then shrubs, climbers and coppice shoots; and finally a succession of different trees).

I did not mean to imply that planted fallows cannot be as efficient as (or more efficient than) natural ones. If you plant the right things there is no reason to assume that they cannot be at least as efficient. What I said was that in practice, so far, "it has proved difficult to find a planted fallow that acts more quickly than the natural vegetation in forest areas".
LITERATURE CITED


SOIL FERTILITY MAINTENANCE AND CONSERVATION FOR
IMPROVED AGROFORESTRY SYSTEMS IN
THE LOWLAND HUMID TROPICS

B.N. Okigbo and R. Lal*

ABSTRACT

About 80% of the potential arable land area in the world lies in the tropical forest belt. These forests have a marked diversity of plant formations consisting of some 2500 tree species alone. A perfect ecological equilibrium in this closed ecosystem is drastically changed by deforestation for food production. If not adequately managed, a rapid decline and degradation of soil productivity is the result. The problems of soil erosion, and water and nutrient imbalance, are serious indeed. Agroforestry systems have an important role in maintaining the productivity of these soils. A variety of trees are used in different types of fallowing. In traditional farming systems, fallowing for rejuvenation of soil fertility may be: (1) natural forest fallow, (2) natural woodland or bush fallow, and (3) planted fallows. In addition to improving soil fertility and conserving soil and water resources, different tree species used in fallowing have multifarious uses. Maintenance of soil fertility in the case of large-scale commercial farms can also be achieved through the judicious combination of crop residue mulches, reduced tillage systems, and proper cropping sequences and crop combinations. There is a need for research on the identification, germplasm collection and improvement of tree species grown for food, fallowing, and other various uses. Systems of land management should be developed to incorporate tree species as an integrated part of watershed management in agroforestry.

The increased food and agricultural production required by the world's rapidly growing population can be achieved either by increasing the area of land under cultivation or by ensuring more productivity per unit area. The former constitutes the most important method of increasing food production that is widely practised in the tropics. The continued reliance on this method depends on both the availability of land and the techniques of reducing the cost and labor of putting forested lands into production. Of the world's potential arable land area of about 3.2 billion ha, less than half (1.4 billion ha) or 10% of the total land area is being currently utilized (FAO, 1958; Cramer, 1967; Borgstrom, 1969; ERS, 1974; Brunig et al, 1975; and Revelle, 1976). Of the remaining 1.8 billion ha, 1.4 billion lies within the tropics and is covered by forest. According to Sanchez (1976) rainforests cover 52% of tropical America, 38% of tropical

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Asia and the Pacific, and 12% of Africa. However, Africa contains about 27% of the world's tropical rainforest with about 1.26 ha of forest per head, compared to 4.3 and 0.26 ha respectively, for South America and Asia. A large area of forest in West Africa has been destroyed by man, drastically reducing the area of virgin forest. Windhorst (1976) quoting Weck (1961) estimated the area of surviving primary forest and older secondary tropical forest to be 124.3 million ha in Africa, 130.4 million ha in Southeast Asia, and 233.4 million ha in South and Central America.

This paper considers the potentials of agroforestry in increasing agricultural production, and systems of ecologically acceptable and efficient resources management. In addition, the problems of forest clearing, soil conservation, soil fertility maintenance and management in the humid tropics are discussed.

PROBLEMS OF FOREST CLEARING, BURNING AND CULTIVATION

The following climatic conditions promote high biological productivity: (a) daily temperature changes that are greater than the small monthly ranges, (b) a climate that promotes growth during the whole year, (c) small differences in the day length, (d) rainfall distribution with less than 2-3 dry months, (e) temperatures of about 22°C in lowland areas and 18-22°C on mountains, (e.g. elevations of not more than 800 m in the lowlands and 800-1400/1600 m in mountains), and (f) diurnal temperature ranges greater in mountain than lowland humid rainforest (Windhorst, 1975). Annual increases in productivity for tropical conditions compared with those of the temperate region are presented in Table I. The climax vegetation, under the conditions listed above, is tropical rainforest - a plant formation with a marked diversity of species, predominantly trees of over 2500 species. These trees grow in association with shrubs and herbs arranged in a number of strata that provide mechanical support for climbers, stranglers, epiphytes and heterotrops (saprophytes and parasites). Under normal circumstances, these species are in equilibrium with their environment (Richards, 1966; Walter, 1971; Okigbo, 1979). In this closed forest ecosystem, most of the plant nutrients are tied up in the vegetation.
Table 1: Annual increase in dry matter production (t/ha) of selected vegetation types*

<table>
<thead>
<tr>
<th>Type of vegetation</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical rainforest</td>
<td>20</td>
<td>10-35</td>
</tr>
<tr>
<td>Tropical deciduous forests</td>
<td>15</td>
<td>6-35</td>
</tr>
<tr>
<td>Temperate deciduous forest</td>
<td>10</td>
<td>4-25</td>
</tr>
<tr>
<td>Temperate mixed forest</td>
<td>10</td>
<td>6-35</td>
</tr>
<tr>
<td>Tropical savannas</td>
<td>7</td>
<td>2-20</td>
</tr>
<tr>
<td>Temperate prairies</td>
<td>5</td>
<td>1-18</td>
</tr>
<tr>
<td>Crop lands</td>
<td>6.5</td>
<td>1-40</td>
</tr>
</tbody>
</table>

*Source: Sanchez (1976) after Golley and Leith (1972)
There is effective nutrient cycling and rapid decomposition of organic residues (litter) under high temperatures and humidity, thereby enhancing the activities of abundant soil fauna (Dassman et al., 1973). Plants are continuously incorporating carbon compounds into the soil, and micro-organisms are doing the same with atmospheric nitrogen. Consequently, the luxuriant forest vegetation of the humid tropics gives a misleading impression of abundant soil fertility. Soils of the humid tropics are usually of low inherent fertility except those formed over basic volcanic rocks, calcareous rocks and limestone, and alluvial or valley bottom soils where the extent of fertility depends on the parent material (Dassman et al., 1973).

ADVERSE EFFECTS OF FOREST CLEARING, BURNING AND CULTIVATION

The consequences of forest clearing, burning and cultivation in tropical soils have been reviewed by many researchers (Dassman et al., 1973; Wildhorst, 1975; Weyl, 1975; Brunig, 1975; Brunig, et al., 1975; Rehm, 1975; Qureshi, 1978; Okigbo, 1975 and 1979; Lal and Cummings, 1979). Where forests have been cleared, decomposition of organic matter under the activities of micro-organisms at high temperatures and humidity is rapid. Loss of organic matter is also very rapid after burning, a practice widely observed in traditional "slash-and-burn" clearance systems. Burning in tropical moist forests usually results in the following effects on soils: (1) loss of considerable amounts of plant nutrients (usually bound up in the standing vegetation) through volatilization, (2) release of large amounts of plant nutrients onto the soil, (3) loss by leaching of great quantities of temporarily available nutrients which are not rapidly taken up by planted crops, (4) drastic reduction in the availability of certain nutrients due to fixation, (5) nutrient release from the standing vegetation by burning, minimizing sustained long-term agricultural production, (6) problems of high pH that may need correction with liming and (7) problems of excessive root growth.

In addition to the changes in nutrient status by burning, other
properties, discussed below, are drastically altered by deforestation for arable farming.

Soil Temperature

Soil temperature is influenced by factors such as the degree of insulation, soil texture, soil organic matter content and, to some extent, the nature of the clay minerals. These factors are independent and have little room for change. The soil management factors that influence soil temperature include tillage technique, effects of canopy cover, mulching, and irrigation. In the lowland humid tropics, the maximum soil temperature at the beginning of the growing season can be 45-50°C at 5 cm depth, depending on the soil type and methods of seedbed preparation (Lal, 1974). This level of soil temperature can be supra-optimal for crops such as maize (Zea mays) and soybean (Glycine max) (Table 2). Tropical crops such as cowpea (Vigna unguiculata), pigeon pea (Cajanus cajan), and cassava (Manihot esculenta) have a higher range of optimum root zone temperature than maize and soybean. Significant yield reductions can occur due to high soil temperature, particularly so when it occurs in conjunction with drought stress, which is generally the case.

SOIL STRUCTURE AND EROSION

Tropical rains are characterized by high intensity, big drop size, and more energy load or erosive potential than temperate rains (Hudson, 1976). Peak rainfall intensity of 75 to 100 mm/hr is not uncommon, and occasional storms of intensity greater than 150 mm/hr sustained for a period of 5-10 minutes have often been observed. One of the reasons for the high intensity of these storms is the bigger drop size. Medium drop size (D_{50}) of 3.5 mm has been recorded for Ibadan (Aina et al., 1977; Lal et al., 1978) and Zaria (Kowel and Kassam, 1976). As a result of the high-intensity storms with large energy loads, the erosive potential of tropical rains is greater than that of temperate rains.

The variability in tropical rains, both spatial and temporal, has a significant effect on crop production. Whereas rainless periods of 7-15 days duration often occur during the rainy season causing significant yield reductions, frequent storms can also
Table 2: The effects of supra-optimal soil temperature (40°C) in the seedling stage on maize (Zea mays) grain yield*

<table>
<thead>
<tr>
<th>Stress Duration Days</th>
<th>Grain Yield g/plant</th>
<th>Grains/cobs</th>
<th>Unit grain weight g/100 grains</th>
<th>Percent empty grains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>191</td>
<td>477</td>
<td>39.8</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>172</td>
<td>385</td>
<td>36.2</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>149</td>
<td>488</td>
<td>37.9</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>84</td>
<td>310</td>
<td>36.6</td>
<td>27</td>
</tr>
<tr>
<td>8</td>
<td>78</td>
<td>249</td>
<td>36.5</td>
<td>44</td>
</tr>
</tbody>
</table>

*Source: Lal (1974)
cause saturated soil conditions resulting in poor aeration and nutritional imbalances for some upland crops such as cowpea.

One of the consequences of continuous cultivation and soil exposure to high-intensity rains is the progressive deterioration in soil structure, resulting in crusting and low infiltration rate. Deterioration in soil structure and water-intake rate, coupled with high rainfall intensity, results in accelerated soil erosion even on gentle slopes. Soil erosion losses on bare ground surfaces to the extent of 15 to 20 mm of surface layer per annum are common even on gentle slopes of 10-15% inclination in regions of 1000-1500 mm rainfall (Table 3).

This magnitude of soil erosion, allowed to continue for 5-10 years, can result in irreversible soil degradation. Such erosion has been the cause of vast areas of barren unproductive lands throughout the tropics, where lush evergreen forest once prevailed.

DECLINE IN SOIL ORGANIC MATTER CONTENT

Continuously high temperatures in the tropics favour rapid rates of decay of soil organic matter content, particularly under continuous cultivation for food production. In tropical soils, where the predominant constituents are quartz sand and kaolinite, humus and partially decomposed organic matter are important components contributing to (i) the nutrient and water-holding capacity, (ii) the buffer capacity against sudden fluctuations in soil pH, and (iii) the maintenance of a stable soil structure. High rates of decomposition of fresh plant residues per se may not be critical; the important aspect is the effective maintenance of a high level of soil organic matter so that water and nutrient retention and soil structure are favourable for crop production.

WEATHERING ACIDITY AND LEACHING

With the exception of soils derived from basement complex rocks, intensive weathering and high rainfall cause leaching of basic cations thus resulting in the low base saturation and low soil pH of a majority of tropical soils of the Oxisol and Ultisol group. Even in the case of Alfisols, where base saturation is high, the total CEC is 5 to 10 me/100 g of soil; therefore, Alfisols have an inadequate reserve of cations for the maintenance of a
Table 3: Runoff and erosion under various covers of vegetation in parts of West Africa*

<table>
<thead>
<tr>
<th>Locality</th>
<th>Study Period</th>
<th>Percent of slope</th>
<th>Average annual rainfall (mm)</th>
<th>% of annual runoff</th>
<th>Erosion (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Forest</td>
<td>Crop</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ouagadougou (Upper Volta)</td>
<td>1967-70</td>
<td>0.5</td>
<td>850</td>
<td>2.5</td>
<td>20-32</td>
</tr>
<tr>
<td>Sifa (Senegal)</td>
<td>1954-68</td>
<td>1.2</td>
<td>1,300</td>
<td>1.0</td>
<td>21.2</td>
</tr>
<tr>
<td>Bouaké (Ivory Coast)</td>
<td>1960-70</td>
<td>4.0</td>
<td>1,200</td>
<td>0.3</td>
<td>0.1-26</td>
</tr>
<tr>
<td>Abidjan (Ivory Coast)</td>
<td>1954-70</td>
<td>7.0</td>
<td>2,100</td>
<td>0.1</td>
<td>0.5-20</td>
</tr>
</tbody>
</table>

*Source: Charreau (1972) in Mouttapa, F. (1973)
favourable soil pH under continuous and intensive arable farming. Table 4 shows decreases in soil pH, effective CEC, and the relative proportion of basic cations on the exchange complex. It also shows a significant increase in soil exchangeable Mn with continuous farming without adequate use of crop residue mulches. Since the buffering capacity is low, the toxicity of Mn and Al has significantly adverse effects on the productivity of Alfisols, Ultisols and Oxisols.

SOIL-WATER RETENTION AND AVAILABILITY

Accelerated soil erosion, decline in soil structure, and a rapid rate of decay of soil organic matter, decrease the soil's available-water-holding capacity from the already meagre level to a deplorably low one. The majority of tropical lowland soils have a coarse textural surface layer with a maximum of 3 to 5 cm of available water per 30 cm of soil layer (Lal, 1972). The problem of water availability is further accentuated by (i) poor soil physical characteristics, including compaction, (ii) a high gravel concentration (Babalola and Lal, 1977), or (iii) a low soil pH and toxicity of Mn and Al in Ultisols and Oxisols. As a result of low water-retention capacity, imbalance in water availability (both excess and deficit) is one of the major problems for increasing crop production. Transient flooding, causing poor aeration in the root zone, even for a short duration of one to two days following a heavy rain, can cause significant yield reduction in maize and cowpea. Nutritional imbalance in cowpea is often observed on poorly drained soils.

Briefly stated, the clearing of forests, burning, and adoption of row crop and forest exploitation techniques developed in temperate countries usually culminate in the following: (i) progressive destruction of natural ecosystems, (ii) replacement of balanced ecosystems, (iii) decrease in the productivity of the ecosystems as a result of soil erosion, leaching and loss of nutrient, general impoverishment and other damage by abiotic and biotic factors, (iv) loss of capacity for self-regulation by biological ecosystems, and (v) final loss of capacity of self-regulation by socio-economic systems leading to their eventual degradation (Brunig, 1975). The various effects of forest clearing
Table 4: Effects of three years of cultivation after forest clearing on pH, CEC and exchangeable cations under different treatments (After Juo and Lal, 1977)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Effective CEC</th>
<th>Exchangeable cations, me/100 g</th>
<th>Mn ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH-H₂O</td>
<td>Ca</td>
<td>Mg</td>
</tr>
<tr>
<td>Bush fallow</td>
<td>6.5</td>
<td>3.34</td>
<td>0.89</td>
</tr>
<tr>
<td>Panicum maximum</td>
<td>6.7</td>
<td>5.31</td>
<td>1.39</td>
</tr>
<tr>
<td>Leucaena</td>
<td>6.4</td>
<td>4.12</td>
<td>1.14</td>
</tr>
<tr>
<td>Cajanus cajan</td>
<td>6.4</td>
<td>4.34</td>
<td>1.18</td>
</tr>
<tr>
<td>Soybean</td>
<td>5.7</td>
<td>2.37</td>
<td>0.39</td>
</tr>
<tr>
<td>Maize (without residue mulch)</td>
<td>5.3</td>
<td>3.01</td>
<td>0.46</td>
</tr>
<tr>
<td>Maize (with residue mulch)</td>
<td>6.0</td>
<td>4.58</td>
<td>0.92</td>
</tr>
<tr>
<td>Maize + cassava</td>
<td>6.2</td>
<td>3.92</td>
<td>0.67</td>
</tr>
<tr>
<td>LSD (.05)</td>
<td>0.36</td>
<td>1.03</td>
<td>0.31</td>
</tr>
</tbody>
</table>
are depicted in figures 1 and 2.

It is, therefore, imperative that effective research and planning should be carried out to develop suitable forest clearing, soil management, conservation, and ecologically sound and efficient cropping or farming systems that enhance sustained yields with minimum hazard to the environment. Zero-tillage arable crops farming, tree crop and forest plantations constitute effective systems of providing minimum soil disturbance and adequate soil cover, while providing products useful to man.

FERTILITY MAINTENANCE AND SOIL MANAGEMENT IN TRADITIONAL FARMING SYSTEMS OF TROPICAL AFRICA'S HUMID TROPICS

In the traditional farming systems of tropical Africa, tropical America and, to some extent, tropical Asia and Oceania, there is widespread reliance on forest or bush fallows for the maintenance of soil fertility. The so-called shifting cultivation, in the classical sense of the term, is an intermittent farming and fallowing sequence of activities. It usually involves clearing or slashing of natural forest or bush, with many trees and shrubs left standing at wide intervals or heavily pruned. The debris is burnt to release nutrients and facilitate cropping. In the humid tropics no elaborate piling of vegetation in large or small circles is practised, as in the chitemene system of Northern Rhodesia or Zambia (Allan, 1965).

After burning, arable crops (maize, yams, cassava, vegetables, cucurbits, etc.) are grown, often in mixed culture or relay intercropping systems, for 2-3 years -- and rarely 2-5 years -- before either a decrease in soil fertility or crop yields, and/or excessive weed growth, forces the farmer to move to a new location. In classical shifting cultivation the homestead is moved each time the farmer moves to a new field far from the old homestead. But as a result of population pressure and sedentary culture, shifting cultivation has almost disappeared in West Africa, although temporary homesteads are still built on farms during peaks of clearing and weeding, bird-scaring and farm-tending.

The range of traditional and transitional farming systems now in existence in West Africa is given in Table 5. Shifting
Fig. 1. Environmental disruption caused by deforestation (Goodland and Jookman (1977) in Qureshi (1978))
Fig. 2. Relationships between deforestation and crop failure (Goodland and Jockman (1977) in Qureshi (1978))
<table>
<thead>
<tr>
<th>No.</th>
<th>Place</th>
<th>Annual rainfall (mm)</th>
<th>Crop</th>
<th>Fallow</th>
<th>Periods in the year</th>
<th>Normal Crop</th>
<th>Fallow</th>
<th>Excessive Crop</th>
<th>Normal Fallow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Liberia</td>
<td>2,000-4,500</td>
<td>Rice, manioc</td>
<td>Forest</td>
<td></td>
<td>1-2</td>
<td>8-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Sierra Leone</td>
<td>2,300-3,300</td>
<td>Rice, manioc</td>
<td>Forest</td>
<td></td>
<td>1-5</td>
<td>8</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>3.</td>
<td>Nigeria a. Umuahia</td>
<td>c.2,300</td>
<td>Yams, maize, manioc</td>
<td><em>Acioa barteri</em></td>
<td></td>
<td>1-5</td>
<td>4-7</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>b. Alayi</td>
<td>c.2,300</td>
<td>Yams, maize, manioc</td>
<td><em>Anthonotha</em> sp.</td>
<td></td>
<td>1-5</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Central Congo</td>
<td>1,800</td>
<td>Rice, maize, manioc</td>
<td>Forest</td>
<td></td>
<td>2-3</td>
<td>10-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>West Africa</td>
<td>1,500-2,000</td>
<td>Maize, manioc</td>
<td>Moist semi-deciduous forest</td>
<td></td>
<td>2-4</td>
<td>6-12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Nigeria</td>
<td>c.1,300</td>
<td></td>
<td>Thicket</td>
<td></td>
<td>2</td>
<td>4-5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Ilesha Nigeria</td>
<td>c.1,300</td>
<td></td>
<td>Thicket</td>
<td></td>
<td>2</td>
<td>6-7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Ivory</td>
<td>c.1,300</td>
<td></td>
<td>Elephant grass</td>
<td></td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>6</td>
</tr>
</tbody>
</table>

* Source: Nye and Greenland (1960)
cultivation has been replaced by forest or bush fallow systems of varying periods, during which soil fertility is restored. In areas of low population density, for example in parts of the Cross River and Bendel States of Nigeria, fallow periods may exceed 10 years while in areas of high population density, such as the Anambra and Imo States of Nigeria, fallow periods have been reduced and may be between 5 and 9 years long. In general, the longer the period of fallow the more fertile the soil at the beginning of each cropping phase. However, the level of fertility and yields during subsequent years of cropping, and the length of the cropping phase, often depend on the inherent level of fertility of the soil.

Estimates of annual increases in (1) plant nutrients in forest vegetation, (2) the rate of litter production, and (3) plant nutrients in relation to annual rainfall have been reported by Nye and Greenland (1960) (Tables 6 and 7). Considerable quantities of nutrients are tied up in the vegetation and litter, and burning serves to render these nutrients readily available to the crop and weeds. Soluble nutrients are also more susceptible to leaching and loss by runoff and erosion.

The different kinds of fallow encountered in the traditional farming systems of the humid tropics include: (a) natural forest fallows, (b) natural woodland fallows, and (c) planted fallows.

NATURAL FOREST FALLOWs

These consist of long-term fallows of over 15 years in which the forest re-growth is so advanced as to consist of many large trees with only minor manifestations of such secondary bush or disturbed forest indicator plants as Musanga cecropioides, Trema guineensis, Harunga madagascariensis and Fagara macrophylla. Common species of trees in these fallows include Albizia gummifera, Anthochoeris vogelli, Diospyros confertiflora, Funtumia elastica, Sarcocephalus diderrichii, Lophira alata, Nauclea diderrichii, Brachystegia spp., Khaya ivorensis, Triplochiton scleroxylon, Ficus spp., Cola spp., Celtis spp., and Antiaris spp., with oil palms in more open areas and margins of the forest. Most of the trees are up to 20 m in height, or even more. Only a few protected
Table 6: Mean annual increase in nutrient storage in vegetation (kg/ha)

<table>
<thead>
<tr>
<th>Growth period</th>
<th>Nutrient element</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over first 5 years</td>
<td></td>
<td>116</td>
<td>6.3</td>
<td>90</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Over first 18 years</td>
<td></td>
<td>39</td>
<td>6.0</td>
<td>34</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>* Over first 40 years</td>
<td></td>
<td>40</td>
<td>2.8</td>
<td>17</td>
<td>55</td>
<td>7</td>
</tr>
<tr>
<td>Over first 4 years (excluding roots)</td>
<td></td>
<td>47</td>
<td>35</td>
<td>46</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

* Storage in two very large trees, already standing when the forest regenerated, has been excluded.


Table 7: Rate of litter production (per annum)

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Place</th>
<th>Litter fall (kg/ha)</th>
<th>Nutrients in litter (kg/ha)</th>
<th>Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest (Runinga dominant)</td>
<td>Congo</td>
<td>14,800 (dry matter)</td>
<td>139 4.6 103 127 38</td>
<td>Laedelout (1954)</td>
</tr>
<tr>
<td>Mixed forest</td>
<td></td>
<td>12,500 (dry matter)</td>
<td>228 6.8 48 105 46</td>
<td>&quot;</td>
</tr>
<tr>
<td>Mixed high forest</td>
<td>Ghana</td>
<td>10,720 (oven dry)</td>
<td>203 7.3 64 205 40</td>
<td>Nye (Unpublished)</td>
</tr>
<tr>
<td>Rain forest</td>
<td>Colombiá</td>
<td>10,500 (oven dry)</td>
<td>203 7.3 64 205 40</td>
<td>Jenny (1950)</td>
</tr>
<tr>
<td>&quot;</td>
<td></td>
<td>10,600 (oven dry)</td>
<td>203 7.3 64 205 40</td>
<td>&quot;</td>
</tr>
<tr>
<td>&quot; (Sub-tropical</td>
<td>Queensland</td>
<td>6,800 (oven dry-</td>
<td>107 6.8 34 75</td>
<td>Webb (1956)</td>
</tr>
<tr>
<td>mixed spp.)</td>
<td></td>
<td>leaf only)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperate</td>
<td>New York</td>
<td>3,100 (dry matter)</td>
<td>18 3.3 15 74</td>
<td>Chandler (1941)</td>
</tr>
</tbody>
</table>

useful plants may be present. This kind of fallow predominates in areas of low population density and often far away from home-stead farms. Some of the forest reserves on which taungya systems are currently practised belong to this group.

**NATURAL WOODLAND OR BUSH FALLOWS**

These are the predominant fallows in areas of high population density in south-eastern Nigeria. Plants in these fallows consist mostly of protected shrubs, young trees and some woody climbers and stranglers. In a typical bush or woodland fallow in the Umuahia area of Imo State, Obi and Tuley (1973) reported *Alchornea cordifolia*, *Acioa barteri* and *Anthonotha macrophylla* to be dominant species; *Harunga madagascariensis*, *Dielium guineense* and *Cnestis ferruginea* as abundant species; and the following as common: *Uvaris chamae*, *Monodora tenuifolia*, *Ochna spp.*, *Napoleona vogelii*, *Combretum spp.*, *Quisqualis latialata*, *Glyphaea brevis*, *Cola digitata*, *Bridelia maorantha*, *Phyllanthus discoides*, *Mallotus subulatus*, *M. oppositifolius*, *Griffonia simplicifolia*, *Afselia bella var. bella*, *Albizia sygia*, *A. adianthifolgia*, *Baphia nitida*, *Dalbergia saxatilis*, *Lonchocarpus cyanescens*, *Milletia thomningii*, *Myrianthus arboreus*, *Salacia senegalensis*, *Icacinia mannii*, *Blighia sapida*, *Spondius mombin*, *Diospyros monbutensis*, *Landolphia owariensis*, *Rauwolfia vomitoria*, *Rothmannia spp.*, *Nuclea latifolia*, *Morinda lucida*, *Spathodea cianpanulata*, *Newbouledia haevis*, *Vitex grandifolia* and *Hoslandia opponta*.

**PLANTED FALLOWS**

In areas of high population density where fallow periods have become drastically reduced, farms located some distance away from the compound farms are planted with selected fallow shrubs. In the northern parts of south-eastern Nigeria (Anambra State), *Acioa barteri* constitutes the dominant species, with *Anthonotha macrophylla* and *Alchornea cordifolia* as minor species which may sometimes be absent. In the southern parts of Anambra State and northern parts of Imo State, *Anthonotha macrophylla* and *Acioa barteri* are used, while in south-eastern Imo State and parts of the Cross River State, *Anthonotha macrophylla* is predominant.
In the south-western area of Imo State and in Rivers State, *Alchornea cordifolia* and a new stands of *Acioa barteri* and *Anthonotha macrophylla* are found. In Bendel State, forest fallows and protected secondary bush vegetation are the main kinds of fallow. In parts of Oyo State in south-western Nigeria, *Clivicidia sepium* constitutes the dominant fallow shrub.

In areas of very high population density, continuous cropping results in a predominance of grasses such as *Andropogon tectorum*, *Panicum maximum*, *Aspilia africana*, *Mikania cordata* and *Pueraria phaseoloides*. Similar herbaceous species may constitute the climax vegetation. In some locations, grasses such as *Imperata cylindrica*, *Loudetia spp.*, *Melinis minutiflora*, *Schizachyrium brevifolium* and *Brachiaria spp.*, or weeds such as *Eupatorium odoratum* and *Pteridium aquilinum*, may constitute the terminal succession.

**MULTIPURPOSE USES OF FALLOW SHRUBS AND TREES**

Dominant fallow shrubs such as *Acioa barteri* and *Dialium guineensis* are, in addition to their uses as shrubs, also used as firewood and as sources of charcoal, structural materials, tool handles, browse plants, etc. Trees of the compound farm (such as *Ricinodendron heudelotii*, *Ficus spp.*, *Newbouldia laevis*, etc.), in addition to their value as boundary plants, are also used as fence posts, structural materials, browse plants, stakes, etc. These uses of fallow trees and shrubs ensure their place in traditional farming systems of the humid tropics in preference to herbaceous leguminous cover crops such as *Centrosema pubescens* and *Stylosanthes guianensis*.

**TREE OR BUSH FALLOWS AND FERTILITY MAINTENANCE**

Numerous experiments have been conducted since the early 1930s to test the soil fertility potentials of various fallow and cover crops as compared to traditional bush fallow systems. Experiments at Moor Plantation, Nigeria, involving the use of *Mucuna utilis* in rotation with annual crops indicated that yields of maize and yams were only maintained at a low level. Where
5-10 tons of farm-yard manure per hectare was applied, yields were maintained at a slightly higher level, while the use of Andropogon gayanus fallow with varying periods (2, 4 or 6 years) resulted in the highest yields during the first year after fallow, followed by a rapid decline immediately afterwards (Hardcastle, 1968).

In experiments at Umuahia, Eastern Nigeria, in which seven years of continuous cultivation was compared with the incorporation of green manure with Mucuna utilis with the native fallow system, it was shown that the native system of two years' cultivation followed by four years of bush fallow maintained soil fertility at the initial level. In contrast, six years of rotation including three green manure crops (two of a year's duration each and one of half a year) resulted in low yields with the latter giving no yields of the yam and maize test crops.

As a result of failure of the Mucuna green manuring experiment, some studies with deeper-rooted legumes (Tephrosia, pigeon pea (Cajanuscajan) and Crotolaria spp.) were started in comparison with Acioa fallow, farm-yard manure and compost. Results indicated that farm-yard manure and compost were the only means of improving or maintaining soil fertility with intensive cropping. Ten tons of farm-yard manure was economically better than 5 tons/ha. Tephrosia and Acioa were both capable of restoring fertility after four years of fallow, even on eroded soils, but Tephrosia was inferior to good natural fallow. Calopogonium proved inferior to Tephrosia in falls of one or more years and a four-year Acioa fallow was as good as farmyard manure (Obi and Tuley, 1973).

An experiment was also conducted using Stylosanthes as a cover crop that was grazed, cut and turned in, cut-carried away and returned as manure, or cut and left on the soil surface as a mulch. Results indicated that grazing was inferior to other treatment, while mulching was superior to turning in. It was concluded that no herbaceous cover was as efficient in the regeneration of soil fertility as a woody one. Plant nutrient loss by leaching and loss of soil fertility were rapid following the removal of vegetative cover. Composts and farmyard manure from
goats appeared to have a high potential for the maintenance of fertility under permanent cultivation.

More recent studies indicate that fertilizer use is imperative in the humid tropics under continuous cultivation. It is necessary, however, to determine to what extent the amount of fertilizer can be reduced. Reduction can be achieved through biological di-nitrogen fixation, reduction of nutrient losses through leaching and erosion by better management of organic residues, zero or minimum tillage, and other techniques. In traditional farming systems, mounds are used to concentrate surface soil and organic residues. However, erosion becomes a problem during tropical rainstorms where these ridges are not tied.

ROLE OF TREES IN SOIL AND WATER CONSERVATION AND OTHER USES

For the more efficient use of trees in traditional farming systems, their value as sources of food, fallow plants, cover crops, browse plants, fuel or firewood, and in other ways must be given due consideration.

FOOD CROPS

Trees and shrubs constitute the major components of the dominant vegetation of the humid tropics and they have great potential: (1) in providing effective and continuous soil cover which is often necessary in reducing erosion, (2) in integrated watershed management in upland areas and steep slopes and (3) as windbreaks and in strip-cropping. Trees and shrubs used in any of the above categories can be more valuable if they are also sources of food for man and animals.

Until the advent of exotic Asian and American staple crops (cassava, maize and plantain), which have advantages over some of the major indigenous staple food crops of the humid tropics of West Africa (such as yams), there are many food trees that after many years of experimentation have become incorporated as components of the traditional vege-cultural complex. Others brought under regular cultivation are currently utilized as protected plants in fields outside the compound farms or as
semi-wild and wild plants in fallows. The cultivated tree, shrub or otherwise woody food crops of the humid tropics include: oil palm, Elaeis guineense, Raphia spp., Vernonia amygdalina, Irvingia gabonensis, Tetradium africana, Dacryodes edulis, Chrysophyllum albidum, Pterocarpus stygiawii and Pterocarpus mildbraedii, Tetracarpedium conophorum, Cola lepidota, Cola pachycarpa, Dendretia tripetala, Sunsepalum ducicum, Carcinita kola and Buchholzia coriaceae. In addition to these edible exotic tree and shrub species include regularly cultivated plans such as Manyilera indica, Citrus spp., Cocos nusifera, Artocarpus communis, Anacardium officinalis, Psidium guajava, Persea americana, Carica papaya, and Annona muricata. Most of the above regularly cultivated trees and shrubs are usually grown intercropped in the compound garden or in specific locations. Semi-wild and protected food or edible trees that may be found on the compound farm or on outlying fields include Pentaclethra macrophylla, Canarium schweinfurthii, Ficus spp., Cola argentina, Cola gigantia, Cola verticillata, Heineia crinita, Chrysophyllum delevoyi, Rachystela brariceps, Landolphia ovarienss, Blighia sapida, Monodora myristica, Afzelia bella var. bella, Dialium guineense, and Xylopia aesthiopica. Tree crops that may be classified as often-harvested from the wild include Myrianthus arboreus, Vitex doniana, V. ferruginea, Pterocarpus osun, Afzelia africana, Brachystegia nigerica, Tetrapleura tetraptera and Detarium eitheopicum.

**PLANTED OR COVER FALLOW CROPS**

Some of the trees and shrubs that may be planted in fallows or exist as dominant species in fallows include legumes such as Dialium guineensis, Anthonotha macrophylla, Gliricidia sepium and non-legumes such as Acioa barteri and Alchoronia cordifolia. So far research has been negligible or absent on the improvement of any of these species, efficient ways of managing them in more productive and permanent cropping systems and on their place in rotations.
BROWSE PLANTS AND BOUNDARY PLANTS

Some of the trees and shrubs that are often easily propagated vegetatively and used as browse plants, fence posts or boundary plants include: Ficus spp., Ricinodendron heudelottii, Newbouldia laevis, Dracaena arborea, Spondias mombin, Baphia nitida, Glyphaea brevis, Albizia spp., and Hildegardia bateri.

MISCELLANEOUS USEFUL SHRUBS AND TREES

Miscellaneous useful indigenous or exotic shrubs that may also be found in compound farms include Pandanus candellium, Cola verticillata, Mallotus subulatus, Nuclea latifolia, Rothmannia spp., Lonchocarpus spp., Strophanthus spp., Ficus exasperata, Icacinia mannii, Spathodia campanulata, Markhamia tomentosa, and Moringa oleifera.

IMPROVEMENTS AND SOIL FERTILITY MAINTENANCE FOR COMMERCIAL FARMING

Maintenance of a continuous ground cover is the key to the problems of ecological imbalance caused by forest removal. This continuous ground cover may be achieved through the development of appropriate tillage systems and cropping sequences. Some of these practices are described below.

TILLAGE PRACTICES

Frequent excessive tillage in the harsh climatic conditions of the tropics results in deterioration in tropical soils. Since the major advantages of mechanical seedbed preparation are temporary weed control, the mechanical process can be replaced by chemical or biological techniques of weed suppression, resulting in elimination of tillage for seedbed preparation. With successful weed control crop yields equivalent to those obtained with conventional tillage have been obtained with no-tillage in relatively good seasons with favoured rainfall distribution, and yields superior to those obtained with conventional tillage in periods of frequent droughts (Table 8). No-tillage systems, by preventing erosion and maintaining soil organic matter at a high level, can sustain economical yields continuously, whereas drastic yield
Table 8: Crop response to no-tillage under various soil and ecological conditions in West Africa

<table>
<thead>
<tr>
<th>Crop</th>
<th>Soil</th>
<th>Rainfall</th>
<th>Location</th>
<th>Grain yield with no-tillage (t/ha)</th>
<th>Ratio of grain yield (no-tillage:tilled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>Alfisol</td>
<td>1200</td>
<td>Ibadan</td>
<td>3.17</td>
<td>1.07</td>
</tr>
<tr>
<td>Cowpeas</td>
<td>Alfisol</td>
<td>1200</td>
<td>Ibadan</td>
<td>0.87</td>
<td>1.07</td>
</tr>
<tr>
<td>Soybeans</td>
<td>Alfisol</td>
<td>1200</td>
<td>Ibadan</td>
<td>1.60</td>
<td>0.91</td>
</tr>
<tr>
<td>Maize</td>
<td>Ultisol</td>
<td>2500</td>
<td>Monrovia</td>
<td>2.80</td>
<td>2.13</td>
</tr>
<tr>
<td>Rice</td>
<td>Ultisol</td>
<td>2500</td>
<td>Monrovia</td>
<td>2.9</td>
<td>1.53</td>
</tr>
<tr>
<td>Cassava</td>
<td>Ultisol</td>
<td>2500</td>
<td>Monrovia</td>
<td>14.9</td>
<td>0.73</td>
</tr>
<tr>
<td>Maize</td>
<td>Ultisol</td>
<td>2000</td>
<td>Calabar</td>
<td>1.25</td>
<td>0.79</td>
</tr>
<tr>
<td>Maize</td>
<td>Ultisol</td>
<td>2000</td>
<td>Port Harcourt</td>
<td>1.73</td>
<td>0.93</td>
</tr>
<tr>
<td>Cassava</td>
<td>Ultisol</td>
<td>2000</td>
<td>Port Harcourt</td>
<td>7.1</td>
<td>1.03</td>
</tr>
<tr>
<td>Cowpeas</td>
<td>Ultisol</td>
<td>2000</td>
<td>Port Harcourt</td>
<td>0.30</td>
<td>1.81</td>
</tr>
<tr>
<td>Pigeon peas</td>
<td>Ultisol</td>
<td>2000</td>
<td>Port Harcourt</td>
<td>0.07</td>
<td>0.86</td>
</tr>
<tr>
<td>Maize</td>
<td>Alfisol</td>
<td>1500</td>
<td>Kumasi</td>
<td>2.74</td>
<td>0.84</td>
</tr>
<tr>
<td>Maize</td>
<td>Alfisol</td>
<td>1500</td>
<td>Benin</td>
<td>0.82</td>
<td>1.26</td>
</tr>
<tr>
<td>Maize</td>
<td>Alfisol</td>
<td>1500</td>
<td>Ikenne/Nigeria</td>
<td>3.74</td>
<td>1.05</td>
</tr>
<tr>
<td>Maize</td>
<td>Alfisol</td>
<td>1000</td>
<td>Ilora/Nigeria</td>
<td>4.52</td>
<td>0.89</td>
</tr>
<tr>
<td>Cowpeas</td>
<td>Alfisol</td>
<td>1500</td>
<td>Ikenne/Nigeria</td>
<td>2.03</td>
<td>1.16</td>
</tr>
<tr>
<td>Cowpeas</td>
<td>Alfisol</td>
<td>1000</td>
<td>Ilora/Nigeria</td>
<td>1.32</td>
<td>1.65</td>
</tr>
</tbody>
</table>
declines have been observed with plowing even within 3-5 years after initiating cultivation on forested land. A no-tillage system with crop residue mulches favours the biological activity of earthworms and other soil animals. The "plowing" caused by high earthworm activity under no-tillage systems keeps the soil porous without causing accelerated soil erosion.

SOIL MANAGEMENT AND SOIL AND WATER CONSERVATION

Engineering practices of soil and water conservation and management, contour bunds and terraces are expensive, with a high initial capital input. Besides, if not carried out and maintained adequately, the erosion losses are generally more serious than without them. The principles of soil and water conservation in the tropics should be based on improving infiltration or water intake rate rather than on the safe disposal of excessive runoff. If raindrop impact can be reduced, or prevented by mulches and canopy cover, soil structure will be preserved, thus facilitating high infiltration rates. For example, residue mulch at 6 ton/ha have prevented soil erosion even on steep slopes of up to 10 percent. No-tillage systems with residue mulches have also proven to be extremely effective in combating erosion (Table 9).

Cropping systems that will provide a continuous vegetal cover all the year round should minimize raindrop impact and reduce runoff and erosion. The used of mixed and relay-cropping practices have proven particularly useful. Monoculture cassava had higher runoff water and soil loss than mixed cropping of maize and cassava. Mean water runoff was 28 and 21 percent respectively, for monoculture and mixed cropping (Table 10). Similarly, mean soil loss was 109 and 69 metric tons ha⁻¹yr⁻¹ for the same two treatments.

The effectiveness of practices such as contour ridges for erosion control decreases with increase in slope. Ridges are not effective for slopes steeper than 5% especially when soil is of relatively coarse texture and low in soil organic matter content. In addition, plants grown on ridges are likely to
### Table 9: No-tillage effects on soil and water loss under maize (Lal, 1976b)

<table>
<thead>
<tr>
<th>Slope %</th>
<th>Soil loss (t/ha)</th>
<th>Runoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No-tillage</td>
<td>Plowed</td>
</tr>
<tr>
<td>1</td>
<td>0.03</td>
<td>1.2</td>
</tr>
<tr>
<td>10</td>
<td>0.08</td>
<td>4.4</td>
</tr>
<tr>
<td>15</td>
<td>0.14</td>
<td>23.6</td>
</tr>
</tbody>
</table>

### Table 10: Soil losses and runoff under cassava monoculture and mixed cropping of cassava and maize (After: Aina, Lal and Taylor, 1977)

<table>
<thead>
<tr>
<th>Slope %</th>
<th>Soil loss (t/ha)</th>
<th>Runoff (% of rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cassava</td>
<td>Cassava + Maize</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>87</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>125</td>
<td>86</td>
</tr>
<tr>
<td>15</td>
<td>221</td>
<td>137</td>
</tr>
</tbody>
</table>
suffer from supra-optimal soil temperature and frequent drought stress (Lal, 1974).

MAKING USE OF AVAILABLE WATER SUPPLY

Efficiency of available rainfall can be improved by minimizing the losses due to surface runoff and soil evaporation. Experiments conducted in Northern Nigeria by Lawes (1966) indicated a rainfall efficiency of between 90 and 99 percent with the use of residue mulches of grass, groundnut shells, and sorghum stalks compared with only 30, 49 and 57 percent for soils left undisturbed, soils hoed at fortnightly intervals, and soils hoed after every rainstorm, respectively. Even in the more humid regions residue mulches improve soil water storage and efficiency. Data in Table 11 indicate that the neutron count ratio at 30-cm depth showed a significantly higher soil moisture reserve under mulch, even 21 days after rain, compared with unmulched soil in the same vicinity.

Irrigation is not feasible in many ecological regions of the humid tropics. Wherever it is applicable, however, water-use efficiency under irrigation can be considerably better with zero-tillage and residue mulches than with conventional plowing. For example, the water-use efficiency of cowpea was better with no-tillage than with tillage at all irrigation frequencies. Again, soil moisture storage under plowed and no-till soybean showed a higher moisture reserve under no-tillage than with conventional tillage (Table 12).

The use of residue mulches combined with a no-tillage system should promote the efficient use of available water supply in the humid tropics.

SOIL FERTILITY MAINTENANCE

The productivity of tropical soils depends on the maintenance of their physical, chemical and biological characteristics. The use of fertilizer alone cannot maintain the productive potential at an economic level of crop production. The fertilizer use efficiency of tropical soils has been low because of a considerable loss of applied nutrients in runoff water, eroded
Table 11: Soil moisture storage at 30 cm depth as influenced by mulching and duration without rain (Unpublished data of R. Lal)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Neutron Count Ratio* At Different Days After Rain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Mulch</td>
<td>0.946</td>
</tr>
<tr>
<td>Bare Soil</td>
<td>0.752</td>
</tr>
</tbody>
</table>

* Ratio of the neutron count in soil to that in the shield.

Table 12: Soil moisture storage under ploughed and no-till soybean at different days after rain (Unpublished data of R. Lal)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Neutron Count Ratio At Different Days After Rain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 days</td>
</tr>
<tr>
<td></td>
<td>No-till</td>
</tr>
<tr>
<td>30</td>
<td>0.710</td>
</tr>
<tr>
<td>60</td>
<td>0.851</td>
</tr>
<tr>
<td>90</td>
<td>1.001</td>
</tr>
<tr>
<td>120</td>
<td>1.191</td>
</tr>
</tbody>
</table>
soil, leaching losses, and losses due to volatilization caused by high soil temperature. For example, Lal (1976a) reported the loss of 10 kg/ha/annum of nitrate nitrogen in runoff water, compared with approximately 200 kg/ha/annum of total nitrogen loss in eroded soil from bare fallow plots with a 5% slope. The annual nitrogen loss under maize-maize planted with conventional plowing was about 20 and 3 kg/ha/annum in eroded soil and runoff water respectively. The enrichment ratio of eroded soil is generally 3.5 for soil constituents such as organic carbon, nitrogen and phosphorus.

With the increase in oil prices, fertilizers are expensive and, due to high losses and low efficiency, perhaps uneconomical in various regions of tropical Africa. Fertilizers either are not available to small farmers, or they cannot afford them.

An adequate system of residue cycling, with or without composting and in combination with suitable crop rotations, may help overcome this problem for small farmers. For example, compared with the traditional mounds system of maize cultivation, mulching with leguminous plant materials produced six to eight times more grain (Table 13). Similarly, the continuous use of a no-tillage system maintained higher nutrient levels in the soil than conventional plowing (Table 14).

**SUGGESTIONS FOR RESEARCH IN AGROFORESTRY**

**FOOD TREES**

In an attempt to make the maximum use of trees and shrubs of the humid tropics both as food crops and for miscellaneous purposes, priority should be given to identification, to germplasm collection, the improvement and development of regular production systems, and also to efficient processing, storage and utilization of their products. This would not only provide for the more efficient utilization of available resources but could markedly supplement the narrowing range of foodstuffs available to urban populations in addition to adding variety to the diet. Some trees not only are sources of carbohydrates, fats and proteins but are also rich sources of vitamins.
Table 13: Maintenance of soil fertility with residue mulches (Unpublished data of R. Lal and B.N. Okigbo)

<table>
<thead>
<tr>
<th>Mulch material</th>
<th>Maize grain yield (t/ha) at 14% moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mounds</td>
<td>0.52</td>
</tr>
<tr>
<td>Ridges</td>
<td>1.43</td>
</tr>
<tr>
<td>Flat</td>
<td>2.19</td>
</tr>
<tr>
<td>Maize stover</td>
<td>3.12</td>
</tr>
<tr>
<td>Rice stover</td>
<td>3.27</td>
</tr>
<tr>
<td>Soybean straw</td>
<td>3.77</td>
</tr>
<tr>
<td>Water lettuce</td>
<td>3.93</td>
</tr>
<tr>
<td>Pigeon pea/Cowpea stover</td>
<td>4.30</td>
</tr>
<tr>
<td>S. d.</td>
<td>± 0.97</td>
</tr>
</tbody>
</table>

Table 14: Influence of no-tillage system on nutrient status of an Alfisol (Lal, 1976a)

<table>
<thead>
<tr>
<th>Cropping sequence</th>
<th>pH</th>
<th>Total N</th>
<th>Bray-1</th>
<th>CEC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No-</td>
<td>Plowed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>tillage</td>
<td>(P)</td>
<td>%</td>
<td>ppm</td>
</tr>
<tr>
<td></td>
<td>(Nt)</td>
<td>(P)</td>
<td>Nt</td>
<td>P</td>
</tr>
<tr>
<td>Maize-maize</td>
<td>5.3</td>
<td>5.0</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>Maize-cowpea</td>
<td>5.3</td>
<td>5.1</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Pigeon pea - maize</td>
<td>5.1</td>
<td>5.1</td>
<td>0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>Soybean-soybean</td>
<td>5.5</td>
<td>5.6</td>
<td>0.11</td>
<td>0.07</td>
</tr>
<tr>
<td>Maize-soybean</td>
<td>5.4</td>
<td>-</td>
<td>0.09</td>
<td>-</td>
</tr>
<tr>
<td>Cowpea-cowpea</td>
<td>5.9</td>
<td>6.0</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>LSD (p = 0.05)</td>
<td>± 0.2</td>
<td>± 0.19</td>
<td>± 0.29</td>
<td>± 0.6</td>
</tr>
</tbody>
</table>
FALLOW SHRUBS AND TREES

Some leguminous and non-leguminous trees and shrubs have been identified as useful fallow plants in traditional farming systems of the humid tropics. However, limited research has been carried out to determine the range of their potentials in nitrogen fixation vis-a-vis mineral recycling. Research is also needed to develop efficient methods of utilizing them in shortened fallows by exploiting them for mineral recycling and/or nitrogen fixation. In addition, these species can also be used as browse plants, for making stakes and for other purposes. High priority should be given to the development of methods for their regular cultivation, management and effective utilization in permanent farming systems.

AGROFORESTRY

At present, in some parts of Africa and Asia, forestry plantation establishment and management systems exist in which exploitation is associated with traditional slash-and-burn techniques. In these systems, arable farming is done for the initial two or more years, after which forest plantations are established. At present, with the exception of legal provisions to ensure that the forest is left uncultivated, sometimes for 20-50 years, the so-called *tamusgaye* system is in no way different from the traditional shifting cultivation. There is a need for research into better methods of forest exploitation in agri-silvicultural systems that ensure efficient utilization of as many species of plants as possible. This will require the cooperation of silviculturists with agronomists in developing efficient arable/tree crop intercropping systems that maximize yield and performance of component species at the time they are growing together. Well-planned and improved agro-silvicultural systems involving arable food crops and quick-maturing trees may be an attractive method of having smallholders engage in tree production (e.g. *Gmelina*, *Cassia* spp.). These quick-maturing trees may be harvested for poles, fuel wood, or for pulp every 4-5 years.
TREES IN INTEGRATED WATERSHED MANAGEMENT

One of the reasons that large-scale farms often fail or that land is wastefully used is that row crops like maize are planted on the cleared slopes and crests of hills and in valleys on not only suitable but marginal areas, with all the attendant erosion hazards. This is especially the case before the crop develops a full canopy to protect the soil from erosion. An integrated watershed management system, however, not only uses methods to conserve water (Fig. 3) but it utilizes different crops in various topo-sequences, or contours, starting from the valley bottom with rice to tree crops at the crest. Such a system enhances the growing of different crops under topographic conditions to which they are best adapted (Fig. 4). This constitutes an efficient way of utilizing all the land available and ensures better soil conservation. There is a possibility that small fruit trees, such as Citrus spp. and budded mango (Mangifera indica) can be grown on contour bunds in terraced or contoured fields. Research priority should be given to the development of integrated watershed management systems involving both crops and trees for various oils, topographic situations, and different environmental conditions.

USE OF TREES IN MIXED FARMING SYSTEMS

In the tropics where tsetse flies and trypanosomiasis are endemic, only small livestock such as sheep, goats and poultry can readily be kept. Sheep and goats in these areas often are more adapted to browsing than to relying on graminaceous fodder. Research should be devoted to the development of mixed farming systems based on the feeding of animals with material from trees and shrubs in the dry season. This will be combined with household and farm refuse. In such a system it should be possible easily to determine the number of animals that could profitably be kept to provide sufficient manure to enhance stable food production. It might even be possible to raise enough poultry to produce manure for vegetable and tree-crop horticulture.
**Fig. 3.** Illustrated above the pattern of rainfall providing two rain-fed seasons and also a potentially more productive dry season if excess rainfall is conserved in tanks (i.e., water harvesting) to extend the growing season.

**Fig. 4.** Utilization of different crops on various topo-sequences - see text.
IMPROVED LAND-USE SYSTEMS

The present compound farm system and associated fields involve a somewhat haphazard intercropping of annual crops and planted or volunteer wild tree species. Research should be conducted to determine the most productive and ecologically sound crop and soil management systems. Some important combinations are: (1) complex tree crop/field crop intercropping systems, (2) single crops of trees and arable crops separately ordered in relation to identifiable physiographic features, and (3) cropping systems restricting trees and shrubs to shelter belts or strips of varying width, amenable to separate management.

In this type of research some balance among various systems of production could be attained so as not only substantially to complement conventional food crop production but also to enhance: (1) industrial requirements of plant products, (2) soil conservation and environmental protection, and (3) efficient utilization of natural resources with the minimum hazard to the environment.

DISCUSSION

Nyandat: Dr. Okigbo has dealt mainly with one farming system which is the conversion of forest to arable cropping for annual crops. It should be appreciated that the clearing of forest can be followed by a wide range of farming systems, e.g. annual crops, perennial crops, and an annual crop-dairy cattle mix. Under the last system, the tendency is to remove plant residues (including weeds) to feed to the livestock. If we have to arrive at the right priorities of research in agroforestry, then we need to be specific to recognized farming systems. Moreover, we have to take into account the varying farm sizes that prevail even among the category of small farmers, e.g. in Kenya.

Uriyo: In your paper, there is little or no mention of livestock and its role in maintaining soil fertility. The traditional methods of land use cannot support the farmer at present. How relevant are the recommendations that are made in the paper in view of the diversity of conditions in the humid tropics?

Lal: To date, cattle are not an important component of the farming system in the humid tropical regions of West Africa. Wherever necessary, suitable crop rotations and sequences can be developed with the "no-tillage" system to meet the forage requirements for the cattle.

Bradley: Is it not possible to select cover crops that would control weeds?
Lal: Grasses control the weeds but become a problem in themselves because of difficulty in eradicating them by contact herbicides such as paraquat Styllosanthes guianensis, when established, suppresses weed growth effectively.

Redhead: Are there deleterious effects of insects and fungal pests in the "no-tillage" system?

Lal: We have observed stem-rot to be slightly more on "no-tillage" than on ploughed plots. However, the incidence of stem-borer and the build-up of some parasitic nematodes may be greater when the infested residue is ploughed in rather than left on the soil surface.

Keya: What are the effects of high temperature on (a) nitrogen flush, (b) root development, and (c) survival of soil organisms? Further, what are the effects of termites on infiltration and soil structure?

Lal: High soil temperature decreases the concentration of N, P and K in the shoots of maize and soybean. The mechanism for this low concentration (whether decreased absorption, translocation or non-availability in the soil) is not clearly understood and needs to be investigated. Total root mass of the seedling subjected to high soil temperature stress is also low. Termites, similar to earthworms, improve infiltration rates and soil structure.

Ahm: What are the relative costs of hand weeding and herbicide use? At Kade in Ghana, we found hand weeding to be cheaper than herbicide use.

Lal: With high labour costs, and its non-availability during critical periods, manual labour is quite competitive with herbicides. In some cases, herbicides are cheaper.

Sánchez: Do you have economic studies in the profitability of mulch in farming on a small scale?

Lal: No.

Sánchez: Can you do without herbicides?

Lal: Unlikely.

Pratt: What is the stage of development of "no-tillage"? Is it recommended to farmers?

Lal: Yes. We recommended "no-tillage" for some crops such as maize, cowpea and soybean to both small-scale and large-scale commercial farmers.

A.L.D. Mongi: What is the effect of herbicides on the activity of earthworms?

Lal: Herbicides and insecticides have adverse effects on the activity of earthworms. Soil exposure by ploughing, high soil temperature and lack of organic matter on the soil surface have significantly more adverse effects than the applied chemicals.

Pereira: Are not the grass-weeds the main danger in the use of herbicides by small farmers? Grasses must eventually be destroyed by cultivation or by shading.
Lal: In the herbicide-treated plots, rhizomatous weeds (*Talinum triangulare*, *Imperata cylindrica*) persist. On the contrary, grass weeds (*Brachiaria ruziziensis* and *Rottboellia exaltata*) are a problem in ploughed plots. In some of our large-scale mechanized-planting experiments, guinea grass (*Panicum maximum*) was a serious weed in both treatments.

Pereira: How does the larger farmer mechanize planting through heavy corn residue?

Lal: There are special "no-tillage" planters available that can plant through the crop residue. Fluted power-driven cutting discs and the heavy weight of the machinery help plant through a thick layer of wet or dry residue of the previous crop.

**LITERATURE CITED**


SOIL FERTILITY AND CONSERVATION
CONSIDERATIONS FOR AGROFORESTRY SYSTEMS
IN THE HUMID TROPICS OF LATIN AMERICA

Pedro A. Sánchez*

ABSTRACT

There is no direct information on soil fertility and conservation under agroforestry systems in the humid tropics of Latin America. Data from conventional farming systems is presented to outline research priorities. The selvas of tropical America have mostly Oxisols and Ultisols of low native fertility. Biomass accumulation in tropical forests varies with soil properties. Studies on nutrient cycling indicate also site-specific variations. Slash-and-burn is the best land clearing technique throughout the area. The fertility decline after burning is very fast in the wetter areas under crops but is remarkably slow in grazed pastures in the eastern Amazon. Evidence of obvious erosion is very limited in the Amazon and in the humid tropical highlands with little or no dry season. Erosion is very serious in the densely populated highlands with a strong dry season. Soil research priorities for agroforestry systems include: (1) land resource evaluation, (2) determining critical nutritional requirements of main plant species and varieties, (3) soil management needs for crop-pasture-tree successions or intercropping mixtures, and (4) an overall integration with crop agronomy, pastures and animal science, forestry and ecology.

The humid forested regions cover approximately 30% of the tropical world, but their relative importance is greater in tropical America, where they account for 52% of the area, than in tropical Asia and the Pacific with 38%, and tropical Africa with 12% (Sánchez, 1976). The tropical forested regions of Latin America (Fig. 1), herein referred to as selva, can be defined as those areas located between the tropics of Cancer and Capricorn in the Western Hemisphere with native vegetation of rainforests or evergreen semideciduous forests, having: (1) a udic or

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LOCATION OF HUMID FORESTED AREAS IN TROPICAL AMERICA.

720 million hectares.

49% of the American tropics.

Figure 1: Location of humid forested areas in Tropical America.
Source: Sánchez (1977a).
nearly udic soil moisture regime, (2) a dry season of less than four months, and (3) a potential wet season evapotranspiration above 1060 mm (CIAT, 1979). The 700 million ha of selva and the surrounding 300 million ha of savannas of tropical America represent the largest potential for expanding the cultivated area in the world (National Academy of Sciences, 1977). Temperature, solar radiation, rainfall and topography are generally favourable for agriculture in much of the selva, but the main limiting factors are the low native fertility of its soils and limited infrastructure.

Population pressures all around the Amazon basin as well as the other selva regions, coupled with the opening of a vast road network, oil-drilling and mining, are causing a large influx of settlers into the selva. A total of 24 million ha of forests was cleared in tropical America during the 1966-75 decade representing a rate of 2.4 million ha per year (Sánchez and Cochrane, 1979). It is likely that the annual clearing rate has already increased and will continue to do so as tropical America's population doubles within the next 24 years.

The future of the Amazon is now a matter of worldwide concern. Accounts in books and popular magazines predict major ecological catastrophes when agriculture is introduced, such as turning the selva into brick pavement (McNeil, 1964), a red desert (Goodland and Irwin, 1975) or even into a Latin American Sahel (Friedman, 1977). Others claim that climate will be altered, the course of rivers will change and the earth's oxygen supply will be severely hampered (Anderson, 1972; Reis, 1972). The predictions of this "catastrophic" school of thought fortunately are not supported by scientific evidence (Sánchez and Buol, 1975; Richards, 1977; Alvim, 1978, 1979).

Of more importance are assertions by many ecologists and foresters that sustained crop or livestock production is simply not possible in the acid infertile soils of the selva (Tosi, 1974; Goodland and Irwin, 1975; Budowski, 1976; Shubart, 1977; Goodland et al., 1978). They urgently recommend that no agriculture be allowed to be developed on the well-drained soils of the selva. Latin American agronomists, however, are beginning to provide evidence that agriculture is indeed possible, showing
good research examples and commercial profitability in many cases (Alvim, 1978, 1979; Sánchez, 1977a, b; Serrao et al., 1979; Toledo and Morales, 1979). Policy makers in Amazon countries are also attempting to strike a balance between food production and conservation, suggesting the need for judicious multiple land use for annual crop production, pastures, plantation crops, forestry and national reserves, and leaving unsuited areas untouched (Dourojeanni, 1976; Alvim, 1977). This fits ICRAF’s definition of agroforestry perfectly.

Since the key issue is the soil as a limiting factor, the purpose of this paper is to examine available data about soil management in the selva regions of tropical America.

METHODOLOGY

Three months ago the author requested a computerized literature search about soil problems in agroforestry systems, using the DIALOG system established at CIAT. The search failed to produce a single relevant reference quantifying soil fertility and conservation problems in the Latin American selvas in relation to agroforestry systems as defined by King and Chandler (1978). This came as no great surprise because research in selva regions of this hemisphere has been carried out along strict disciplinary lines such as soil science, agronomy, animal science, plantation crops, forestry and ecology. This limited data was examined as components of potential agroforestry systems. Soil fertility, management and conservation considerations will be discussed in terms of soil geography, nutrient cycling, land clearing, changes in soil properties after clearing, the maintenance of soil fertility in various systems, soil conservation, and research needs.

SOIL GEOGRAPHY AND CHARACTERIZATION

Significant progress has been made in the last 15 years in understanding the geographical distribution and properties of soils of the selva regions*, often supplemented by Landsat and

Radar imagery (Projeto RADAM, 1972-1978; Hammond, 1977). The FAO-UNESCO (1971, 1975) world soil maps have put much of this information into a common nomenclature. This data base permits a first approximation of the geographical extension of major soils, their physical and chemical properties. Table 1 provides an estimation of soils under humid tropical forests in South America. Unfortunately the Mexico-Central America portion of the world soil map did not identify the vegetation of each mapping unit, which would have permitted a similar compilation.

Table 1: Distribution of soil under tropical rainforests or evergreen seasonal tropical rainforests in South America, compiled from FAO-UNESCO (1971) tabular data, and observations by the author

<table>
<thead>
<tr>
<th>FAO Mapping Legend</th>
<th>Soil Taxonomy</th>
<th>Million of equivalent ha</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferralsols</td>
<td>Oxisols</td>
<td>480</td>
<td>68.6</td>
</tr>
<tr>
<td>Acrisols&lt;sup&gt;1/&lt;/sup&gt;</td>
<td>Ultisols</td>
<td>131</td>
<td>18.7</td>
</tr>
<tr>
<td>Gleysols</td>
<td>Aquepts</td>
<td>42</td>
<td>6.0</td>
</tr>
<tr>
<td>Lithosols</td>
<td>(Lithic groups)</td>
<td>17</td>
<td>2.4</td>
</tr>
<tr>
<td>Luvisols&lt;sup&gt;2/&lt;/sup&gt;</td>
<td>Alfisols</td>
<td>16</td>
<td>1.9</td>
</tr>
<tr>
<td>Arenosols</td>
<td>Psamments</td>
<td>6</td>
<td>0.8</td>
</tr>
<tr>
<td>Fluvisols</td>
<td>Fluvents</td>
<td>6</td>
<td>0.8</td>
</tr>
<tr>
<td>Andosols</td>
<td>Andepts</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>Vertisols</td>
<td>Vertisols</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>700</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

<sup>1/</sup> Includes 7 x 10<sup>6</sup> ha of Dystric Nitosols

<sup>2/</sup> Includes 9 x 10<sup>6</sup> ha of Eutric Nitosols

Table 1 shows that 87% of the area is covered by Oxisols and Ultisols. These are mostly well-drained soils with excellent physical properties but with very low native fertility. Oxisols are more important in areas affected by the Guayaná and Brazilian shields, while Ultisols are the main soils of the true Amazon basin deposits (Sánchez and Buol, 1974) and of the Central American selvas. Most of them have very low pH values, high
Exchangeable aluminium saturation, are low in exchangeable bases and have low cation exchange capacity. Shortly after clearing and burning, these soils become deficient in most essential elements, particularly phosphorus. Those with a clayey topsoil texture also have high phosphorus fixation capacity. Ultisols with sandy topsoil textures, however, are susceptible to compaction and erosion. There are about 38 million hectares of poorly-drained Ultisols in this region with soft plinthite in the subsoil. Because they are located mainly in flat, basin-like areas, exposure of soft plinthite layers by erosion and subsequent hardening is not likely to be extensive. Thus, the danger of laterite formation so often mentioned in the literature is limited to about 5% of the selva, with low probabilities of exposure.

Approximately 6% of the area is covered by poorly-drained alluvial soils (Gleysols or Aquepts) along the banks of large rivers. These flood plains, called *várzeas* in Brazil, are generally of high native fertility but susceptible to yearly flooding. Also included in this group are the swampy areas called *aguajales* in Peru, with low native fertility and similar areas along the quasi-divide between the Orinoco and the Rio Negro in the Venezuelan Amazon.

The most interesting point of Table 1 is the presence of 16 million ha of Alfisols with high native fertility, including 9 million ha of soils classified as Eutric Nitosols or *Terra Roxa Estruturada* in the Brazilian Amazon. The discovery of *Terra Roxa* areas along the Transamazonic highway and the Rondônia territory has resulted in strong agricultural development based on cacao and associated crops in Brazil (Falesi, 1972; Alvim, 1977). These soils are also found in considerable extensions in Ecuador, the High Selva of Peru and in Surinam. Figure 2 illustrates the differences in native soil fertility between these Alfisols and the more extensive Ultisols and Oxisols. Alfisols are also important in some of the intermediate elevation areas along the Andes.

Other soils with high native fertility include 6 million ha of well-drained alluvial soils (Fluvisols), most of which are already in extensive production; volcanic ash soils along the
Figure 2: Topsoil fertility status in Alfisols, Oxisols and Ultisols of the Amazon basin. Source: Alvim (1977).
mountain regions and adjacent flood plains in Colombia and Ecuador; and Vertisols in Peru, Ecuador and Central America. The total area of well-drained soils with moderate-to-high native soil fertility totals 24 million ha or only 3.4% of the total.

Table 1 also shows a considerable extension of extremely poor soils: 17 million ha of shallow soils (Lithosols), mostly on steep topography, and six million ha of deep sandy soils, often called Giant Tropical Podzols. Both kinds are best left in their natural state, as their agricultural potential is severely limited.

BIOMASS AND NUTRIENT CYCLING

Considerable advances have also been made in quantifying the biomass and nutrient cycling in tropical America's selvas. A few years ago, the only solid data was for classic studies in Zaire and Ghana (Bartholomew et al., 1953; Greenland and Kowal, 1960). Ecologists and foresters have provided new valuable basic information indicating large differences between sites, which can be analyzed in relation to soil properties. Table 2 summarizes the biomass nutrient content of three locations in Latin America in comparison with the classic study in Ghana. The virgin rainforest on a well-drained but extremely infertile Ultisol near Manaus has a larger total biomass and nitrogen content than the others, in spite of the fact that only 8% of the trees are leguminous (Fittkau and Klinge, 1973). The montane rainforest from the Venezuelan Andes, growing on a fertile Inceptisol, is rich in nitrogen, potassium and calcium, while the virgin rainforest on a poorly drained Oxisol of the middle Magdalena Valley of Colombia is low in all nutrients. At this last location, secondary forest fallows of known age were also compared, thereby providing an opportunity to examine the rate of re-growth of the fallow phase of shifting cultivation in nearby areas (De las Salas, 1978). It is interesting to know that the 16-year old fallow accumulated about twice as much phosphorus and potassium as the virgin rainforest because of higher P and K contents in the leaves and twigs. This is an indication that secondary forests may have a higher nutritional status than the
<table>
<thead>
<tr>
<th>Location</th>
<th>Age of forest</th>
<th>Biomass dry matter</th>
<th>Element accumulation</th>
<th>Soil Taxonomy</th>
<th>Topsoil pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(years)</td>
<td>t/ha</td>
<td>N  P  K  Ca  Mg  Al</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manaus, Brazil¹</td>
<td>Virgin</td>
<td>504</td>
<td>3294 67 500 528 274</td>
<td>Orthoxic Paleudult</td>
<td>3.8</td>
</tr>
<tr>
<td>Mérida, Venezuela²</td>
<td>Virgin montane</td>
<td>462</td>
<td>1088 62 1470 894 253</td>
<td>Aquic Humitropept</td>
<td>-</td>
</tr>
<tr>
<td>Carare, Colombia³</td>
<td>Virgin</td>
<td>184</td>
<td>740 27 277 431 133 10</td>
<td>Aerico Ochraquox</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>16 yr</td>
<td>203</td>
<td>712 55 495 558 156 125</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 yr</td>
<td>68</td>
<td>357 22 320 181 40 58</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 yr</td>
<td>19</td>
<td>162 16 119 88 26 20</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>Kade, Ghana⁴</td>
<td>Virgin</td>
<td>290</td>
<td>1017 69 495 1618 232</td>
<td>Ustalf.</td>
<td>5.2</td>
</tr>
</tbody>
</table>

virgin forests. This may be related to the presence of P-accumulating species as observed by Tergas and Popenoe (1971) in secondary fallow re-growth in Guatemala. In this regard it is also intriguing to note that the 2-, 5- and 16-year-old secondary forest fallows in the Carare study accumulated two, five, and twelve times as much aluminium in the biomass as did the original virgin forest (De las Salas, 1978). Changing the virgin rainforest into secondary forest fallows by shifting cultivation is commonly considered a damage to the ecology due to losses in species diversity (Richards, 1977). These data suggest that attention should be paid to the nutrient composition of the fallows as well.

Another commonly held view is that tropical rainforests essentially feed themselves, since most selva soils are very poor in nutrients (Goodland and Irwin, 1975). Nutrient-cycling studies, however, show that the bulk of the nitrogen and phosphorus in the ecosystem is located in the topsoil, where it cannot be lost upon burning (Table 3). This is not the case with potassium, calcium and magnesium, which are concentrated in the biomass, except in high base status soils such as the Alfisol from Ghana.

Table 3: Proportion of total nutrients stored in the soil in tropical forest ecosystems (same location and sources as previous table)

<table>
<thead>
<tr>
<th>Location</th>
<th>Nutrient Additions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Manaus, Br.</td>
<td>73</td>
</tr>
<tr>
<td>Mérida, Ven.</td>
<td>81</td>
</tr>
<tr>
<td>Carare, Col.</td>
<td>71</td>
</tr>
<tr>
<td>Kade, Ghana</td>
<td>81</td>
</tr>
</tbody>
</table>

Some degree of quantification about the amounts of nutrients transferred from the forest to the soil is also emerging. Table 4 shows data on annual litter additions from the previously mentioned sites. Fassbender (1977) has assembled additional data,
but without relating them to soil properties. The salient point of Table 4 is the extremely small amount of phosphorus added annually to the soil, and the large differences between sites. In sites where the nutrient composition of the rainwash was also recorded, potassium additions through this mechanism were more than twice the amount added through litter decomposition (Fassbender, 1977; De las Salas, 1978).

Table 4: Annual nutrient additions from tropical rainforests to the soil via litter (same location and sources as previous table)

<table>
<thead>
<tr>
<th>Location</th>
<th>Forest</th>
<th>Litter dry matter t/ha/yr</th>
<th>Nutrient Additions kg/ha/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manaus, Br.</td>
<td>Virgin</td>
<td>7.3</td>
<td>106 2 13 18 13</td>
</tr>
<tr>
<td>Mérida, Ven.</td>
<td>Virgin</td>
<td>4.6</td>
<td>57 3 20 31 12</td>
</tr>
<tr>
<td>Carare, Col.</td>
<td>Virgin</td>
<td>12.0</td>
<td>141 4 17 90 20</td>
</tr>
<tr>
<td>Carare, Col.</td>
<td>16-yr-old</td>
<td>9.5</td>
<td>108 2 29 53 18</td>
</tr>
<tr>
<td>Kade, Ghana</td>
<td>Virgin</td>
<td>12.5</td>
<td>199 7 68 206 45</td>
</tr>
</tbody>
</table>

Knowledge about the nutrient-cycling dynamics of the ecosystem in its natural state may be useful in predicting what changes will take place when agroforestry systems are introduced. The techniques are laborious and expensive, but the differences illustrated suggest that at least litter and rainwash measurements should be made. The absence of data for sulphur and micro-nutrients is a major gap, because many of these nutrients rapidly become limiting after forest clearing.

LAND CLEARING

The choice of land-clearing method is the first and probably most crucial step affecting the future productivity of agroforestry systems. Several comparative studies conducted in the Latin American selvas confirm that land-clearing methods that involve
burning are superior to different types of mechanical clearing because of: (1) the fertilizer value of the ash, (2) soil compaction caused by bulldozing, and (3) topsoil displacement in mechanized land clearing.

**NUTRIENT ADDITIONS BY THE ASH**

The nutrient content of the ash has been directly determined only upon burning a 17-year-old secondary forest on an Ultisol in Yurimaguas, Peru. The data of Seubert *et al.* (1977) in Table 5 show significant beneficial effects of ash on soil chemical properties (Figure 3), which produced consistently higher yields of a wide variety of crops during the first two years after clearing (Table 6). Variability in the quantity of ash and its nutrient content occurs because of differences in soils, clearing techniques and the proportion of the forest biomass actually burned. Silva (1978) estimated that only 20% of the forest biomass was actually converted to ash when burning a virgin forest on an Ultisol of southern Bahia, Brazil. Silva also analyzed the ash composition of the burned parts of individual tree species and observed very wide ranges (0.8 to 3.4% N, 0 to 14 ppm P, 0.06-4.4 me Ca/100 g, 0.11-21.03 me Mg/100 g, and 34-345 me K/100 g). This information suggests the presence of certain species that can be considered accumulators of specific nutrients.

Table 5: Nutrient contribution of ash and partially burned material to an Ultisol of Yurimaguas, Peru after burning a 17-year-old forest

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
<th>Total additions kg/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1.72%</td>
<td>67</td>
</tr>
<tr>
<td>P</td>
<td>0.14%</td>
<td>6</td>
</tr>
<tr>
<td>K</td>
<td>0.97%</td>
<td>38</td>
</tr>
<tr>
<td>Ca</td>
<td>1.92%</td>
<td>75</td>
</tr>
<tr>
<td>Mg</td>
<td>0.41%</td>
<td>16</td>
</tr>
<tr>
<td>Fe</td>
<td>0.19%</td>
<td>7.6</td>
</tr>
<tr>
<td>Mn</td>
<td>0.19%</td>
<td>7.3</td>
</tr>
<tr>
<td>Zn</td>
<td>132 ppm</td>
<td>0.3</td>
</tr>
<tr>
<td>Cu</td>
<td>79 ppm</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Source: Seubert *et al.* (1977)
Figure 3: Effects of two land clearing methods on changes in topsoil (0-10 cm) properties in a Typic Paleudult of Yurimaguas, Peru. Source: Seubert et al. (1979)
Table 6: Effects of land-clearing methods on crop yields at Yurimaguas. (Yield is the average of the number of harvests indicated in parenthesis)

<table>
<thead>
<tr>
<th>Crops</th>
<th>Fertility level*</th>
<th>Slash and burn</th>
<th>Bulldozed Burned</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>--- t/ha** ---</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Upland rice (3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>1.3</td>
<td>0.7</td>
<td>53</td>
</tr>
<tr>
<td>NPK</td>
<td>3.0</td>
<td>1.5</td>
<td>49</td>
</tr>
<tr>
<td>NPKL</td>
<td>2.9</td>
<td>2.3</td>
<td>80</td>
</tr>
<tr>
<td>Corn (1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>0.1</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>NPK</td>
<td>0.4</td>
<td>0.04</td>
<td>10</td>
</tr>
<tr>
<td>NPKL</td>
<td>3.1</td>
<td>2.4</td>
<td>76</td>
</tr>
<tr>
<td>Soybeans (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>0.7</td>
<td>0.2</td>
<td>24</td>
</tr>
<tr>
<td>NPK</td>
<td>1.0</td>
<td>0.3</td>
<td>34</td>
</tr>
<tr>
<td>NPKL</td>
<td>2.7</td>
<td>1.8</td>
<td>67</td>
</tr>
<tr>
<td>Cassava (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>15.4</td>
<td>6.4</td>
<td>42</td>
</tr>
<tr>
<td>NPK</td>
<td>18.9</td>
<td>14.9</td>
<td>78</td>
</tr>
<tr>
<td>NPKL</td>
<td>25.6</td>
<td>24.9</td>
<td>97</td>
</tr>
<tr>
<td>* 50 kg N/ha, 172 kg P/ha, 40 kg K/ha, 4 t/ha of lime.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>** Grain yields of upland rice, corn and soybean; fresh root yields of cassava, annual dry matter production of <em>Panicum maximum</em>.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source: Seubert et al. (1977).</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The fertilizer value of the ash is likely to be of less importance in fertile soils. Cordero (1964) observed that the increases in phosphorus and potassium availability caused by burning an Entisol of pH 7 in Santa Cruz, Bolivia, did not increase crop yields. The soil was already high in these elements. Information on ash composition from different soils and clearing methods, therefore, will contribute significantly to our understanding of soil dynamics.
SOIL COMPACTION

Conventional bulldozing has the clearly detrimental effect of compacting the soil, particularly coarse-textured Ultisols. Significant decreases in infiltration rates, increases in bulk density and decreases in porosity have been recorded on such soils in Surinam (Van der Weert, 1974), Peru (Seubert et al., 1977) and Brazil (Schubart, 1977; Silva, 1978). Table 7 shows the decreases in infiltration in the latter three sites. The slash-and-burn clearing had little effect on infiltration rates but bulldozing decreased them tremendously. Comparisons between sites are difficult because of differences in the time span used in measuring. The Manaus example illustrates the compaction observed in degraded pastures in much of the Amazon.

Table 7: Effects of bulldozer clearing in decreasing infiltration rates in Ultisols from Yurimaguas, Peru, Manaus and Belmonte, Bahia, Brazil

<table>
<thead>
<tr>
<th>Clearing Method</th>
<th>Yurimaguas</th>
<th>Manaus</th>
<th>Belmonte</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undisturbed forest</td>
<td>-</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>Slash and burned (1 year)</td>
<td>10</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>Bulldozed (1 year)</td>
<td>0.5</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Bulldozed and 5 year pastures</td>
<td>-</td>
<td>0.4</td>
<td>-</td>
</tr>
</tbody>
</table>

Sources: Seubert et al. (1977); Schubart (1977) and Silva (1978).

TOPSOIL CARRY-OVER

The third major consideration is the degree of topsoil carry-over, not by the bulldozer blade, which is normally kept above the soil, but by dragging uprooted trees and logs. Although no quantitative data is available, topsoil scraping in high spots and accumulation in low spots is commonly observed. The better jungle re-growth near windrows of felled vegetation suggests that topsoil carry-over can result in major yield reductions (Sánchez, 1976). For example, Lal et al. (1975) in Nigeria observed
that corn yields decreased by 50% when the top 2.5 cm of an Alfisol was removed.

ALTERNATIVE LAND-CLEARING METHODS

The negative effects of bulldozer land-clearing are now well-known to farmers and development organizations. Government credits for large-scale mechanized land-clearing operations have been sharply reduced in the Brazilian Amazon since 1978. Also the practice of completely destroying the forest versus its partial harvesting before burning is being questioned. Silva (1978) has provided the first quantitative estimate of the possible benefits of such a practice. He compared the two extremes, slash-and-burn and bulldozing, with removing the marketable trees first, then cutting the rest and burning it. All the advantages of burning on soil fertility were observed in this latter treatment, with no significant differences for the conventional slash-and-burn method, but with a valuable increase in income. The lack of differences is probably due to the small proportion of the total biomass that is actually burned. Indeed many farmers in the Amazon harvest wood first; some of them developing profitable lumber mills while clearing land for pasture establishment.

Other alternative methods consist of mechanized clearing followed by burning, using two bulldozers dragging a heavy chain, or large tree-crusher machines which literally walk over the felled forest. The latter alternative provides a better burn (Toledo and Morales, 1979). In the case of the chain-drag system, the remaining logs can be pushed away into windrows with a root-rake after burning. These combined operations capitalize on the fertilizer value of the ash, but still cause some degree of soil compaction and topsoil removal. They are also more expensive because two or more machine operations are needed, increasing costs and the logistical support needed for maintaining and transporting heavy equipment in jungle areas. The traditional slash-and-burn system is clearly the best unless one is prepared to add additional fertilizer and tillage operation to compensate for its disadvantages in soil fertility and compaction. The same situation occurs when clearing forests in Southeastern United States Ultisols, but the problem is solved by adding additional
inputs. Many of the failures of large-scale operations observed by this author in the Amazon can be directly attributed to improper land clearing methods.

SOIL DYNAMICS AFTER CLEARING

When a tropical forest is cleared and burned the following changes in soil properties generally occur within the first year. (1) Large volatilization losses of biomass nitrogen and sulphur occur upon burning, and soil organic matter decreases with time until a new equilibrium is reached. (2) The pH of acid soils increases, aluminium saturation values decrease, and exchangeable bases and available phosphorus increase, all because of the nutrient content of the ash. These changes are gradually reversed with time. (3) Soil temperatures increase and moisture regimes fluctuate more because more solar radiation reaches the soil surface (Sánchez, 1976).

The above generalizations can now be examined for site specificity. Most of the available data is based on sampling nearby sites of assumed known age after clearing, thus confounding time and space dimensions and increasing the already large variability in such soil samples. The available literature of this type up to 1976 has been summarized elsewhere (Sanchez, 1973, 1976). Fortunately there are five studies in which soil dynamics are being followed as a function of time: in Yurimaguas in Peru; Manaus, Belém and southern Bahia in Brazil; and Carare in Colombia. Most of them, however, are limited to what happens during the first year, the oldest being only 4 years old. Nevertheless they illustrate the differences that take place within sites as a function of time. Additional new information from time-space studies will also be discussed and identified as such.

SOIL ORGANIC MATTER

De las Salas and Folster (1976) estimated that 25 t/ha of C and 673 kg N/ha were lost to the atmosphere when a virgin forest on a wet Oxisol in the middle Magdalena Valley of Colombia was cut and burned, by measuring the biomass changes before and after burning, but before the first rains. I am not aware of
comparable figures from other ecosystems in Latin America, to determine whether these losses are representative or not. Nevertheless, volatilization losses accounted for only 11 to 16% of the total C, and about 20% of the total N in the ecosystem (De las Salas, 1978). Consequently, assertions that most of the carbon and nitrogen in the vegetation is volatilized upon burning deserve careful scrutiny. Another unknown factor is whether or not a proportion of the volatilized elements is returned back to nearby areas via rainwash.

The influence of burning on the first thin organic-rich layer consisting of litter-topsoil interphase was also determined by De las Salas (1978). The C/N ratio of this material increased from 8 to 46 within 5 months, suggesting that the volatile losses were rich in nitrogen.

The literature has conflicting information about the losses of soil organic matter when the cropping phase begins. Larger losses will occur in soils with higher original organic matter contents (Sánchez, 1976). This effect, however, is attenuated by the topsoil clay content. Turenne (1969, 1977) found an inverse relationship between organic carbon losses and clay contents in Oxisols of French Guyana.

Another supposedly detrimental effect of burning is a decrease in soil microbiological activity. Silva's (1978) southern Bahia study indicates that there were no significant differences caused by various degrees of burning on fungal flora, but there was a decrease in the bacterial and actinomycetal population during the first 30 days after the conventional burn. Figure 4 shows the time trend in cellulose decomposition activity. Burning actually had a stimulating effect on the organic matter decomposing microflora, probably because of the increase in phosphorus and other nutrients, plus the higher soil temperatures incurred upon exposing the topsoil to direct sunlight. This, however, was not the case in the even more exposed bulldozer clearing, probably because of topsoil carry-over and soil compaction. The partial sterilization effect in the conventional burn may account for the lower microbiological activity during the first 25 days after burning.
Figure 4: Effects of degrees of burning intensity on microbial activity as measured by cellulose decomposition rates as a function of time after burning a rainforest on an Ultisol of southern Bahia, Brazil. Adapted from Silva (1978).
The dynamics of organic carbon during the first four years of continuous upland rice cropping on an Ultisol from Yurimaguas, Peru, are shown in Figure 5. There is an actual increase in organic carbon right after burning, probably a result of ash contamination. This is followed by a plateau for the first 6 months, then a sharp decrease is observed after the first rice crop was harvested, and finally an equilibrium is reached during the first year. The annual decomposition rate during the first year is in the order of 30%, but this rate diminishes and reverses itself during the second year of cropping at high fertility levels (Villachica, 1978). This sharp decomposition rate resulted in a very large increase in topsoil inorganic nitrogen during the first 6 months at Yurimaguas (80 kg N/ha in the top 50 cm), which quickly disappeared because of leaching and/or crop uptake (Seubert et al., 1977). This "nitrogen flush" probably contributes to the initial lush growth of the first crop after burning. No other data on profile inorganic nitrogen dynamics in the Latin American selvas were found in the literature search.

Turenne (1969, 1977), working on Oxisols from French Guyanian fallows of known age, has made valuable observations on organic matter dynamics during the fallow phase. He observed that beginning with the second year of forest-fallow, the topsoil C/N ratio began to decrease while the fulvic acid composition of the organic matter increased, indicating the beginning of a nitrogen-enrichment process. Turenne also observed that the litter layer re-establishes itself after four years of fallow and that it builds up as much organic matter in 10 years as is found in a 31-year old forest.

Figure 6 shows the results of a time-space study of De las Salas and Folster (1976) at Carare, Colombia. A sharp initial decline in organic carbon and nitrogen was noted, but the curve turned upward during the second year, surpassing the virgin forest levels in the 16-year-old fallow. A 16-year-old pasture consisting of a mixture of Hyparrhenia rufa, Panicum maximum and other grass species, produced topsoil organic carbon and nitrogen levels equal to that of the virgin forest. Although
YURIMAGUAS ULTISOL (0-10 cm.)

Figure 5: Changes in chemical properties of an Ultisol continuously cropped to upland rice (8 crops), without fertilization at Yurimaguas (1972-76). Compiled from data by Seubert et al. (1977) and Villachica and Sánchez (in press).
Figure 6: Topsoil (0-10 cm) organic matter status in the Carare forest, Middle Magdalena Valley, Colombia, in nearby sites with known age and type of vegetation. Aeric Ochraquox soil pH 3.8, 3000 mm rainfall. Adapted from De las Salas and Folster (1976) and De las Salas (1978).
this comparison is limited by the usual variability and small sample size (two plots in each treatment), it should cast doubt on statements asserting that grass pastures have detrimental effects on soil properties in selva regions.

CHANGES IN SOIL ACIDITY AND NUTRIENT AVAILABILITY

The changes in topsoil properties before clearing and the first sampling after burning of several properly sampled true-time studies are summarized in Table 8. This table shows the general trends, and deviations thereof. Soil pH values increase after burning but not to neutrality. Exchangeable Ca+Mg levels are doubled or tripled, but there is a significant variability among adjacent plots on the same soil as shown by the two Yurimaguas sites. This particular difference is attributed to an initially higher base status in Site II and a better quality burn. Exchangeable K also increases drastically but the effect is short-lived because of rapid leaching. This probably explains why there were no increases in the Yurimaguas II and Belém sites, which were sampled at 3 and 12 months after burning. Exchangeable Al decreases in proportionate amounts to increase in Ca+Mg, suggesting a straight liming effect. An exception to this statement occurs in the more fertile southern Bahia site. Aluminium saturation decreases in all cases, to levels below that considered as critical (60%) except in one case. Available P, commonly considered the most limiting nutrient, also increases with burning, surpassing the critical level of about 10 ppm P in some cases, but again with considerable variability within sites. Regardless of these differences there is no question that the fertility of acid soils increases considerably after burning.

FERTILITY DECLINE PATTERN

These relationships begin to reverse themselves with time. Figure 3 illustrates the changes occurring within the first 10 months after clearing in Yurimaguas. Silva (1978) has reported almost identical results at the other end of the continent, in southern Bahia. Inorganic N (not shown) and K are the first elements to be depleted, while the others show a slower decline.
Table 8: Summary of changes in topsoil chemical properties before and shortly after burning tropical forests in Ultisols and Oxisols of the Amazon

<table>
<thead>
<tr>
<th>Soil Property</th>
<th>Timing</th>
<th>Yuri-magas 1/ (2 sites)</th>
<th>Manaus 2/ (X 7 sites)</th>
<th>Belém 3/ (X 60 sites)</th>
<th>Belmonde 4/ Bahia (1 site)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months after burning:</td>
<td>1</td>
<td>3</td>
<td>0.5</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>pH (in H₂O)</td>
<td>Before:</td>
<td>4.0</td>
<td>4.0</td>
<td>3.8</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>After:</td>
<td>4.5</td>
<td>4.8</td>
<td>4.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Exch. Ca+Mg (me/100 g)</td>
<td>Before:</td>
<td>0.41</td>
<td>1.46</td>
<td>0.35</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>After:</td>
<td>0.88</td>
<td>4.08</td>
<td>1.25</td>
<td>1.97</td>
</tr>
<tr>
<td></td>
<td>Δ</td>
<td>0.47</td>
<td>2.62</td>
<td>0.90</td>
<td>0.94</td>
</tr>
<tr>
<td>Exch. K (me/100 g)</td>
<td>Before:</td>
<td>0.10</td>
<td>0.33</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>After:</td>
<td>0.32</td>
<td>0.24</td>
<td>0.22</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Δ</td>
<td>0.22</td>
<td>(0.07)</td>
<td>0.15</td>
<td>0.00</td>
</tr>
<tr>
<td>Exch. Al (me/100 g)</td>
<td>Before:</td>
<td>2.27</td>
<td>2.15</td>
<td>1.73</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>After:</td>
<td>1.70</td>
<td>0.65</td>
<td>0.70</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Δ</td>
<td>(0.59)</td>
<td>(1.50)</td>
<td>(1.03)</td>
<td>(0.72)</td>
</tr>
<tr>
<td>Al satn. (%)</td>
<td>Before:</td>
<td>81</td>
<td>52</td>
<td>80</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>After:</td>
<td>59</td>
<td>12</td>
<td>32</td>
<td>30</td>
</tr>
<tr>
<td>Avail. P (ppm)</td>
<td>Before:</td>
<td>5</td>
<td>15</td>
<td>-</td>
<td>6.3</td>
</tr>
<tr>
<td>Olsen in Peru, After:</td>
<td>16</td>
<td>23</td>
<td>-</td>
<td>7.5</td>
<td>8.5</td>
</tr>
<tr>
<td>NC in Brazil)</td>
<td>Δ</td>
<td>II</td>
<td>8</td>
<td>-</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Calculated from data by: 1/ Seubert et al. (1977) and Villachica and Sánchez (in press)
2/ Brinkmann and Nascimento (1973)
3/ Hecht (unpublished data)
4/ Silva (1978)

Figure 5 shows the four-year trend in unfertilized plots at Yurimaguas grown to two crops of upland rice a year. Yields of the first three crops were of the order of 1.2 t/ha, declining to 0.5 t/ha in the fourth crop and to negligible amounts afterwards (Bandy, 1977). The soil was so infertile that not much weed growth was observed. Its surface was also heavily compacted by exposure to rains, because
the poor rice growth did not provide an adequate canopy.

Shifting cultivators seldom continue the cropping period for such a long time. They normally abandon their fields when they expect less than half the yield in the forthcoming crop than in the previous one (Sánchez, 1976). Figure 7 illustrates when this would happen in different soils and with different crops. In the fertile Mollisol from Petén, Guatemala, only two crops of maize will be planted. Weed control is the main limiting factor. In the fertile, but poorly drained Alfisol from Yurimaguas, more than three consecutive upland rice crops can be expected if the weeds are controlled. In the infertile, well-drained Ultisol at the same location, only 2 crops of rice or cassava, and one rotation of rice-corn-soybeans (in 1 year) can be expected. From Figure 7 it is apparent that weed control is the main limiting factor in the more fertile soils, while fertility decline is the main cause of yield decline in the acid Ultisols.

MAINTENANCE OF SOIL FERTILITY UNDER ANNUAL CROPS

FARMER EXPERIENCE IN SELECTING BETTER SOILS: ALTAMIRA

One straightforward strategy to retard the yield-decline pattern is the selection of better soils. An excellent example is given in a survey by Morán (1977) showing the ingenious selection criteria used by one type of shifting cultivator near Altamira, along the Transamazonic highway of Brazil. The "caboclos" native to the region select sites with trees of relatively thin trunks such as açaí (Euterpe oleracea), babaçu (Orbignya martiana) and morocó (Bauhinia macroptachia). The "colonos", or new settlers attracted by government colonization projects, look for virgin forests with thick tree trunks such as acapu (Vouacapona americana), caju-çu (Anacardium giganteum) and jarana (Holoppyzidium jarana). After one year of similar slash-and-burn practices, the caboclos' soils had a totally superior chemical status to that of the colonos (Table 9). This data suggests that caboclos were able to identify areas of Alfisols by vegetation, while the new settlers went for the Ultisols and Oxisols. The caboclos also grew mostly cassava, while the colonos planted rice, corn,
Figure 7: Yield decline pattern in several shifting cultivation systems without fertilization. Adapted from Sánchez (1976).
Table 9: Topsoil (0-10 cm) properties of soils selected by caboclos and colonos near Altamira, Pa., Brazil. Mean of 3 samples taken a year after felling and burning

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Caboclo Thin</td>
<td>10 YR 4/4-3/2</td>
<td>6.2</td>
<td>1.7</td>
<td>26</td>
<td>0</td>
<td>7.1</td>
<td>0.1</td>
<td>8.2</td>
<td>0</td>
</tr>
<tr>
<td>Colono Large</td>
<td>7.5 YR 4/5-3/3</td>
<td>4.3</td>
<td>2.3</td>
<td>2</td>
<td>5.5</td>
<td>1.1</td>
<td>0.2</td>
<td>6.8</td>
<td>81</td>
</tr>
</tbody>
</table>

* Effective calcium carbonate equivalence

Source: Morán (1977)

and beans, all without fertilization. As a result of the judicious selection of soils and adapted crops by the traditional shifting cultivators, the caboclo's farm income was twice as much as the new settlers' income (Morán, 1977). Although the indicator species are likely to differ in other regions, this is a good example of accumulated experience as a way to prolong the cropping period. A quantification of these differences in tree species by chemical analysis would be most useful.

INTENSIVE CONTINUOUS CROP PRODUCTION: YURIMAGUAS

The fertility requirements for continuous crop production in an Ultisol from Yurimaguas after clearing and burning a 17-year-old secondary forest have been investigated since 1972 using a variety of cropping systems and fertilization rates (North Carolina State University 1973, 1974, 1975, 1976; Sanchez, 1977a, b, c; Bandy, 1977; Villachica, 1978). Figure 8 shows the yield pattern of an annual rotation of upland rice, corn and soybeans (three crops a year) during the first three years. Without
Figure 8: Performance of the rice-corn-soybean system with time after clearing in Yurimaguas. Source: Sánchez (1977).
fertilization yields dropped sharply within six months after clearing, showing that the beneficial effect of burning lasts only a semester in this very rainy environment. The sequence of nutrient limitations in their order of appearance is outlined in Table 10. This shows how dynamic the system is and explains the low yields obtained without fertilization in Figure 8. The increase in yield from the seventh crop onwards is due to the identification and solution of these fertility problems. A fertilization scheme for this situation is presented in Table 11. Maintenance fertilization as such begins with the second year and is supported by a soil-testing programme. Further experience shows that peanuts (Arachis hypogea L.) can replace corn (Zea mays) since then grow well under these conditions, are not limited by solar radiation as is corn, and would eliminate nitrogen fertilization needs in two out of three crops in the yearly rotation.

This fertilization scheme is costly (about US $875/ha/year) but the yields are high. Bandy (1977) shows that the scheme is profitable with a net return of US $2.91 per dollar invested in fertilizers and lime at 1973 prices in Yurimaguas for the rice-soybeans-peanuts rotation. This calculation includes the high cost of transporting fertilizers from industrial areas.

LOW INPUT CONTINUOUS CROP PRODUCTION: YURIMAGUAS

The high fertilization requirements previously described limit the adoption of an intensive system to areas with readily available credit and fertilizers as well as a working marketing system. Other strategies were also investigated for continuous cropping at lower costs. One is a five-crop-a-year relay intercropping of cassava, corn, soybeans and peanuts, which produces 30% more total yield per year than if the crops were grown in monocultures (Wade, 1978; Bandy, 1977; Sánchez, 1977a,b). Another is the use of kudzu (Pueraria phaseoloides) as a mulch or green manure. Kudzu supplies enough nutrients to produce soybeans, peanuts, cowpeas and upland rice yields on the order of 80 to 90% of that achieved in heavily fertilized plots without organic additions (Table 12).
Table 10: Time of appearance of fertility limitations in an upland rice-corn-soybean annual rotation after burning a secondary forest in an Ultisol in Yurimaguas, Peru

<table>
<thead>
<tr>
<th>Months after clearing</th>
<th>Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial boost in pH, inorganic N, P, K, Ca, Mg, S, and micronutrients, decrease in Al saturation to below toxic levels. Effect of ash.</td>
</tr>
<tr>
<td>10</td>
<td>Organic C decomposition to new equilibrium level completed. Al saturation increases, surpassing toxicity level of 60% for corn and soybeans. Available P below critical level (12 ppm P via Olsen method). Mg becomes critical at 0.2 me/100 g for soybeans and 0.4 for corn.</td>
</tr>
<tr>
<td>12</td>
<td>Liming to pH 5.5 and applications of 80-26-80 kg N, P, K/ha per crop except N for soybeans increases yields. K applications solve K deficiency but create K/Mg imbalance when ratio &gt;1.2. Mg applications needed. B deficiency evident. S, Cu, and Mo probably limiting (S became limiting immediately after clearing in bulldozed plots). Mo deficiency depends on Mo status in seed.</td>
</tr>
<tr>
<td>24</td>
<td>Nutrient removal by cropping depletes soil further. Rates of N, P, K and Mg have to increase.</td>
</tr>
<tr>
<td>48</td>
<td>Zn deficiency appears.</td>
</tr>
</tbody>
</table>

Source: Villachica (1973) and Villachica and Sánchez (in press)

Economic analyses of these and other combinations, including the use of the traditional rice-cassava-plantain-fallow system reported by Cate and Coutu (1977) show that the net income of a small farm family in Yurimaguas can reach US $6,000 per year assuming a capital investment of US $1,000 prorated over 3 years.
Table 11: Suggested fertility maintenance scheme for intensive crop production in Yurimaguas. Three crops a year: rice, corn, soybeans, or preferably rice-peanuts-soybeans

<table>
<thead>
<tr>
<th>Months after clearing</th>
<th>Crop No.</th>
<th>Fertilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>Slash and burn clearing. Short-statured upland rice planted without fertilization. Yields 3 t/ha. Soil tested near harvest to determine Al saturation.</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>Apply dolomitic lime at 3.5 x exch. Al and incorporate with hand tractor. Apply 100 kg P/ha as single superphosphate to correct P and S deficiencies, and 60 kg K/ha. If dolomitic lime unavailable add 30 kg Mg/ha per crop.</td>
</tr>
<tr>
<td>12 onwards</td>
<td>5</td>
<td>Maintenance applications (kg/ha per crop) of 50 P, 50-80 K, Mg to keep K/Mg ratio at about 1.2. 1 kg B and 1 g Mo/kg seed. N rates should be 80 for rice, 120 for corn and none for soybeans and peanuts. Soil testing every 6 months to check for Al toxicity, P, K, Mg and micronutrients. Apply 2 kg Cu/ha every 3 crops.</td>
</tr>
<tr>
<td>24</td>
<td>9</td>
<td>May need to add more lime. Watch for Zn becoming critical.</td>
</tr>
</tbody>
</table>

Source: Villachica (1978) and Villachica and Sánchez (in press)

Table 12: Effects of mulching and incorporating Pueraria phaseoloides without fertilization on the yields of five consecutive crops relative to bare plots fertilized with a basal dose of 2 t/ha of lime, 150 kg P/ha, 1 kg B/ha, 1 kg Mo/ha, and 120 kg N/ha per non-leguminous crop, and 60 kg K ha/crop. Yields in parenthesis. Yurimaguas, Peru

<table>
<thead>
<tr>
<th>Treatments (unfertilized)</th>
<th>1st crop Soybeans (1.10)</th>
<th>2nd crop Cowpeas (0.74)</th>
<th>3rd crop Corn (4.17)</th>
<th>4th crop Peanuts (2.33)</th>
<th>5th crop Rice (2.74)</th>
<th>Mean effect % yields of bare, fertilized plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare soil</td>
<td>9</td>
<td>59</td>
<td>.33</td>
<td>55</td>
<td>64</td>
<td>44</td>
</tr>
<tr>
<td>Kudzu mulch</td>
<td>-</td>
<td>97</td>
<td>72</td>
<td>63</td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>Kudzu incorp.</td>
<td>109</td>
<td>77</td>
<td>88</td>
<td>79</td>
<td>99</td>
<td>90</td>
</tr>
</tbody>
</table>

Source: Wade (1978)
Continuous cropping is estimated to require about seven ha per year. This family income level compares very favourably with the 1977 average annual rural family income of US $750 in the Yurimaguas area and US $1,500 for the top 25% of the families in the barriadas (slums) of Lima, mostly immigrants from Peru's rural areas.

MAINTENANCE OF SOIL FERTILITY UNDER PASTURES

Pasture-based beef production is the largest single activity of cleared land in the Amazon basin, and a major source of controversy, particularly in Brazil. There are about 3.7 million ha of cultivated pastures in forest areas of the Amazon, according to estimates by Kirby (1976) and Serrão et al. (1979). Most of them consist of *Panicum maximum*, are not fertilized, and have a carrying capacity of one animal unit/ha, producing about 100 kg/ha of annual liveweight gain. After the first three to four years, pasture productivity begins to decline, secondary growth invades and the pasture slowly changes into secondary forest fallows. Serrão et al. (1979) estimate that 20% of the area planted to pastures in the Brazilian Amazon is in some state of degradation. This has raised serious questions as to the future of this very important farming system in the Amazon (Goodland and Irwin, 1975; Schubart, 1977; Fearnside, 1978). The Brazilian government has essentially suspended credits for new land clearings for pasture and is concentrating its research efforts to reclaim these degraded pastures.

A series of studies conducted primarily in the Paragominas area along the Belém-Brasilia highway, in northern Mato Grosso and near Belém has shed interesting information about soil dynamics as a function of time in pasture production (Falesi, 1976; Baena, 1977; Serrão et al., 1979; Fearnside, 1978; Hecht, 1978). Soil samples were taken in pastures of known age in several farms. Although sample size is small, time and space are confounded and variability is very high, a clear trend has emerged from these studies: pastures retard the rate of fertility decline, maintaining constant for several years the benefits of burning, particularly a high soil pH, elimination of aluminium toxicity, high
calcium and magnesium, and for the first four to five years, sufficient levels of phosphorus.

Figure 9 summarizes the data for a clayey Oxisol from Paragominas and a loamy Oxisol from northern Mato Grosso. This figure suggests a remarkable degree of nutrient recycling and maintenance of soil fertility under pastures in the eastern Amazon. Observations on animal productivity indicate that its decline is associated with available P levels decreasing below 4 ppm. Serrão et al. (1979) state that the speed of this decline is faster in clayey than in loamy soils. Since P fixation in Oxisols and Ultisols increases as a function of topsoil clay content (Pope, 1976; Sánchez, 1977b), it is not surprising that the clayey Oxisols show pasture degradation symptoms earlier than the loamy ones. Since guinea grass (*Panicum maximum*) responds very strongly to P fertilization, it is also not surprising that it tends to disappear from pasture and is overgrown by jungle re-growth. Serrão and coworkers found that excessively high grazing pressures also accelerate pasture degradation.

A look at Figure 9 suggests that these pastures are periodically burned as the sharp increases in bases and available P show. It also illustrates large site-to-site variability.

The solution to this apparently hopeless situation in the eyes of certain ecologists (Schubart, 1977; Fearnside, 1978) is remarkably simple: clear the jungle re-growth by hand, burn the pasture, and broadcast 25 kg P/ha, half as single superphosphate and half as rock phosphate. When Serrão and coworkers (1979) did this in a 13-year-old degraded pasture at Paragominas, its botanical composition changed from 75 to 80% weeds and jungle re-growth to 90 to 95% *Panicum maximum*. Ongoing experiments observed by this writer suggest that animal liveweight gains will increase remarkably.

There are still questions about how persistent *Panicum maximum* will be, since its fertility requirements are relatively high, and whether nutrients other than P and S (which were applied in the single superphosphate) will become limiting. The particular concern is available K which hovers around the critical level, and of course available N. Research underway is studying
Figure 9: Changes in topsoil properties of *Panicum maximum* pastures of known age in eastern Amazonia (sampled at the same time). Adapted from Serrao *et al.* (1979).
the adaptation of grass species that require lower levels of P, e.g. Brachiaria humidicola and Andropogon gayanus, and the introduction and test for persistence of legume species such as Pueraria phaseoloides, Stylosanthes capitata, Desmodium ovalifolium and many others. A related limiting factor is the tolerance of pasture species to devastating insect and disease attacks in the Amazon, such as spittlebug on Brachiaria decumbens and Anthracnose on Stylosanthes guianensis. Also, the forage value of some of the jungle re-growth species is considerable, according to a recent study by Hecht (1979).

At the other extreme of the Amazon, in the wetter region of Pucallpa, Peru, Toledo and Morales (1979) report that productive grass-legume pastures fertilized with 22 kg P/ha/year as simple superphosphate have persisted for at least three years, producing about 377 kg/ha of annual liveweight gains with a carrying capacity of three animals/ha in mixtures of Hyparrhenia rufa and Stylosanthes guianensis. Without the legume, similarly fertilized pastures produced a maximum of 149 kg/ha of annual liveweight gain with a carrying capacity of 2.1 animals/ha.

These data are most encouraging because they indicate a very high beef production potential in Amazon jungle pastures with minimal inputs. Also the Brazilian data suggest a significant degree of nutrient recycling in extensively managed pastures. The sharp differences in fertility decline between the cropping data shown in Figures 3 and 5 and the pasture data in Figure 9 probably reflect more than just the effect of nutrient recycling by the grazing animal. The Paragominas area has a ustic or nearly ustic soil moisture regime with a strong four-month dry season. The contribution of the ash may be larger because of a more intense burn. The dry season may also decrease leaching losses and even reverse the flow of nitrates, potassium and other cations upwards during the dry season. Also, farmers burn the weed and forage re-growth every two to three years in Paragominas, which facilitates nutrient recycling. The situation in Pucallpa is similar to the Yurimaguas, Manaus and southern Bahia cropping regimes, but unfortunately no soil dynamics data is available from this location.
The maintenance of soil fertility under tropical pastures is not new. A similar time-space study conducted by Bruce (1965) after clearing a tropical rainforest in South Johnstone, Australia, shows a decline in topsoil organic matter content with unfertilized *Panicum maximum*, but a complete maintenance of the original topsoil organic carbon and nitrogen levels with *Panicum maximum - Centrosema pubescens* pastures up to 16 years of age (Figure 10). The data for a 16-year-old pasture in the Carare, Colombia study shown in Figure 6 also indicates that pastures can build up the organic matter level of soils as fallows in shifting cultivation regions.

SOIL FERTILITY MAINTENANCE UNDER PERMANENT CROPS AND FORESTRY

I found only one piece of evidence on this subject from the humid tropics of Latin America: evidence of incipient nutrient recycling of several permanent crops in the southern Bahia study of Silva (1978). Table 13 shows an increase in the exchangeable base contents on the top five cm of the soil 34 months after burning. The increase is most marked in the young oil palm plantation with a *Pueraria phaseoloides* cover crop, followed by pasture, and with a lesser degree in the cassava-banana intercropping that precedes cacao planting. There must be additional relevant data on this subject, but I was unable to find it.

SOIL CONSERVATION

Another data gap occurred when searching for data on soil erosion in the humid tropics of Latin America. Although claims of devastating erosion are common (Goodland and Irwin, 1975; Schubart, 1977), there is no single quantitative evidence of the magnitude of this process. I recently travelled extensively through the Amazon of Brazil, Peru and Ecuador and the Colombian and Ecuadorian sierras looking at erosion problems. Two conclusions can be made from these visual observations: (1) The extent of obvious gully erosion in shifting cultivation or pasture systems of the Amazon is insignificant. One can see erosion caused by road construction, urban development, and drainage outlets – civil engineering erosion. (2) The extent of soil
Figure 10: Long-term effects of unfertilized guinea grass (*Panicum maximum*) pastures, with and without *Centrosema pubescens*, on the topsoil organic matter after clearing a rainforest in South Johnstone, Australia.

Source: Adapted from Bruce (1965).
Table 13: Effects of cropping systems on the topsoil (0-5 cm) exchangeable bases content 34 months after clearing a virgin rainforest on an Ultisol of Southern Bahia (30 months after planting crops and 18 after planting pastures). Silva (1978)

<table>
<thead>
<tr>
<th>System</th>
<th>Months after clearing</th>
<th>Sum of exchangeable bases (Ca+Mg+K) me/100 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Rainforest</td>
<td>0</td>
<td>1.15</td>
</tr>
<tr>
<td>After burning</td>
<td>1</td>
<td>2.09</td>
</tr>
<tr>
<td>Rubber-kudzu</td>
<td>34</td>
<td>2.60</td>
</tr>
<tr>
<td>Cassava/bananas</td>
<td>34</td>
<td>2.80</td>
</tr>
<tr>
<td>Pasture</td>
<td>34</td>
<td>4.00</td>
</tr>
<tr>
<td>Oil palm-kudzu</td>
<td>34</td>
<td>4.50</td>
</tr>
<tr>
<td>LSD .05</td>
<td>34</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Erosion in the Andean region is high in ustic soil moisture regimes, with a strong dry season, but also very limited in the udic, high rainfall upland areas. Again, most of the obvious erosion observed in the latter areas was directly caused by civil engineering and not agronomic miscalculation.

The reason for the above generalizations is quite simple: the best protection against erosion is to have a plant canopy to protect the soil. In high rainfall areas, whether on the mountains or in the Amazon basin, there is always something growing, perhaps just weeds or secondary fallow. Nevertheless the soil is protected, except for the crucial one or two months after burning, but even there the tangle of charred logs, tree stumps and partially burned material provides a degree of cover. I am more concerned about large-scale erosion in the ustic highlands of Latin America which appear to be more fragile ecosystems than the selvas themselves. Watters (1971), however, reports
that newcomers to the shifting cultivation systems can cause significant soil erosion in hillsides of Venezuela with a strong dry season.

The general absence of gully erosion or exposed soils does not imply the absence of significant sheet erosion. Its importance is unknown in the Latin America selvas and needs to be quantified in order to obtain an accurate appraisal of soil erosion problems.

**IMPLICATIONS FOR AGROFORESTRY RESEARCH**

Where does agroforestry fit in all these considerations? Its desirability has been well expressed in Latin America (Budowski, 1976; Dourejeanni, 1976), and examples of successful operations have been cited by Bishop(1978), Haufe(1977), Montenegro and Masson(1977), Fournier(1977) and many others. The point is that very little effort is underway to test quantitatively combinations of annual crops with pastures, pastures with permanent crops, annual crops with pastures and trees, and others included in the concept of agroforestry. The research needs I see from the soil fertility and management point of view are the following:

1. Systematic land appraisals and quantitative classification of soils according to their suitability for different plant species to be grown in agroforestry combinations.

2. Assembling of available knowledge and filling in the gaps about the critical nutrient requirement levels for the different species and cultivars of species to be grown in agroforestry combinations, both in terms of soil tests and plant chemical analysis.

3. Selection of one site, or possibly several, in the Latin American selvas, based on land evaluation studies, where research on a single factor is going on and expanding it to form an integrated research programme on the ecosystem including soil, crop agronomy, pastures and livestock production, permanent crops, forestry, ecology, and economics. One site could serve as the catalytic centre, preferably with international support, and be complemented by a series of regional trial sites.
Development of improved components of agroforestry systems that farmers could adapt to the systems they already have. Inventing entire systems, although fascinating from the research viewpoint, has very limited applicability because farming systems are put together by farmers and are extremely site-specific. Agroforestry research should include system components, e.g. which grass-legume pastures grow best under oil palm or coconuts, and how to establish crop-pasture-tree successions, their soil fertility requirements, and similar basic issues.

**DISCUSSION**

**Tejwani:** When was kudzu mulch applied and what are the economics of it?

**Sánchez:** Kudzu was applied as a mulch to each crop. It was not grown in place. As for economics, one kg N kudzu costs as much as one kg N as urea. The difference is that with kudzu it was a family's labour costs, while cash for fertilizer is in short supply.

**Lal:** Sheet erosion is a more serious problem on arable land than gully erosion. The Amazon has one of the highest sediment loads among the rivers of the tropics.

**Sánchez:** The Amazon sediment load comes mostly from the Andes, not the Selva.

**Lal:** "Local specificity" has been taken too far. Basic information on various parameters of soil and microclimate will help in the extrapolation of the results to different agro-ecological environments.

**Sánchez:** I agree. The very similar results between Ibadan and Yurimaguas confirm your viewpoint.

**Pereira:** Bulldozing can be done without serious compaction if a chain or cable is used followed by a root-rake but the soil conservation aspects must be planned in advance. From air photographs of the Amazonian clearing it is evident that this is not being done.

**Sánchez:** Bulldozing is likely to cause less soil compaction in highly aggregated Oxisols, as in your experience, than the Ultisols with sandy topsoils. I agree with your second point.

**Bradley:** Kudzu may not be a problem with rubber trees where it can be controlled by slashing or with herbicides. But in Amazonia (Brazil) it is a serious problem with fruit trees.

**Dommergues:** You mentioned that burning had a stimulating effect on the decomposition of organic matter. Another effect that should be stressed is the dramatic increase in nitrification, which is responsible for the depletion of inorganic nitrogen through leaching and denitrification that you reported. The duration of the nitrification boost is less than 5-8 months.
Sanchez: Yes. I found a large inorganic N flush peak (80 kg N/ha in the top 50 cm) within 3-6 months after clearing, which decreased rapidly afterwards.

King: You emphasized the beneficial aspects of kudzu. I have found that in attempting to establish Pinus caribaea with a kudzu ground cover, the kudzu resulted in a loss of growth because it damaged the leading shoots of the Pinus. What is your experience?

Sanchez: The kudzu should be kept from climbing the trees. An area of about one metre around the tree could be kept clear using a machete. Herbicides may be used. However, if unchecked, kudzu will climb over virgin rainforest trees.

King: In your recommendations you stated that you would wish that there be quantitative land classification. What exactly do you mean by this?

Sanchez: Soil taxonomy (a natural system) is used to serve as your library of soil properties. There is a need for a technical soil classification system for specific practical uses of agroforestry. Perhaps a combination of the Fertility Capability Soil Classification system and adopting the Woodland Suitability Soil Classification system to the tropics would be more useful.

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MANAGEMENT OF ACID SOIL SAVANNAS: THE LLANOS ORIENTALES OF COLOMBIA

Doeko Goosen*

ABSTRACT

The Llanos Orientales (Eastern Plains) form a vast plain extending from the Andes mountains to the Orinoco river, between 500 and 150 m above sea level. The low to very low fertility of their soils is the most important limiting factor for agriculture. Extensive grazing is the main land use. The quality of grass vegetation is deteriorating due to seasonal overgrazing and burning practices. Near the mountains, the alluvial fans and terraces have slightly higher fertility due to more recent addition of alluvial sediments, and commercial agriculture is practised using fertilizers. Farther away from the mountains, more adverse conditions prevail: the soils are poorer, the contrast between dry and wet seasons is more pronounced, and the accessibility is less. Apart from low fertility, the soils to the south and east of the Meta river have some physical properties unfavourable for commercial agriculture. Soil cohesion tests have showed that the well-drained soils of the level areas, when disturbed, are susceptible to degradational processes. Under more intensified systems of agriculture, degradation could easily be reactivated. In several savanna zones forest remnants still exist. To the south the boundary between savanna and forest is sometimes remarkably sharp, indicating that at least part of the savanna is man-made, in the sense that yearly burning has enlarged the savanna area to the detriment of the forest. Reversing this process will be time-consuming and require a large input of personnel and money. Two methods of improvement are proposed. The first would be on a short-term basis, improving the cattle grazing. Based on experiments carried out over the last 10 years, each cattle farm could have a relatively small area, e.g. up to 5% with improved pasture under seasonal irrigation, to provide enough fodder during the dry season. The second method, on a long-term basis, could involve the establishment of perennial vegetation, first in trial areas, and perhaps later on a larger scale. Much investigation is still needed to find out which perennial vegetation would be most suitable for the area while at the same time giving useful produce. The investment would be large and returns can be expected only after many years.

The Llanos Orientales (Eastern Plains) cover about 240,000 sq km in eastern Colombia. They form vast tropical savanna plains including some forest areas, especially near the Andes Cordillera.

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at the western boundary. To the south, the forest increases and
the geographical boundary between the savannas and the tropical
rainforest is usually taken to be the boundary between the water-
sheds of the Amazon and the Orinoco river. But the transition
is gradual. Near the Andes the land is approximately 500 m above
sea level. Toward the east it drops gradually to an altitude
of 200 to 150 m above sea level. The total human population of
the area was estimated at 500,000 in 1978. Most of the people
emigrated from western Colombia. In the recent decade there has
been an accelerated migration.

CLIMATE
The north-eastern trade winds are strongest in the period
December-April. This is also the period of minimum rainfall.
When the equatorial belt of low pressure shifts to the north,
the winds abate and the wet season starts. It is this rhythm
of winds and rains that determines the climatic pattern of the
Llanos. In the south-west rainfall is around 5,000 mm per year,
but it drops quickly towards the north-east. A rainfall of
3,000 to 4,000 mm per year is more typical for the south-western
region (Fig. 1). Then gradually the rainfall becomes less to-
wards the north-east, reaching values of about 1,000 mm per year
near the Orinoco river. The dry period here starts earlier and
ends later than in the south-west. The relative humidity of the
air is about 80% in the wet season but it falls in the dry season
to values of 50% to 60%. The annual mean air temperature is 25
to 28°C. The daily variation fluctuates between 20 and 33°C
(taken as annual average minimum and average maximum daily air
temperatures.)

GEOLOGY
Except for some small outcrops pertaining to the Guyana
shield, most of the surface sediments in the Llanos are young.
The oldest—presumably dates from the Pleistocene and is found
south and east of the Meta river. This river is a tributary of
the Orinoco and it traverses the Llanos from the south-west to
the north-east (Fig. 2). The sediments are mainly horizontal,
Fig. 1: Generalized rainfall map of the Llanos Orientales (after: FAO report, 1965)
Fig. 2: Landscape map of the Llanos Orientales (after: FAO report, 1965)
although numerous fault lines can be traced. Such faults are the cause of local differences in height, resembling differences in terrace levels. The oldest sediments referred to do not show a typical alluvial pattern although nearest the Cordillera more gravel and stones are found, demonstrating that the Andes Cordillera must have been one of the main sources of the sediments. Towards the east the material is devoid of stones and fine sands, silts and clays predominate. Near the Orinoco the somewhat higher areas are sandy, while the lower areas have more silt and clay. It is possible that strong aeolian activities in the past have influenced the distribution of finer and coarser materials.

Generally speaking, the Llanos area is one of subsidence. The region to the north and west of the Meta river is apparently still actively subsiding. It is in this area where more recent sediments are found, possibly not older than Holocene.

Physiographically, three major divisions (see Fig. 2) can be distinguished in the High Plains. They are, from north-east to south-west: (1) the level, poorly-drained High Plains, similar to the Aeolian Plain but without dunes; (2) the level, well-drained High Plains where relief is slightly more pronounced; and (3) the dissected High Plains, also called serranía, with steep hills and V-shaped valleys, partly filled by colluvial wash.

The level, poorly-drained High Plains occupy extensive areas in the north-eastern part of the High Plains. They are intercalated with the level, well-drained High Plains, which are more predominant towards the south-east and south-west. The dissected High Plains in the southern part of the High Plains are more extensive than the other two units combined. In many places the transition is abrupt. The processes of degradation leading to this dissected land-type have apparently been active over vast areas, also in the Amazon area of Colombia and Brazil, because the serranía continues in similar forms, although now mainly covered with forest.

The above description of the geological history of the land-types in the Llanos Orientales is far from complete. One of the difficulties lies in the absence of dating for the various events.
Another problem is the uncertainty about some sedimentary processes that have led to the building up of these vast plains. In some samples traces of volcanic glass have been found, and from this it may be deduced that volcanic activity is related to sedimentary processes in the Llanos. In these and other aspects the Llanos remain an interesting area for further studies.

**SOILS**

The original soil parent material derived from erosion products of the eastern Andes Cordillera, was probably highly weathered at the time of deposition. From the geological history it can be deduced that lixiviation in the past must have been a very active process. The addition of volcanic ashes, as presumed, may have led to a higher nutrient status for some time, but the still-continuing process of lixiviation has led to the present situation in which practically all soils are low to very low in nutrient content. Except in some recent alluvial soils that occupy only small areas, there are hardly any weatherable minerals. The dominant minerals are kaolinite and quartz.

The polygenetic history of the soils makes a precise taxonomic classification somewhat difficult. In the better-drained soils, features of an argillic horizon have been recognized by some, while others have found these not significant enough and have recognized an oxic horizon. Still others, on the basis of laboratory analysis, have judged that the cation exchange capacity, although low, is frequently just a little bit too high for the recognition of an oxic horizon, and have thus recognized only a cambic horizon. Another matter is the distribution and content of iron oxides in the profiles. In most of the well-drained soils the iron content is more or less evenly distributed, with a slight tendency to increase downward. Continuous ironstone is found only in soils that have been truncated heavily by degradational processes. In the dissected high plains and along some eroded riverbanks, such ironstone is present locally. The poorly-drained soils have a very low iron content in the final metre. Below that patches of iron concentration are present, sometimes continuous enough to consider it as soft plinthite.
It is outside the scope of this paper to discuss extensively the various soils and their taxonomic classification. But it is necessary to emphasize the importance of the matter, not only because it is still under debate, but also because it appears that in other acid savanna soils of the world similar problems of classification exist. If international correlation is to be effective, standardized procedures of description, analysis and classification are of the utmost necessity.

In selecting a few soils for discussion, we give the description of two profiles, in the FAO survey (1964) called respectively series Horizontes (Table 2) and Guanapalo (Table 3). Horizontes is representative of the level, well-drained High Plains while Guanapalo is representative of the poorly-drained High Plains and of the level, poorly-drained parts of the Aeolian Plain. The Horizontes profile has been classified as a Typic, well-drained Oxisol (FAO, 1964), (Oxic) Palehumultic Dystropept (Goosen, 1971) and Typic Haplustox (Guerrero, 1972). In the FAO legend it would be classified as Orthic Ferralsol. On the Experimental Farm "Carimagua", situated more or less in the central and typical part of the well-drained High Plains, experiments have been carried out regarding the use possibilities of these soils. One of the first conclusions was that large-scale agriculture should not be considered at present because: (1) the disturbance of the topsoil leads to a high degree of sheet and rill erosion, even on slopes of about 1-2%, and (2) the chemical fertility is so low that the cost of applying fertilizers is prohibitive under the present situation of its availability and transport costs. It is however considered possible to apply moderate amounts of fertilizers on improved pastures, which would increase the carrying capacity four- to five-fold. At present the carrying capacity under extensive grazing is one head of cattle per 4-12 hectares. The first problem is to reduce the acidity of the soils, mainly to bring down the exchangeable aluminium. Table 1 shows the modifying effects of lime after two months.
Table 1: Effect of lime on pH and exchangeable Al of Llanos soil

<table>
<thead>
<tr>
<th>CaCO₃ (Tons/ha)</th>
<th>pH (H₂O)</th>
<th>Exchangeable Aluminium (meq./100 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.5</td>
<td>3.6</td>
</tr>
<tr>
<td>1/2</td>
<td>4.6</td>
<td>3.5</td>
</tr>
<tr>
<td>2</td>
<td>5.0</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>5.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Source: Grupo de Trabajo FAO/UNDP (1972).

In order to determine the agricultural potential of the area, some experiments are in progress with corn, rice and cassava. Before adopting a fertilizer-agriculture system, however, it will be necessary to protect the soils against erosion as a first priority. The results of fertilization alone are often overshadowed by the damage of erosion. The amount of fertilizer needed at present is however too large and it may be uneconomic to apply it.

The Guanapalo profile, representative of the poorly-drained areas at both sides of the Meta river, is situated in land not easily accessible. It has been classified by FAO (1964) as Typic Albaquox and by Goosen (1971) as Ultic Plinthaquept (Oxic). In the FAO legend it is a Humic Gleysol. Because of the difficult access no experiments have as yet been carried out on these soils in their natural position. At the Centre for Integrated Development Las Gaviotas, the topsoil has been gathered into seeding beds for growing vegetables under a shade of palm leaves supported on bamboo structures. The author had occasion to see this on a visit in 1975 when this method had been installed for the first year. No data are available to indicate whether this method leads to a continuous production of vegetables, but at least it is a method to consider seriously for small-scale application on individual farms. For large-scale agriculture, the areas with Guanapalo soils have been considered in the past as suitable for rice. Again there are two problems: (1) the very low fertility of the soils coupled with difficult access would make artificial fertilization prohibitively costly, and (2) the low physical stability of the soils would lead to serious soil degradation.
HORIZONTES SERIES: fine clayey (Oxic) Paleustic Dystropept.

Area: 10 km E of the river Manacacas, 25 km S of the river Meta, on the broad summit of the level High Plains, soil association Aa, elevation 200 m.

Vegetation: Savanna of the Trachypogon vestitus type.

Parent material: Llanos loess.

Topography: Level, with convex gentle slope towards the broad and shallow drainage ways.

Drainage: Well-drained.

All 0-19 cm Very dark gray brown (10YR 3/2) clay; weak fine, blocky structure; friable, slightly plastic, slightly sticky; abundant roots and pores; pH 4.8; smooth and clear boundary.

B21 19-35 cm Strong brown (7.5YR 4/5) clay; moderate fine, blocky structure with clay skins in channels of roots and macro-organisms; friable, plastic, and sticky; common roots and pores; few dark coloured streaks from A horizon; pH 5.0; smooth and gradual boundary.

B23 66-100 cm Yellowish red (5YR 6/8) clay; weak, fine, blocky structure; friable; slightly plastic and slightly sticky; common roots and pores; some dark-coloured streaks of upper horizons; pH 5.1; smooth and gradual boundary.

B31 100-125 cm Red (2.5YR 5/8) clay, with strong brown (7.5YR 6/6) mottles along root channels; massive structure; very friable, slightly plastic and slightly sticky; few roots and pores; pH 5.2.

Diagnostic horizons:

0-19 cm Ochric epipedon;
19-100 cm Cambic horizon.

Analytical data:

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth in cm</th>
<th>Particle size distribution (microns, %)</th>
<th>%C</th>
<th>%N</th>
<th>C/N</th>
<th>pH (H2O)</th>
<th>P ppm</th>
<th>Free Fe2O3 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A11</td>
<td>0-8</td>
<td>47 17 -18 13 5</td>
<td>2.7</td>
<td>0.17</td>
<td>16</td>
<td>4.4 3.3  2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A12</td>
<td>8-19</td>
<td>51 23 -10 13 3</td>
<td>1.8</td>
<td>0.13</td>
<td>14</td>
<td>4.4 2.2  2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B21</td>
<td>19-35</td>
<td>62 10 -12 13 3</td>
<td>1.0</td>
<td>0.11</td>
<td>9</td>
<td>4.7 0.9  2.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B22</td>
<td>35-66</td>
<td>65 8 -13 10 4</td>
<td>0.7</td>
<td>0.07</td>
<td>10</td>
<td>5.0 1.6  3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B23</td>
<td>66-100</td>
<td>56 12 -21 9 2</td>
<td>0.5</td>
<td>0.06</td>
<td>8</td>
<td>5.4 0.5  2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B31</td>
<td>100-125</td>
<td>59 7 -22 9 3</td>
<td>0.4</td>
<td>0.05</td>
<td>8</td>
<td>5.7 3.0  -</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Profile description and analytical data for the soil series Horizontes, typical for the level, well-drained High Plains. Similar soil profiles have been classified as Typic, well-drained Oxisol, Typic Haplustox and Orthic Ferralsol.
**PROFILE D-11**

(Described February 29, 1968 by Daxo Woven and Marco Cano)

**Guanapalo Series**: coarse silty (Oxic) Ultic Plinthaquept.

**Area**: 20 km S of Paso Nuevo, between two escarceos of the level, poorly drained High Plains, soil association As, elevation 190 m.

**Vegetation**: Savanna of the *Mesoactum* type.

**Parent material**: Llanos loess.

**Topography**: Flat, very gently undulating microrelief of escarceos.

**Drainage**: Poorly drained.

**Alg** 0-15 cm Very dark grey silt loam; weak, fine subangular blocky structure; non-sticky, non-plastic; abundant roots and pores.

**A2g/B2lg** 15-55 cm Dark grey brown to grey brown silt loam; non-sticky, slightly plastic; few roots; abundant pores.

**B2lg/B22g** 55-80 cm Light grey silt loam, with red mottles increasing downwards; non-sticky, slightly plastic; no roots; common pores.

**Note**: This incomplete profile description is based on auger samples.

**Diagnostic horizons**: 0-35 cm Umbrie epipedon; 35-80 cm Cambic horizon.

**Analytical data:**

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Particle size distribution (microns, %)</th>
<th>C/N</th>
<th>%C</th>
<th>pH (H2O)</th>
<th>P ppm</th>
<th>Free Fe2O3 %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>clay &lt; 2</td>
<td>fine silt</td>
<td>coarse silt</td>
<td>fine sand</td>
<td>coarse sand</td>
<td></td>
</tr>
<tr>
<td>Alg</td>
<td>0-15</td>
<td>13</td>
<td>26</td>
<td>49</td>
<td>11</td>
<td>1</td>
<td>3.8</td>
</tr>
<tr>
<td>A2g/B2lg</td>
<td>15-55</td>
<td>16</td>
<td>23</td>
<td>42</td>
<td>12</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>B2lg/B22g</td>
<td>55-80</td>
<td>16</td>
<td>23</td>
<td>46</td>
<td>13</td>
<td>2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Exchangeable cations (me/100 g soil)**

<table>
<thead>
<tr>
<th></th>
<th>Ca</th>
<th>Mg</th>
<th>K</th>
<th>Na</th>
<th>Al</th>
<th>H</th>
<th>Total exch. bases (me/100 g soil)</th>
<th>Cation exch. cap. (me/100 g soil)</th>
<th>Base sat. %</th>
<th>Pw %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>tr</td>
<td>0.1</td>
<td>0.1</td>
<td>2.8</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
<td>11.7</td>
<td>3</td>
<td>1.7</td>
</tr>
<tr>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>2.5</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.5</td>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
<td>3.9</td>
<td>10</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 3: Profile description and analytical data for the soil series Guanapalo, typical for the level, poorly drained Aeolian Plain to the West of the Meta river, and for the level poorly drained High Plains to the East of the Meta river. Similar soil profiles have been classified as Typic Albaquox, Typic Tropaquept and Humid Gleysol.
The High Plains have a geological history that includes periods in which degradational processes have been very active. The dissected serranía of the plains landscape continues in the Amazon area where most of the Quaternary surface sediments have a geological history similar to that of the High Plains. It is thought that various processes of erosion coupled with mass movements have caused this degradation or denudation. At a locality south of the Meta river, seven terrace levels were found within the serranía landscape, suggesting that the degradation might have been connected with a similar number of periods with conditions propitious for the degradational processes to act. Since at present the intense dissection does not seem to be active, one might conclude that certain extreme conditions must have prevailed during the periods of degradation. Other evidence for past processes of degradation is found in the level, well-drained High Plains. The nearly level, slightly convex summits show a fossil pattern of reticular gully erosion, while on the gentle slopes leading to the drainage-ways, parallel rills or gullies, also of a fossil nature, are found. Again it remains a matter of conjecture to postulate certain extreme conditions under which the processes of erosion leading to these patterns might have been active.

On the nearly level and gentle slopes many anthills are found. The anthills on the gentle slopes have lower end "wash-tails" of fine sand derived from sheet erosion. Due to selective erosion, the particles finer than fine sand are washed away completely while the coarser particles, in this case fine sand, are deposited at the down-slope side of the anthills. This form of sheet erosion is still active and it accentuates the Llanos' susceptibility to erosion. One of the results is that the whole soil profile down to the depth of the ants' activity becomes lighter in texture. This process should be taken into account when discussing the processes of soil formation.

The poorly-drained soils on both sides of the Meta river have lower physical stability than the well-drained soils. The level land shows a specific microrelief, which consists of low,
long, curving and nearly parallel ridges called escarceos. These ridges were formed by a process of liquefaction and soil flow active at some time in the past (Goosen, 1971). The total Llanos with escarceos is estimated at two million ha. They also occur in Venezuela and in the Colombian Amazon area, while microrelief patterns very similar to those of the escarceos have been reported from quite a number of countries, including Australia, Russia, Sudan, Somalia, Zambia, Honduras, Brazil and Uruguay.

The areas where such microrelief occurs are poorly drained during certain periods while the relief in general is always level. If indeed liquefaction and soil flow have been responsible for the formation of the escarceos, then one must conclude that the soils have an extremely low cohesion. This conclusion is supported by various analyses. Probably one of the main reasons for the low cohesion is the low content of free iron oxides, that when present in higher amounts, act as a cementing agent. The soil minerals are mainly of a non-active nature, indicating that the chemical bonds between the clay particles are rather insignificant. Thus, any system of agriculture involving the regulation of water will result in serious problems of physical soil management because of the extremely low soil strength in terms of cohesion and friction. The cultivation of such soils will probably lower the cohesion even more and, in our opinion, it is virtually certain that walls of ditches and canals would collapse and that in a dry and ploughed state the surface soil would be extremely susceptible to wind erosion.

LAND UTILIZATION

Because of the generally poor properties of the Llanos soils, large-scale agriculture should not be considered until a rational land use system which ensures least site deterioration is developed. The experiments carried out hitherto support this view. It is foreseen that extensive grazing will remain, for quite some time, the more common form of land utilization even though pasture quality is deteriorating due to bad grazing practices. In the wet season a large biomass grows and the cattle selectively graze the better grasses. The poor quality grasses shoot up and
dry out during the dry season when the cattle have more difficulty in finding fodder. The savannas are burnt in order to promote the sprouting of young grass with the first rains but the quantity of fodder is low and the cattle have to roam for long distances. The combination of these factors leads to the present situation in which the grass vegetation is of rather low quality in the more accessible regions. In the more remote regions the savannas are of better quality, but only because of the generally undisturbed grass vegetation and not because of the soils. The popular belief that the more remote areas would also have better soils, is unfounded; it is based only on the fact that the grass composition there has deteriorated less than in the more accessible areas.

Starting from the presumption that cattle grazing will remain the more common form of land utilization, methods should be introduced to neutralize some of the negative effects of the present practices. While it must be assumed that people will continue to burn the savannas in the dry season, the effect and the time of burning on the duration, pasture production and quality should be evaluated. More studies on the establishment of improved pastures, as is being done at Carimagua, should be carried out with a view to providing fodder during the dry season. Since some of the species have a low resistance to burning practices, burning should be avoided on improved pastures. Depending upon the location, additional irrigation will be necessary. With respect to this, one of the difficulties is to tap the deeper groundwater in the well-drained areas. Experiments with cheap wind-mills are not yet conclusive. In the poorly-drained areas it is easier to provide some additional irrigation during the wet season. If the cattle are allowed too early in these areas the surface soil and the grass sods can be heavily trampled, so due care should be exercised to determine the appropriate time to let the cattle onto the irrigated pastures.

Fertilizers will be necessary for the improved pastures as the soils do not have sufficient nutrients to sustain a grass vegetation meant for intensive use, even for a few months each year. A rather high influx of people into the Llanos, especially in recent decades, has put increased pressure on governmental
agencies e.g. for credit, roads and bridges, marketing facilities, and agricultural extension. Land utilization types sufficiently profitable to pay for connected services need to be found. The people going into the area are barely able to grow some subsistence crops and keep some cattle. On a long-term basis it is difficult to establish commercial agriculture for high-bulk, low-value products. Therefore alternative systems of land utilization should be considered and investigated.

One of the essential methods of soil management is to keep the soil under vegetation as much as possible, which is best achieved by using perennial vegetation. One of the first questions is whether the area, given the present soils and climate, would be suitable for tree growth in general. This is certainly possible. At present there are remnants of forest in several zones of the savannas. Some of them are in a somewhat oval shape, aligned in the direction of the wind. This creates the impression that their form is influenced by the yearly burning of surrounding savannas. This burning, propagated by strong winds in the dry season, affects the borders of existing pieces of forest. Most of the waterways have gallery forest and at the leeward side the forest extends farther, presumably because it is more against the ravaging influence of the savanna burning than on the windward side. Towards the south, savannas may end abruptly at the northern side of a river while at the southern side of the river a forest of the Amazon type starts without any significant change in soil patterns. This virtually proves that the yearly burning is at least partially responsible for the extension of the savannas. Regeneration of the natural vegetation is, therefore, thought to be possible. Under the present conditions such a process is very slow. In the south-eastern area of the Llanos Orientales, forest land was cleared in the first half of the 18th century and abandoned toward the end of that century. Since then secondary forest has grown, but it is still possible to distinguish these areas from surrounding forest areas where no clearing has taken place.

The establishment of perennial vegetation requires a lot of care. This is demonstrated by what is being done around many farm buildings. Around many farms one can see fruit trees, such as
citrus, mango and marañon. The seedlings are watered daily in the dry season and farm and household manure is used in fertilizing them. Given this kind of care the trees attain full size and bear fruit. For the poorly-drained areas no such experience is available because no farm buildings are constructed in these areas.

CONCLUSION

Considering the facts as presented in the foregoing, the conclusion is that the level, well-drained savannas can be utilized for extensive grazing, provided that a small percentage of the land is utilized for improved pastures under intensive management. The level, poorly-drained savannas can be utilized for extensive grazing, but the establishment of improved pastures is more difficult because of the extremely low soil cohesion.

On a long-term basis investigations should be carried out with regard to the establishment of tree vegetation. Technically it appears feasible. It requires, however, a large investment over a long period of time. One should have no illusion in expecting returns within a short period. Therefore, it is unrealistic to expect the individual farmers to introduce a system of agroforestry. First a number of pilot areas are needed to demonstrate the feasibility. The selection of the types of perennial vegetation should be done on the basis of the joint cooperation between various specialists.

DISCUSSION

Sánchez: The Carimagua soils are chemically representative of the High Plains of the Llanos (South of the Meta)?

Goosen: Correct. However, due to the erosion of two geological faults, the geohydrology of the Carimagua area is not quite representative. The groundwater available is deeper than normal for the High Plains (South of the Meta).

Pratt: What is your idea of the place of agroforestry in stabilizing erosive soils of the Llanos Orientales?

Goosen: To maintain soil stability, or rather to avoid processes of degradation (including erosion), it is necessary to maintain a permanent vegetative cover. Tree growth is possible. Long-term experiments are advocated to demonstrate that useful produce can be obtained; and I think it can be done.
Sanchez: Agriculture is, indeed, possible in the Llanos Orientales: rice and peanuts on the Piedmont, and profitable improved cattle production based on Brachiaria decumbens at the commercial level (7.2% net profit per year) in the Altillanura.

Goosen: This is in agreement with what I stated.

Sanchez: The devastation of the gallery forests, especially in Venezuela, needs to be stopped. There is need to provide live fences, fuel wood, and poles. There is need for browse species, especially legumes. Current research has shown that Leucaena leucocephala plantations are good on acid soils. Desmodium sp. and kudzu also grow well under oil palm plantations. Food and wood production are potentially profitable in the Llanos Orientales and agroforestry has a vital part to play in future agricultural systems.

Goosen: The recommendations of the FAO study, published in 1965, still remain valid in essence and are in general agreement with the findings of more recent research:

LITERATURE CITED


SOIL FERTILITY STATUS, MAINTENANCE AND CONSERVATION FOR AGROFORESTRY SYSTEMS ON WASTED LANDES IN INDIA

K.G. Tejwani*

ABSTRACT

The paper outlines the problem of wasted lands in India, highlighting, in particular, the research base available for managing these lands and the role of vegetation in: (1) erosion control, (2) reducing the peak rate of runoff, (3) improving infiltration, and (4) rehabilitating and maintaining soil conditions. The technology for increasing production from wasted lands with special reference to grasses and trees, and the programmes for the conservation and utilization of wasted lands in India are discussed. With the recent emphasis on agroforestry, research on agroforestry in retrospect and prospect is discussed and future lines of work are indicated. Training needs and facilities available in India are also discussed.

That most of the land in India suffers from severe erosion and destruction of the production base is now well realized and accepted. It was estimated in 1968 (Anonymous, 1968) that out of the reporting area of 305 m ha (total geographical area of India is 328 m ha), 145 m ha were in need of conservation measures (Table 1).

The principal causes of soil erosion, namely faulty cultivation practices of agricultural lands, over-grazing, and clear-felling on steep slopes, are all well known and perhaps need no elaboration. However, in India there are certain social and economic factors that contribute to the intensification of the hazards of erosion. Very big human and cattle populations and the consequent small size of land holdings, cause a severe strain on land-water-plant systems. In India, the physical limit to the cultivable area has already been reached. It has been estimated that as against 0.292 ha of cultivated land per capita in 1971, there will only be 0.175 ha per capita by the year 2000

*Director, Central Soil and Water Conservation Research and Training Institute, Dehra Dun, U.P. 248195, India.
Table 1: Extent of the soil conservation problem in India

<table>
<thead>
<tr>
<th>Land use</th>
<th>Area (million ha)</th>
<th>Area requiring total soil conservation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>61.2</td>
<td>20</td>
</tr>
<tr>
<td>Cultivable waste lands</td>
<td>17.4</td>
<td>15</td>
</tr>
<tr>
<td>Permanent pastures and other grazing lands</td>
<td>14.8</td>
<td>14</td>
</tr>
<tr>
<td>Land under miscellaneous tree crops and groves</td>
<td>4.2</td>
<td>1</td>
</tr>
<tr>
<td>Fallow lands:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) Fallow lands other than current fallows</td>
<td>9.2</td>
<td>8</td>
</tr>
<tr>
<td>(11) Current fallows</td>
<td>11.1</td>
<td>7</td>
</tr>
<tr>
<td>Net area under cultivation</td>
<td>137.9</td>
<td>80</td>
</tr>
<tr>
<td>Other land uses (not available for agriculture, forest, etc.)</td>
<td>50.2</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>306.0</td>
<td>145</td>
</tr>
</tbody>
</table>

(Anonymous, 1976a, b). Similarly, the forest area per capita, which is already very low (0.120 ha in 1971) will have decreased to 0.075 ha in the year 2000, and the availability of fuel will decrease from 0.32 m³ in 1971 to 0.25 m³ in the year 2000.

The data in Table 1 are noteworthy in that 33% of forest lands, 86% of cultivable waste lands, 95% of permanent pastures and grazing lands, 74% of fallow lands, and 24% of land under trees and groves, are subject to severe erosion. In general, 55% of lands not used for agriculture are subject to severe erosion. The degradation of the forest lands, pasture land in the river catchments, the so-called waste lands, and about 2.3-4.0 m ha of gullied lands, contribute to make floods and sediment the greatest threats to the well-being of the people and the economy of India. For example, a survey of 21 reservoirs has indicated that they receive sediment at an average rate of 8.51 ha m/100 km²/yr, as against the designed inflow of 3.02 ha m/100 km²/yr. This represents 182% more inflow of sediment than
the designed inflow (Gupta, 1975). The land area under agriculture and forest is 150.1 and 72.2 million ha, respectively.

The large quantities of sediment lodged in tanks, reservoirs, streams and river beds reduce their capacity to hold or convey water, which results in more and heavier flooding. The maximum area affected by floods in a single year in India during the period 1953-1970 was 20.88 m ha; this increased to 25.09 m ha during the period 1953-1976. This was in spite of the fact that up to the end of the Fourth Five-Year Plan (FYP), i.e. up to March 31, 1974, some 8.0 m ha of land had been provided flood protection work at a total cost of R. 3,473.6 m. Further, in spite of the expenditure on flood control measures during the past two or more decades and the positive benefits brought to specific areas, the total area and average crop area affected by floods continue to be on the increase (Paknaik, 1977a, b).

It is estimated that agricultural land contributes about 50% of G.N.P.; forest lands contribute about 1.5% (exclusive of unrecorded removals); and the so-called waste lands do not contribute anything. It is obvious that the forest lands and the so-called waste lands are not only contributing very little of their potential to the production of fuel, timber, fodder and fibre, but they also cause damage by sedimentation and floods. No wonder then that these are termed the wasted lands. Fortunately India has been aware of the potential of these lands and she has made concerted efforts to provide an appropriate research base to develop and increase their production potential and also to provide appropriate land development and management programmes. The scope of this paper will, therefore, be to review: (a) the research base available for the management of these wasted lands, (b) the results of this research, (c) the developmental programmes executed in their management, and (d) future lines of research in agro-forestry with special reference to soil fertility, maintenance and conservation.

THE RESEARCH BASE AVAILABLE IN INDIA FOR MANAGING WASTED LANDS

During the preparation of India's first five-year plan, it became obvious that while the problems of degradation and destruction of the production base were broadly known, the appropriate
science and technology for their solution, backed by scientific investigations, were not known. Consequently, a chain of soil conservation research, demonstration and training centres (Table 2) was established late in the first FYP and early in the second.

Table 2: Soil and Water Conservation Research Centres in India

<table>
<thead>
<tr>
<th>Location</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehra Dun</td>
<td>North Western Himalayan Region</td>
</tr>
<tr>
<td>Chandigarth</td>
<td>Sub-montane tracts in the north-western region in India, with special reference to Siwalik hills</td>
</tr>
<tr>
<td>Ootacamund</td>
<td>Southern hill area with high rainfall</td>
</tr>
<tr>
<td>Bellary</td>
<td>Semi-arid black soil region</td>
</tr>
<tr>
<td>Kota</td>
<td>Ravine problem, specifically on the banks of the Chambal river</td>
</tr>
<tr>
<td>Vasad</td>
<td>Ravine problem, specifically on the banks of the rivers of Gujarat State</td>
</tr>
<tr>
<td>Agra</td>
<td>Ravine problem, specifically on the banks of the Yamuna river</td>
</tr>
<tr>
<td>Hyderabad</td>
<td>Red soil, semi-arid region</td>
</tr>
<tr>
<td>Chattrra (Nepal)</td>
<td>North-eastern Himalayan region with special reference to the Kosi river catchment</td>
</tr>
<tr>
<td>Jodhpur</td>
<td>Rajasthan Desert and arid lands in India</td>
</tr>
<tr>
<td>Udajgiri (Orissa)</td>
<td>Eastern lateritic soil region (not started)</td>
</tr>
<tr>
<td>Rehmankhera</td>
<td>Ravine lands on the banks of the Conti river (U.P. State Govt.)</td>
</tr>
<tr>
<td>Hazaribagh</td>
<td>Catchment of Damodar Valley (Damodar Valley Corporation)</td>
</tr>
</tbody>
</table>

These centres were expected to work on all land use aspects on a watershed basis. The management of lands not suited for agriculture, i.e. forest lands, pasture lands, eroded lands and the so-called wasted lands was a major component of their charter. Under it, they would: (1) evolve suitable methods of soil erosion...
in control forests and grasslands; (ii) study and recommend various tree species and methods to reafforest denuded and highly eroded areas; and (iii) study and recommend suitable grasses and legumes, and methods for the improvement of grasslands and the stabilization of earthen structures.

In addition, these centres had the responsibility of imparting specialized training in soil and water conservation to supervisory officers and middle-level staff of the various state governments in India. The first seven centres (Table 2) are the constituents of the Central Soil and Water Conservation Research and Training Institute, Dehra Dun. The Indian Council for Agricultural Research has established: (1) the Indian Grassland and Fodder Research Institute at Jhansi, which is expected to work on grasslands and silvo-pastoral systems with particular reference to the production of fodder, (2) the ICAR Agricultural Research Complex at Shillong, for research on alternative farming systems for shifting cultivation, and (3) the Central Arid Zone Research Institute at Jodhpur, for research in arid and desert regions in India.

In the sixth FYP, it is proposed to have three more centres for soil and water conservation based on integrated land use principles in: (i) the Bundelkhand region, (ii) the deep black soil, high rainfall region in Madhya Pradesh, and (iii) shifting cultivation, in Orissa. There will be four operational research projects in the Himalayas, likely to be located in the States of Jammu and Kashmir, Himachal Pradesh, Uttar Pradesh and Sikkim. These seven units will also be the constituents of the Central Soil and Water Conservation Research and Training Institute, Dehra Dun.

SOIL AND WATER CONSERVATION ON WASTED LANDS

The wasted lands by definition, as stated above, are lands that are not suited for agriculture but are suited for the growing of grasses and trees. In the USDA land capability classification system they constitute land classes V, VI, VII and VIII, which are lands with one or more severe limitations of slope, erosion, stoniness, rockiness, shallow soils, wetness, flooding, climate, etc.
VEGETATION AND EROSION CONTROL

Establishing vegetative cover is one of the most effective ways of soil and water conservation. The data collected in alluvial soils, red soils, black soils and lateritic soils on different slopes and climatic conditions by different workers in India have clearly indicated that natural fallow (i.e. grasses and shrubs) or grasses alone give the least and negligible runoff and soil loss. Cultivated fallows gave the maximum runoff and soil loss; while crops gave variable rates depending on their characteristics. For example, clean-cultivated, row-planted bidi tobacco in alluvial soils gave the highest rate of runoff in black soils. Cultivated legumes also reduced the rate of runoff considerably (Kanitkar et al., 1960; Chinnamani et al., 1965; Vesudevaish et al., 1965; Gupta et al., 1966; Singh et al., 1967; Verma et al., 1968; and Tejwani and Mathur, 1972).

VEGETATION AND INFILTRATION

Infiltration studies under different vegetative covers have been conducted at Bellary, Ootacamund, Dehra Dun and Ranchi (Table 3). At Bellary and Ranchi infiltration rate was the lowest under agricultural land and the highest under woodland. At Ootacamund, the Shola forest, broom and blue gum plantations had much higher infiltration rates than grazed grasslands.

At Dehra Dun, in the Doon Valley and adjoining uplands in the Himalayas and Siwaliks, it was observed that the infiltration rates under different forest areas varied considerably, depending upon the condition of the forest floor (Patnaik and Virdi, 1962). The Bidhuali sal forest, with good leaf litter, showed very high rates of infiltration (9.00 cm in the first hour, 5.90 cm in the second hour, and 5.85 cm in the third hour), whereas at Harawala in the Himalayan upland, the sal forests, with little leaf litter and a compact surface, showed low rates of infiltration (3.71 cm in the first hour, 2.00 cm in the second hour, and 2.20 cm in the third hour). In the Siwalik Range, the average infiltration rates were 4.00 cm for the first hour, 2.00 cm for the second hour and 2.10 cm for the third hour, whereas under the compact eroded soils of sal forests the average infiltration rates were 2.80 cm for the first hour, 1.20 cm for the second hour, and 1.40 cm for the
### Table 3: Infiltration rates under different vegetative covers

<table>
<thead>
<tr>
<th>Vegetative cover/land use</th>
<th>filtration rate (cm/hr)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bellary</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woodland</td>
<td>17.00</td>
<td>For one hour run</td>
</tr>
<tr>
<td>Grassland</td>
<td>2.60</td>
<td>&quot;</td>
</tr>
<tr>
<td>Agricultural land</td>
<td>1.00</td>
<td>&quot;</td>
</tr>
<tr>
<td><strong>Ootacamund Study No. 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shola forest</td>
<td>16.84</td>
<td>For three hours run</td>
</tr>
<tr>
<td>Blue gum plantation</td>
<td>20.69</td>
<td>&quot;</td>
</tr>
<tr>
<td>Grazed grassland</td>
<td>5.13</td>
<td>&quot;</td>
</tr>
<tr>
<td><strong>Ootacamund Study No. 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shola forest</td>
<td>12.50</td>
<td>&quot;</td>
</tr>
<tr>
<td>Broom (<em>Cytrus scaparius</em>)</td>
<td>11.25</td>
<td>&quot;</td>
</tr>
<tr>
<td>Grazed grassland</td>
<td>6.25</td>
<td>&quot;</td>
</tr>
<tr>
<td><strong>Ranchi</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>20.00</td>
<td>&quot;</td>
</tr>
<tr>
<td>Permanent natural grass</td>
<td>8.00</td>
<td>&quot;</td>
</tr>
<tr>
<td>Cultivated farm land</td>
<td>2.00</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

*Mistry and Chatterjee, 1965*

third hour. Since abundant leaf litter on the forest floor resulted in high infiltration rates, efficient management of forests in watersheds should aim at the conservation of litter.

**INFLUENCE OF VEGETATION ON SOILS**

Forest vegetation has great influence on forest soils. This vegetation draws heavily not only on the soil but also on deep layers of parent material and deep rocks, and then deposits mobilized material in the form of leaf litter, dead twigs and branches.
Table 4: Leaf litter (kg/ha/annum) added to land by different tree species

<table>
<thead>
<tr>
<th>Tree species</th>
<th>Leaf litter</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Ootacamund</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shola forest</td>
<td>2,019</td>
<td></td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>1,958</td>
<td>Samraj <em>et al.</em>, 1977</td>
</tr>
<tr>
<td><em>Acacia mearnsii</em></td>
<td>1,079</td>
<td></td>
</tr>
<tr>
<td><em>E. globulus + A. mearnsii</em></td>
<td>2,218</td>
<td></td>
</tr>
<tr>
<td><em>Agra</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Acacia nilotica</em></td>
<td>27,175</td>
<td></td>
</tr>
<tr>
<td><em>Dalbergia sissoo</em></td>
<td>6,648</td>
<td>Singh, J.P., 1974</td>
</tr>
<tr>
<td><em>Dehra Dun</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Shorea robusta</em></td>
<td>6,947</td>
<td>Tejwani <em>et al.</em>, 1975</td>
</tr>
</tbody>
</table>

It is interesting to note (Table 4) that while *E. globulus* shed almost twice the leaf litter shed by *Acacia mearnsii* (a legume tree) in pure plantations, the total leaf fall in mixed plantations of both these tree species is the same as that of *E. globulus*. Under semi-arid conditions at Agra, *A. nilotica* (another legume tree) shed a very large quantity of leaf litter (27,175 kg/ha/annum).

Table 5: Plant nutrients (kg/ha/annum) added by leaf litter to soil

<table>
<thead>
<tr>
<th>Forest type</th>
<th>Plant nutrient</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Shola</td>
<td>23</td>
<td>1.3</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>25.4</td>
<td>0.7</td>
</tr>
<tr>
<td><em>Acacia mearnsii</em></td>
<td>19.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

*Data not available
The leaf litter improves the soil's physical and chemical properties (Table 5) and its fertility if the litter is allowed to remain in situ. Where it is removed or the forest floor is burned there will be no advantage. Tejwani et al. (1975) reported less soil moisture, more splash and less organic carbon when leaf litter was removed or burned as compared to leaving the leaf litter on the surface (Table 6).

Table 6: Effect of management of leaf litter of Shorea robusta on soil characteristics

<table>
<thead>
<tr>
<th>Soil characteristic</th>
<th>Leaf litter not removed</th>
<th>Leaf litter removed</th>
<th>Leaf litter burned</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil moisture (%) in 23 cm soil depth</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>16.8</td>
<td>11.0</td>
<td>12.0</td>
</tr>
<tr>
<td>April</td>
<td>10.0</td>
<td>8.3</td>
<td>9.0</td>
</tr>
<tr>
<td><strong>Splash erosion (g soil splash)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>0.27</td>
<td>2.73</td>
<td>2.08</td>
</tr>
<tr>
<td>April</td>
<td>0.12</td>
<td>1.51</td>
<td>0.83</td>
</tr>
<tr>
<td><strong>Organic carbon (%) in 23 cm soil depth</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.94</td>
<td>0.75</td>
<td>0.78</td>
</tr>
</tbody>
</table>

It is also obvious that if leaf litter is removed, virtually all the plant nutrients are removed from the land; however, if the leaf litter is burned, the ash is added to the soil.

**VEGETATION AND PEAK RATE OF RUNOFF**

Vegetation determines the disposition of rainfall by interception, infiltration and detention. It not only reduces the total runoff but it also delays and reduces the peak rate of runoff. The delay in and reduction of the peak rate of runoff moderates floods. For example, Mathur et al. (1976) have reported that afforestation with Eucalyptus species at Dehra Dun reduced the total runoff by 28% and the peak rate of runoff by 73%.
In a watershed area of 2 ha, representative of the Siwalik ranges at Chandigarh, the total runoff and peak rate of runoff were reduced by 60.4% and 61.1%, respectively, as a result of using: (i) earthen debris basins, (ii) earthen pondage banks, and (iii) staggered contour trenches planted with *Eucalyptus* hybrid and *Acacia catechu* (Kaushal *et al.*, 1975).

In another series of experiments, conducted at Chandigarh, it was shown that soil and water conservation practices such as contour terracing and afforestation reduced the runoff by 41%, while practices like annual burning, overgrazing, and tree cutting plus overgrazing, increased runoff in watersheds by 69%, 88% and 71%, respectively (Gupta *et al.*, 1974).

Studies conducted at Chandigarh (Misha *et al.*, 1977) in a watershed of 20 ha, representative of the Siwalik region, showed that with appropriate soil and water conservation measures the rate of sediment could be reduced from 80 to 6-7 t/ha/annum within 4 years. Thereafter the rate of sediment decreased gradually and it was only 2.9 t/ha during the year 1976-77. Runoff as percent of rainfall was reduced from 23.5% in 1964 to about 10% on an average; peak rate of discharge was reduced from 0.065 in 1964 to 0.034 cumec* in 1977. Jalote and Malik (1974) reported complete stabilization of 270 ha of severely eroded land by afforestation in the catchment of Gomati river.

**TECHNOLOGY AVAILABLE FOR INCREASING PRODUCTION ON WASTED LANDS**

**SELECTION OF SUITABLE GRASS SPECIES FOR USE ON WASTEDLANDS AND MAINTENANCE OF GENETIC RESOURCES**

Considerable work has been done to select grass species that will not only protect these wasted lands but will also produce fodder, fibre; etc. (Table 7).

---

* m³ sec⁻¹
Table 7: Important grasses and legumes for stabilization and production of fodder and fibre on wasted lands

<table>
<thead>
<tr>
<th>State</th>
<th>Grass and legume</th>
<th>Yield (kg/ha)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bihar (Upper Damodar catchment)</td>
<td><em>Stylosanthis gracilis</em></td>
<td>19,000 (green)</td>
<td>Perennial legume. Very aggressive and suppresses other vegetation. Drought resistant. Adds a lot of leaf litter (Pandey et al., 1967)</td>
</tr>
<tr>
<td></td>
<td><em>Calapogonium orthocarpum</em></td>
<td>36,000 in one cut (green)</td>
<td>Mukherjee and Prasad (1966) selected promising strains for Bihar. This grass also reported from Madhya Pradesh, South Rajputana, parts of Deccan (Blatter and McCann, 1935)</td>
</tr>
<tr>
<td>Mysore</td>
<td><em>Pennisetum pedicellatum</em></td>
<td>6,800 (hay)</td>
<td>Black soil, semi-arid region (Krishnamurti, 1958)</td>
</tr>
<tr>
<td>Punjab</td>
<td><em>Chrysopogon fulvus</em></td>
<td>5,250</td>
<td>Ambala Siwalik region</td>
</tr>
<tr>
<td></td>
<td><em>Bulaliopsis binata</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uttar Pradesh</td>
<td><em>Chrysopogon fulvus</em></td>
<td>19,170</td>
<td>Alluvial soils, humid tropical valley climate</td>
</tr>
<tr>
<td></td>
<td><em>Bulaliopsis binata</em></td>
<td>16,290</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Pueraria hirsuta</em></td>
<td>11,200 to 18,725</td>
<td>Perennial legume, provides excellent cover before monsoon, aggressive</td>
</tr>
<tr>
<td>Lesser Himalayas</td>
<td><em>Pennisetum purpureum</em></td>
<td>-</td>
<td>Up to an elevation of 1500 m</td>
</tr>
<tr>
<td></td>
<td><em>Chrysopogon fulvus</em></td>
<td>-</td>
<td>-do-</td>
</tr>
<tr>
<td></td>
<td><em>Apluda mutica</em></td>
<td>-</td>
<td>-do-</td>
</tr>
<tr>
<td></td>
<td><em>Heteropogon contortus</em></td>
<td>-</td>
<td>-do-</td>
</tr>
<tr>
<td></td>
<td><em>Exilephorum commosum</em></td>
<td>-</td>
<td>-do-</td>
</tr>
<tr>
<td></td>
<td><em>Chrysopogon fulvus</em> (northern slopes)</td>
<td></td>
<td>(Mathur et al., 1969)</td>
</tr>
<tr>
<td></td>
<td><em>Themeda anathera</em> (warmer slopes)</td>
<td>1,500 to 2,600 m</td>
<td>Dabadghao, 1964</td>
</tr>
<tr>
<td></td>
<td><em>Arundinella nepalensis</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Pennisetum orientale</em></td>
<td>-</td>
<td>Comes up on road side cuts</td>
</tr>
<tr>
<td>Tamil Nadu</td>
<td><em>Trifolium repens</em></td>
<td>-</td>
<td>High rainfall; high elevation (1100 m and above)</td>
</tr>
<tr>
<td></td>
<td><em>T. repens var. pedino</em></td>
<td>-</td>
<td>Good pasture plants, all legumes (Madhavrao et al., 1978)</td>
</tr>
<tr>
<td></td>
<td><em>T. incarnum</em></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>T. subterraneum</em></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>T. dubium</em></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Vicia villosa</em></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>V. angustifolia</em></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>V. sativa</em></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Clitoria ternatea</em></td>
<td>12,500</td>
<td>Legume for dry areas</td>
</tr>
<tr>
<td></td>
<td><em>Glycine javanica</em></td>
<td></td>
<td>Legume for high rainfall warm climate</td>
</tr>
<tr>
<td></td>
<td><em>Pennisetum clandestinum</em> (Kikuyu grass)</td>
<td></td>
<td>Very good for covering steep unstable areas. Forms good cover but may run wild</td>
</tr>
</tbody>
</table>
SELECTION OF SUITABLE TREE SPECIES FOR USE ON WASTED LANDS

A number of tree species have been introduced and tried, and the following are recommended for protective and production purposes (Table 8).

Table 8: Important tree species for protection and production of fodder, fuel and timber from wasted lands

<table>
<thead>
<tr>
<th>Centre, workers</th>
<th>Number of species tried</th>
<th>Promising species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehra Dun (Gupta; Vishwanatham et al., 1977)</td>
<td>Eucalyptus spp.</td>
<td>E. hybrid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E. citriodora</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E. camaldulensis</td>
</tr>
<tr>
<td>Chandigarh (Sud et al., 1977)</td>
<td>12</td>
<td>E. paniculata</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E. resinifera</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E. camaldulensis</td>
</tr>
<tr>
<td>Kota (Joshie et al., 1977)</td>
<td>3</td>
<td>E. camaldulensis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E. tereticornis (Kota)</td>
</tr>
<tr>
<td>Ootacamund (Haldorai et al., 1977)</td>
<td>24</td>
<td>E. tereticornis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E. saligna</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E. globulus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E. sesbania</td>
</tr>
<tr>
<td>Agra (Puri and Singh, 1977)</td>
<td>4</td>
<td>E. tereticornis</td>
</tr>
<tr>
<td>Chandigarh (Sud et al., 1977)</td>
<td>13</td>
<td>Acacia spp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. suma</td>
</tr>
<tr>
<td>Kota (Joshie et al., 1977)</td>
<td>3</td>
<td>A. nilotica</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. tortilis</td>
</tr>
<tr>
<td>Vasad (Pradhan and Vasava, 1977)</td>
<td>7</td>
<td>A. tortilis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. catechu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. benthamii</td>
</tr>
<tr>
<td>Ootacamund (Haldorai et al., 1977)</td>
<td>3</td>
<td>A. mearnsii</td>
</tr>
<tr>
<td>Bellary (Subbayan, 1977)</td>
<td>8</td>
<td>A. nilotica</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. nubica</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. planifrons</td>
</tr>
<tr>
<td>Agra (Puri and Singh, 1977)</td>
<td>3</td>
<td>A. nilotica (Vasad)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. tortilis (Bellary)</td>
</tr>
</tbody>
</table>

* Prajapati and Joshi (1977) have reported that Acacia nilotica planted in ravines at Kota as a protective cover has a yield potential of 2 tonnes fuel/ha/annum.
OTHER TREE SPECIES

In the ravine lands of Gujarat, bamboo (*Dendrocalamus strictus*), teak (*Tectona grandis*), and Shisham (*Dalbergia sissoo*) have been very successfully introduced. It was observed that bamboo plantations can be managed by removing 30% of the old culms from the total. As a result of new growth, this gives a high ration of new culms to old (61%) (Pradhan and Vasava, 1977).

At Dehra Dun, among the tropical pines introduced, *Pinus patula* has performed very well, reaching average increments of 96.8 and 2 cm per annum, respectively, in height and basal diameter (Vishawanatham and Nambiar, 1977).

TECHNIQUES FOR INCREASING PRODUCTION FROM WASTED LANDS

CLOSURE OF AREAS

A study of the natural flora of the eroded areas has shown that only poor types of annual and unpalatable grasses grow in place of the desirable climax associations that would normally exist in the prevailing soil-climatic environments. For example, in Gujarat ravines *Aristida* spp. and *Themeda triandra* were growing in place of the desirable *Dichanthium-Cenchrus* association (Tejwani, *et al.*, 1961). In the ravine lands of Vasad and Kota, as a result of closure to grazing and other biotic interference, (a) *Aristida funiculata* and *Themeda triandra* were replaced by *Apluda mutica* (a tall annual grass) and perennials like *Eremopogon faveolatus*, *Heteropogon contortus*, *Dichanthium annulatum* and *Cenchrus* species, (b) the runoff and soil loss progressively decreased from the area as the natural vegetation improved, and (c) there was not only qualitative but also quantitative increase in the yields of grasses (Tejwani, *et al.*, 1961; Singh, 1971 and Singh and Verma, 1971). With closure to biotic interference there is also very good regeneration of trees and, ultimately, the land becomes a forest type in accordance with prevailing soil climatic conditions.
Table 9: Effect of closure on regeneration of tree species at Vasad Gujarat - (Pradhan & Vasava, 1974)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acacia nilotica</td>
<td>49</td>
<td>55</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Acacia aburnea</td>
<td>Nil</td>
<td>4</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Acacia senegal</td>
<td>23</td>
<td>42</td>
<td>81</td>
<td>259</td>
</tr>
<tr>
<td>Azadirachta indica</td>
<td>20</td>
<td>20</td>
<td>80</td>
<td>133</td>
</tr>
<tr>
<td>Holoptelia integrifolia</td>
<td>Nil</td>
<td>6</td>
<td>18</td>
<td>69</td>
</tr>
<tr>
<td>Prosopis spicigera</td>
<td>60</td>
<td>74</td>
<td>98</td>
<td>88</td>
</tr>
<tr>
<td>Cassia auriculata</td>
<td>57</td>
<td>44</td>
<td>63</td>
<td>44</td>
</tr>
<tr>
<td>Gymnospora montana</td>
<td>3</td>
<td>6</td>
<td>6</td>
<td>64</td>
</tr>
<tr>
<td>Zizyphus spp.</td>
<td>101</td>
<td>98</td>
<td>321</td>
<td>331</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>313</strong></td>
<td><strong>349</strong></td>
<td><strong>737</strong></td>
<td><strong>1028</strong></td>
</tr>
</tbody>
</table>

Percentage increase over 1960-61: 11, 135, 228

With closure to grazing, the number of trees and shrubs increased progressively (Table 9), with Azadirachta indica, Prosopis spicigera, and Holoptelia integrifolia increasing consistently in number from 1961-1974 (Pradhan & Vasava, 1974). By 1974 the study area had 6,563 trees of more than 50 cm g.b.h., which worked out to a stocking of 80 trees/ha (Pradhan, 1977). Similar results were obtained at Agra where, after 10 years of closure, edible species increased from 44.6% to 48.5% and non-edible species decreased from 42.9 to 30.1% (Prajapati, 1974). Bhimaya et al. (1967) reported that forage yield in an arid zone in Rajasthan, after two years of protection and controlled grazing, increased by 148, 92 and 116% in "poor", "fair" and "good" range condition classes, respectively (Table 10).
Table 10: Forage yield (air dried, kg/ha) in different types of rangelands in arid zone

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor (9)*</td>
<td>337</td>
<td>450</td>
<td>837</td>
<td>688</td>
<td>642</td>
<td>770</td>
<td>885</td>
</tr>
<tr>
<td>Fair (10)</td>
<td>552</td>
<td>873</td>
<td>1065</td>
<td>869</td>
<td>817</td>
<td>1074</td>
<td>835</td>
</tr>
<tr>
<td>Good (4)</td>
<td>704</td>
<td>1068</td>
<td>1523</td>
<td>1263</td>
<td>1480</td>
<td>1163</td>
<td></td>
</tr>
</tbody>
</table>

* Figures in parentheses indicate the number of paddocks studied

Man and Ahuja (1975) reported that forage production varied with rainfall; i.e. the greater the rainfall, the higher the forage production in the arid zone of Rajasthan; they further observed that, within the same rainfall zone, forage production was higher on finer soils. Ahuja et al. (1973) reported that soil conservation measures increased forage production significantly (Table 11).

Table 11: Effect of soil conservation measures on forage yield (air dry kg/ha) in an arid zone of Rajasthan (av. of 9 years, 1961-1970)*

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Treated</th>
<th>Control</th>
<th>% Increase due to treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contour furrowing</td>
<td>1565</td>
<td>213</td>
<td>635</td>
</tr>
<tr>
<td>Contour bunding</td>
<td>1623</td>
<td>603</td>
<td>169</td>
</tr>
<tr>
<td>Contour trenching</td>
<td>1321</td>
<td>490</td>
<td>170</td>
</tr>
</tbody>
</table>

* Yields in 1969 were negligible due to extreme drought

The average increase in forage yields as a result of contour furrowing, contour bunding and contour trenching, as compared to no treatment, were 635, 169 and 170% respectively. Contour-furrowed plots gave better response than contour-bunded or contour-trenched ones, since contour furrows were very close
to each other and thus contributed to better soil moisture conservation and distribution (Murthy and Mathur, 1971; Wasiullah et al., 1972).

**FODDER-FUEL PLANTATIONS**

In semi-arid areas people need fodder for cattle and trees for fuel and timber. An experiment (Table 12) at Vasad with fodder and fuel-cum-timber tree species (*Acacia nilotica*) during 1960-61 showed the species chosen can be grown together without reduction in the yield of fodder (Dayal, 1974).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure grass block of <em>Cenchrus ciliaris</em></td>
<td>1960-61</td>
</tr>
<tr>
<td></td>
<td>1961-62</td>
</tr>
<tr>
<td></td>
<td>1962-63</td>
</tr>
<tr>
<td></td>
<td>1963-64</td>
</tr>
<tr>
<td></td>
<td>1964-65</td>
</tr>
<tr>
<td></td>
<td>1965-66</td>
</tr>
<tr>
<td></td>
<td>1966-67</td>
</tr>
<tr>
<td></td>
<td>1960-61</td>
</tr>
<tr>
<td>Pure grass block of <em>Dichanthium annulatum</em></td>
<td>2790</td>
</tr>
<tr>
<td></td>
<td>4180</td>
</tr>
<tr>
<td></td>
<td>6135</td>
</tr>
<tr>
<td></td>
<td>4919</td>
</tr>
<tr>
<td></td>
<td>6318</td>
</tr>
<tr>
<td></td>
<td>5192</td>
</tr>
<tr>
<td></td>
<td>5224</td>
</tr>
<tr>
<td></td>
<td>4965</td>
</tr>
<tr>
<td>Fuel-cum-grass block with <em>C. ciliaris</em></td>
<td>3948</td>
</tr>
<tr>
<td></td>
<td>3636</td>
</tr>
<tr>
<td></td>
<td>5873</td>
</tr>
<tr>
<td></td>
<td>4697</td>
</tr>
<tr>
<td></td>
<td>7277</td>
</tr>
<tr>
<td></td>
<td>5585</td>
</tr>
<tr>
<td></td>
<td>6193</td>
</tr>
<tr>
<td></td>
<td>5316</td>
</tr>
<tr>
<td>Fuel-cum-grass block with <em>D. annulatum</em></td>
<td>3375</td>
</tr>
<tr>
<td></td>
<td>4378</td>
</tr>
<tr>
<td></td>
<td>3314</td>
</tr>
<tr>
<td></td>
<td>6423</td>
</tr>
<tr>
<td></td>
<td>6754</td>
</tr>
<tr>
<td></td>
<td>4887</td>
</tr>
<tr>
<td></td>
<td>4938</td>
</tr>
<tr>
<td></td>
<td>4867</td>
</tr>
<tr>
<td>Average</td>
<td>3315</td>
</tr>
<tr>
<td>% increase in yield over 1960-61</td>
<td>28.0</td>
</tr>
</tbody>
</table>

There were no significant differences in the forage yields of *Cenchrus ciliaris* or *Dichanthium annulatum*. Overall mean forage yield increased from year to year; there was a 101% increase in 1964-65 as compared to 1960-61. This increase was partly due to closure and protection of the area and partly to the improvement works of broadcasting of seeds and planting of grasses. Fodder grown together with *A. nilotica* did not differ in yield level from that on pure grass stands during the first six years, when the tree intercrop had not yet developed crowns to cast any
considerable shade. Prajapati and Joshie (1977) reported a yield potential of two tonnes of fuel/ha/annum in a 20-year-old plantation of *Acacia nilotica* that was grown as a protective forest in ravines in a black soil, semi-arid region at Kota, but they did not report the yield of the grass, which was also harvested.

It was observed at Dehra Dun (Mathur and Joshie, 1972) that if class V and VI land in Doon valley was planted with *Chrysopogon fulvus* (grass), at 0.75 m x 0.75 m and *Dalbergia sissoo* (tree), at 9.14 m x 9.14 m, not only were high yields of grass (10.55 tonnes/ha/annum) obtained but also about 97 trees/ha were available for exploitation as fuel after 15 years.

In the Siwalik region, in a mixed fuel plantation of *Eucalyptus* hybrid and *Eulaliopsis binata* (a fodder and industrial grass used for ropes and paper making), in a period of four years and three months after plantation, there was standing fuel stock of 55.35 tonnes/ha, while an average grass yield of 5.57 tonnes of air-dry grass/ha/annum was obtained in four years; when *Eulaliopsis binata* was grown alone it gave an average yield of 14.49 tonnes of air-dry grass/ha/annum in four years. Such high yields were also obtained by planting tall plants of *Eucalyptus* hybrid (average initial height of seedlings 2.74 m) on tie ridges 15 cm high and 2 m x 2 m (Mishra and Sud, 1978).

Kuala and Gyanchand (1977) have summarized the silvopastoral approach to land use in arid zones in India as follows:

"Considering that the livestock husbandry occupies the most important place in the economy of the arid region and that frequent droughts result in loss of cattle wealth owing to the shortage of fodder resources, it is necessary that range improvement should be completed with the raising of fodder tree and shrub species which not only give the much-needed forage during the scarcity periods, but also give shade and shelter to the grazing animals, and thereby help to utilize forage uniformly on the range. In addition, fodder trees and shrubs will ameliorate the micro-climatic conditions and thereby create conditions conducive to the natural regeneration of grasses which are higher in succession."
"Studies have shown that a density of 14 per cent of Zizyphus nummularia is optimum for increased forage production (Kaula and Ganguli, 1963). *Prosopis cineraria* is an important forage-tree species which grows in cultivated fields (sometimes more than 60-80 trees per hectare) without any detriment to the crops in association with it. The tree is lopped for its protein-rich (19.7%) leaves. Studies have shown that complete lopping (lopping of the entire tree) gives a significantly higher fodder yield (58-72 kg per tree) than the lopping of the lower two-thirds and the lower one-third of the crown (28.48 and 19.73 kg per tree, respectively).

"There was no significant difference between two-thirds and one-third lopping treatments (Bhimaya et al., 1964). Sixteen indigenous tree and shrub species which have been found to be browsed by different species of livestock, at one time or another, have been studied for their palatability and nutritive value (Ganguli et al., 1964). Among the many exotic fodder tree species tried at Jodhpur and Pali, *Acacia aneura* (Australia), *Pittosporum phillyraeoides*, *Brasiletia mollis* (Venezuela), *Geofforea decorticana* (Chile), *Prosopis alba* (Argentina) and *Colophospermum mopane* (Southern Rhodesia) showed great adaptability. All these species had flowered and produced viable seeds. *C. mopane* was even found to be naturally regenerating in the arboretum at Jodhpur (Kaul, 1970). It is, therefore, necessary that the planting of fodder tree and shrub species should form an essential part of any range-improvement programme in the zones."

Prajanati et al. (1971), on the other hand, reported that in semi-arid areas *Prosopis juliflora* exerted a definite adverse effect through its roots on the growth and yield of *Sorghum vulgare* up to a distance of about 30 m (four to five times the height of *P. juliflora*). Similar adverse effects were observed on the growth and yield of many other crop plants.

**ECONOMICS OF GROWING GRASSES AND TREES**

Afforestation trials carried out in the ravines at Vasad have shown that *Dendrocalamus strictus* (Bamboo), *Tectonia grandis* (Teak), *Dalbergia sissoo* (Shisham) and *Eucalyptus camaldulensis* are very promising (Table 13).
Table 13: Net annual income from various tree species (Vasad)

<table>
<thead>
<tr>
<th>Species</th>
<th>Rotation (years)</th>
<th>Cost of production (Rs/rotation/ha)</th>
<th>Gross income (Rs/rotation/ha)</th>
<th>Net annual Income (Rs/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalbergia sissoo*</td>
<td>30</td>
<td>3,380</td>
<td>23,356</td>
<td>666</td>
</tr>
<tr>
<td>Dendrocalamus strictus</td>
<td>30</td>
<td>3,380</td>
<td>44,475</td>
<td>1,370</td>
</tr>
<tr>
<td>Eucalyptus camaldulensis* (3 rotations)</td>
<td>24</td>
<td>12,824</td>
<td>13,478</td>
<td>477</td>
</tr>
<tr>
<td>Tectona grandis**</td>
<td>15 (years for ballies)</td>
<td>1,300</td>
<td>17,500</td>
<td>1,080</td>
</tr>
</tbody>
</table>


Aggarwal et al. (1977) carried out an economic evaluation of 17-year-old fodder-fuel plantations of Dalbergia sissoo and Acacia catechu and the grasses Chrysopogon fulvus and Eulaliopsis binata (Table 14).

Table 14: Economic evaluation of fodder-fuel plantation

<table>
<thead>
<tr>
<th>Grass species*</th>
<th>Treatment</th>
<th>Total of establishment and maintenance cost for 17 years (Rs/ha)</th>
<th>Summed up value of income from grass for 17 years (Rs/ha)</th>
<th>Total Benefit Income cost from trees for 17 years (Rs/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. fulvus</td>
<td></td>
<td>Rs/ha</td>
<td>Rs/ha</td>
<td>Rs/ha</td>
</tr>
<tr>
<td>C. fulvus D. sissoo. 4.55 m x 4.55 m</td>
<td>11,130</td>
<td>8,941</td>
<td>2,711</td>
<td>1.044</td>
</tr>
<tr>
<td>C. fulvus D. sissoo. 9.15 m x 9.15 m</td>
<td>6,835</td>
<td>10,089</td>
<td>8,684</td>
<td>2.746</td>
</tr>
<tr>
<td>C. fulvus D. sissoo. 13.75 m x 13.75m</td>
<td>5,518</td>
<td>9,378</td>
<td>2,638</td>
<td>2.177</td>
</tr>
<tr>
<td>C. fulvus D. sissoo. 18.30 m x 18.30m</td>
<td>4,657</td>
<td>9,355</td>
<td>2,275</td>
<td>2.497</td>
</tr>
<tr>
<td>E. binata A. catechu 4.55 m x 4.55 m</td>
<td>11,136</td>
<td>35,498</td>
<td>2,652</td>
<td>3.425</td>
</tr>
<tr>
<td>C. fulvus A. catechu 9.15 m x 9.15 m</td>
<td>6,835</td>
<td>8,657</td>
<td>1,140</td>
<td>1.433</td>
</tr>
<tr>
<td>C. fulvus A. catechu 13.75 m x 13.75m</td>
<td>5,518</td>
<td>8,328</td>
<td>649</td>
<td>1.629</td>
</tr>
<tr>
<td>C. fulvus A. catechu 18.30 m x 18.30m</td>
<td>4,657</td>
<td>9,026</td>
<td>367</td>
<td>2.016</td>
</tr>
</tbody>
</table>

*see text for full names
Eulaliopsis binata grass with Acacia catechu gave the highest gross income (Rs. 35,498/- per ha): Chrysopogon fulvus grass with and without trees gave Rs. 9,110/- (average of 7 Chrysopogon treatments) and Rs. 11,447/- per ha, respectively; Chrysopogon fulvus with Dalbergia sissoo and Acacia catechu fetched an increase of Rs. 9,141/- (average of 4 D. sissoo treatments) and Rs. 8,670/- (average of 3 A. catechu treatments) per ha, respectively. Spacing of the trees did not show any significant increase or decrease in the yield of Chrysopogon fulvus grass. On average, Dalbergia sissoo and Acacia catechu gave an income of Rs. 4,077/- (average of 4 D. sissoo treatments) and Rs. 1,202/- (average of 4 A. catechu treatments) per ha, respectively. Dalbergia sissoo at 9.15 m x 9.15 m spacing and Acacia catechu at a spacing of 4.55 m x 4.55 m gave the maximum income of Rs. 8,684/- and Rs. 2,652/- per ha, respectively, among the tree spacings. The data indicated that for fuel-wood purposes, the trees at a closer spacing of 4.55 m x 4.55 m or 9.15 m x 9.15 m would be more profitable than at a wider spacing.

It may be observed that for all the treatment combinations the benefit/cost ratio was more than unity. From these b/c ratios, it was inferred that Dalbergia sissoo at 9.15 m x 9.15 m + Chrysopogon fulvus for fuel and fodder; Chrysopogon fulvus alone for fodder and Acacia catechu and Eulaliopsis binata for fuel and fibre requirement are economically justified to be grown in the wasted lands of Doon Valley.

DEVELOPMENT PROGRAMMES FOR CONSERVATION AND UTILIZATION OF WASTED LANDS

India can be counted among the few countries in the world that have undertaken large-scale programmes of soil and water conservation. It is a measure of the foresight of the country's planning that a programme with such long-range benefits is being given an important place. Up to the end of the 5th FYP (31/3/1978) India had invested Rs. 5,107 m to treat 21.8 m ha of land (Table 15) with soil and water conservation measures on agricultural lands, forest lands, grass lands and wasted lands (Anonymous, 1978).
Table 15: Physical achievements of the soil conservation programme

<table>
<thead>
<tr>
<th>Period</th>
<th>Area treated</th>
<th>Expenditure</th>
<th>Average cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m ha</td>
<td>%</td>
<td>m Rs.</td>
</tr>
<tr>
<td>First Plan (1951-56)</td>
<td>0.30</td>
<td>1.4</td>
<td>16.0</td>
</tr>
<tr>
<td>Second Plan (1956-61)</td>
<td>1.27</td>
<td>5.8</td>
<td>203.7</td>
</tr>
<tr>
<td>Third Plan (1961-66)</td>
<td>4.49</td>
<td>20.6</td>
<td>774.2</td>
</tr>
<tr>
<td>1966-69</td>
<td>4.57</td>
<td>21.0</td>
<td>867.8</td>
</tr>
<tr>
<td>Fourth Plan (1969-74)</td>
<td>7.31</td>
<td>33.6</td>
<td>1611.3</td>
</tr>
<tr>
<td>Fifth Plan (1975-78)</td>
<td>3.81</td>
<td>17.6</td>
<td>1633.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>21.75</td>
<td>100</td>
<td>5106.9</td>
</tr>
</tbody>
</table>

* May not be representative as major expenditure was likely to be on creation of the infrastructure

Not only have the total area treated and the total outlay increased in each plan, but the quality and content of the programme have also improved over the years. During the first and second FYPs the work was confined mainly to contour bunding in agricultural lands and afforestation of denuded areas. During the third FYP, in addition to the above two programmes, work was extended into catchments of 13 major river valley projects. In both agricultural and non-agricultural lands the programme was diversified to include practices like nala bunding, percolation tanks, and the reclamation of ravines. Limited attempts were also made to treat coastal areas suffering from problems of sand dunes and salinity. During the period 1966-1969 the programme continued to follow the same trend as in the third FYP. During the fourth FYP the concept of setting up an integrated land-use programme on a watershed basis was advocated. In addition to the on-going programme of the third FYP, the centrally-sponsored scheme of the reclamation of ravines was started in the states of Gujarat, Madhya Pradesh, Rajasthan and Uttar Pradesh. During the plan soil and water conservation programmes were begun in catchments of eight more river valleys.
During the fifth FYP, the programmes of the fourth FYP were continued. Work in catchments of nine more river valleys was also included. This programme is now in progress in catchments of 31 river valleys. During the fifth FYP soil and water conservation work was firmly oriented on watershed management. The projections progressively pushed toward integrated and comprehensive treatment of all types of land uses according to their needs and capabilities. However, much remains to be done in this direction.

It is interesting to observe that right from the inception of this development programme in the first plan, treatment of wasted lands by afforestation, nala bunding, check dams, gully plugging, percolation tanks, and ponds has received attention both in the state government and central government programmes, and some useful results have been obtained.

An evaluation of large-scale afforestation of ravines, (Anonymous, 1970) in the Districts of Mathura, Agra, Aligarh and Mainpuri, initiated in 1952-32 showed that as against an expenditure of Rs. 3.73 million, assets of Rs. 6.16 million had been created over a period of 16 years (including Rs. 0.89 million received in cash in 14 years by the sale of grass, small timber and fuel and trees worth Rs. 4.74 million growth on the ground).

The results of the treatment of some of the catchments of reservoirs have been very encouraging. For example, in 16 sub-watersheds of D.V.C. the sediment load has been reduced from 0.30 to 0.019 ha m/km²; in five major reservoirs of Bhakra, Machund, Panchet, Maithon and Hirakud, the sediment rate was reduced by 16.3 to 42% (Patnaik, 1977). A sediment load of 0.18 ha m/km² was reduced to 0.15 ha m/km² when 770 ha of agricultural land were treated with soil and water conservation measures and 16,000 ha were afforested in the Ram Ganga catchment of 307,644 ha (Patnaik, 1974).

AGROFORESTRY RESEARCH IN INDIA: RETROSPECT AND PROSPECT

India has been aware of the problem of the degradation of land from the second half of the 19th century. Deforestation and soil erosion in the hill districts of Punjab received attention as early as 1855 and were followed up by a series of reports in 1879, 1924, 1927, 1929, 1931, 1933, 1935, 1937 and 1946.
Deforestation, over-grazing and ravine erosion received the attention of the government of the United Provinces (now Uttar Pradesh) as early as 1912-20, while severe erosion due to deforestation in North Bengal and Assam was reported as early as 1928. Sporadic efforts have also been made to solve these problems from time to time. Since 1951, both research base and development programmes for the wasted lands have received greater attention, as shown in the preceding paragraphs. While afforestation and grass-land development have been the cornerstone of these programmes, researchers endeavoured to consider the possibility of growing fodder-fuel species together since the late 1950s. The results of these experiments are reported in the preceding paragraphs. These studies have been referred to as fodder-fuel plantations in degraded/denuded habitats (i.e. wasted lands). With emphasis only on fodder and forage production in which grasses and fodder shrubs/trees are combined, the studies have been referred to as silvo-pastoral studies.

When trees are grown on agricultural lands along with agricultural crops the term farm forestry has been used. The term agroforestry has recently been defined as a "sustainable land management system which increases the overall yield of the land, combines the production of crops (including tree crops) and forest plants and/or animals simultaneously or sequentially, on the same unit of land and applies management practices that are compatible with the cultural practices of the local population" (King and Chandler, 1978). This definition obviously includes farm forestry, silvo-pastoral, horti-pastoral and fodder-fuel plantation systems.

Agroforestry, as applicable to lands not suited for agriculture, is a sustainable management of lands (that are not suited to agriculture) for increasing production of tree crops, including horticultural trees, grasses, agricultural crops (for very short durations whenever practical) and/or animals simultaneously or sequentially on the same unit of land, and one that applies management practices compatible with the cultural practices of the local population.

The unit of management of land under these conditions can be a watershed, or part of a watershed, provided the emphasis
is on trees/grasses that will protect the land as well as produce fodder, fuel, fruit, etc.

In retrospect, it is obvious that considerable attention has been paid and is being paid to agroforestry, especially on lands not suited to agriculture. This is evident from a large number of studies under progress at the Central Soil & Water Conservation Research & Training Institute (Appendix I), the Indian Grassland and Fodder Research Institute, and the Central Arid Zone Research Institute.

In prospect it will be necessary to focus greater attention on agroforestry for the utilization of wasted lands in developing countries where pressure of human and cattle populations is very high on the land-water-plant systems. It will be necessary to identify multi-purpose trees with two or more uses as fuel, fodder, food, fruit, fibre, industrial raw material or timber. Since there is a shortage of fuel and fodder in India, the emphasis may continue to be laid on fuel and fodder production. As more than one crop (i.e. trees, grasses, agricultural crops) will be grown together, it will be necessary to study their compatibility, their effect on soil-building/deteriorating processes, the techniques of propagation, fertilization, harvesting and use and the economic evaluation of the promising systems of agroforestry so identified.

TRAINING AND EDUCATION

It is obvious that neither the research can be conducted nor development work be executed unless educated and trained manpower is available. Fortunately, India happens to be in a comfortable position in this regard, as at present it has a large number of agricultural universities, forest colleges and research institutes engaged in teaching and training programmes in the area of land-water-plant management. India also realized the importance of giving special attention to land management, as evidenced by the establishment of training centres for soil and water conservation in the 1950s. The soil conservation centres managed by the Central Soil & Water Conservation Research & Training Institute have up to the end of September 1978,
trained 1,101 officers and 3,560 middle-level technicians. These courses have also been used by FAO and the Colombo Plan. Trainees from Korea, Philippines, Nepal, Malaysia, Ceylon, etc. have been trained. The syllabus for these courses is comprehensive for management of land-water-plant systems. A summary outline of the syllabus is given in Appendix II. Since the courses deal with the technology of soil-water conservation, the emphasis is on doing and evaluating rather than class-room work. At least 50% of the time is utilized for practical exercises and project planning formulation and evaluation. A scrutiny of the syllabus will indicate that there is very great emphasis on afforestation, grassland management, silvo-pastoral systems and farm forestry (Part 5, Part 7, Part 8 and Part 9 of Appendix II). These courses last for 5½ months and are given regularly; the starting dates are March 16 and October 1 every year. Apart from the regular courses, the institute organizes short and special courses as and when the need arises. Up to December 1978, 286 officers had been trained in such courses. The institute has qualified, experienced and trained faculty and the necessary facilities for conducting these courses. Thus, the institute will be in a position to train manpower from neighbouring countries in the management of land-water-plant systems, either through its regular courses or through special courses.

APPENDIX I

STUDIES ON AGROFORESTRY IN PROGRESS AT CENTRAL SOIL AND WATER CONSERVATION RESEARCH AND TRAINING INSTITUTE, DEHRA DUN AND ITS CENTRES

A. UTILIZATION OF LANDS NOT SUITED FOR AGRICULTURE

<table>
<thead>
<tr>
<th>Tree and grass species</th>
<th>Treatments</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Dalbergia sissoo</td>
<td>Tree species, their spacing and grass species</td>
<td>Fodder fibre and fuel plantation in sub-tropical regions</td>
</tr>
<tr>
<td>Acastia catechu</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chrysopogon fulvus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eulaliopsis binata</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Eucalyptus spp.</td>
<td>Tree spacing with one grass species</td>
<td>Fodder and fuel plantation in sub-tropical regions</td>
</tr>
<tr>
<td>Chrysopogon fulvus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Agave spp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eulaliopsis binata</td>
<td></td>
<td>Fibre plantation in sub-tropical regions</td>
</tr>
</tbody>
</table>
4. *Albizia lebbek*  
*Bauhinia purpurea*  
*Ficus rexfunghi*  
*Leucaena leucocephala*  
*Chrysopogon fulvus*  
*Panicum repens*

5. *Broussonetia papyrifera*  
Spacing and harvesting cycle

6. *Acacia nilotica*  
*Dichanthium annulatum*  
*Chloris bournii*  
*Cenchrus ciliaris*  
*Eulaliopsis binata*

7. **Approved project for fodder tree and grass plantations**

8. **Raw material for decorative paper for use by cottage industries**

9. **Fodder fuel plantation in semi-arid regions and in ravine lands**

10. **Fuel and fibre grass plantations**

8. **Utilization of ravine lands for fodder, fuel, timber, etc. in semi-arid regions**

9. **Evaluation of grass for sub-tropical regions**

10. **Evaluation of grasses for semi-arid and sub-humid regions**

11. **Evaluation of tree species for fuel and oil content in semi-arid, sub-humid subtropical and temperate regions**

**Purpose**

12. **Evaluation of tree species for fuel and small timber under semi-arid climate**

13. **Utilization of semi-arid area and ravines in semi-arid regions for fodder and fuel; management of *P. juliflora* plantation**

14. **Utilization and management of plantation in ravine lands in semi-arid regions**

15. **Evaluation of fast growing tree species as industrial soft wood**
16. *Acacia nilotica*  
*Prosopis juliflora*  
*Tamarix ramosissima*  
*Brachiaria mutica*  
3 tree species and 1 grass species  
Utilization of salt-affected ravine lands in semi-arid regions

17. Collection of perennial legumes and their intercropping with grasses  
Evaluation of legumes with and without inter-cropping with grasses in semi-arid areas

18. Responses of grasses and trees to application of nitrogen

**B. UTILIZATION OF LANDS SUITED TO AGRICULTURE**

1. *Eucalyptus hybridii*  
*Eucalyptus globulus*  
*Grewia oppositifolia*  
*Maize*  
*Wheat*  
3 tree species  
2 agricultural crops  
Growing of fodder-fuel plants association with agricultural crops in sub-tropical regions

2. *Eucalyptus globulus*  
*Potato*  
Growing of fuel and oil-bearing plants along with potatoes

3. *Acacia nilotica*  
*Tobacco; cotton*  
Growing of fuel-fodder tree species in gullies and tobacco and cotton on agricultural land

4. Various crops in agricultural lands and grasses on narrow based contour terraces

**APPENDIX II**

CENTRAL SOIL AND WATER CONSERVATION RESEARCH AND TRAINING INSTITUTE, 218, KAULAGARH ROAD, DEHRA DUN (U.P.)-248195 - INDIA

SYLLABUS (Summary)

REGULAR COURSE - SOIL CONSERVATION TRAINING FOR OFFICERS  
5½ MONTHS

Frequency: 2 Courses a year starting on March 16 and October 1 of every year

PART 1.00 INTRODUCTION  
1.10 History of erosion  
1.20 Soil conservation in India  
1.30 Principles of soil erosion

PART 2.00 SOIL AND WATER CONSERVATION ENGINEERING  
2.10 Introduction  
2.20 Surveying and cartography
2.30 Hydrologic cycle rainfall and runoff
2.40 Hydraulics
2.50 Soil mechanics
2.60 Sedimentation
2.70 Grassed waterway
2.80 Contour cultivation and contour trenching
2.90 Bunding, terracing and diversion
2.100 Erosion control structures
2.110 Farm pond
2.120 Gully control
2.130 Agricultural drainage
2.140 Conservation irrigation
2.150 Water spreading
2.160 Stream bank control
2.170 Torrent control
2.180 Land slide control
2.190 Control of erosion of high way and railway
2.200 Watershed management

PART 3.00 SOIL-PLANT-WATER RELATIONSHIPS
3.10 Physical properties of soils
3.20 Chemical properties of soils
3.30 Biological characteristics of soils
3.40 Soil formation
3.50 Soil classification
3.60 Soil interpretation
3.70 Soil-moisture relationships
3.80 Soil plant nutrient relations
3.90 Soil management

PART 4.00 SOIL CONSERVATION AGRONOMY
4.10 Problems of crop land management
4.20 Tillage and tilth
4.30 Classification of crops
4.40 Cropping systems
4.50 Manures and fertilizers
4.67 Agronomic practices in erosion control
4.70 Dry farming
4.80 Management practices for maximum production
4.90 Agricultural equipment for soil conservation

PART 5.00 SOIL CONSERVATION FORESTRY
5.10 National forest policy
Forests in relation to its environment
Forest management
Regeneration of forests
Wind erosion and its control
Special problems of soil erosion
Grass land development and management for soil and water conservation
Farm forestry
Shifting cultivation
Wild life management
Watershed management

PART 6.00  COMMUNICATION
Personal development
Information

PART 7.00  SOIL CONSERVATION PLANNING AND APPLICATIONS
Soil conservation planning in field

PART 8.00  SPECIAL ASSIGNMENT - Each trainee is required to opt for any one of the following projects:
1. Watershed management for sediment control
2. Irrigation and drainage
3. Measures for erosion control in agricultural land
4. Measures for erosion control in grass lands and forest areas
5. Ravine control and reclamation
6. Grass land development and management
7. Afforestation of eroded and degraded areas
8. Stabilization of coastal sand dunes
9. Soil and water conservation in arid areas
10. Dry farming techniques - semi arid areas
11. Saline and alkali land reclamation
12. Runoff and sediment measurement
13. Development of farm forestry on eroded areas and coastal lands

PART 9.00  STUDY TOURS - Visit to see state works in the field-spot analysis of the problem and evaluation of the treatment benefits along with cost benefit review. Acquainting with plan projects in operation in the States - 2 weeks.
DISCUSSION

Pereira: When the catchment areas have been restored and the grazing guards withdrawn, do the people respect the vegetative cover or do they return to over-exploitation?

Tejwani: Protection of grasslands and plantations is, indeed, a serious problem. However, our experiences are not so discouraging. The people protect the system when they are emotionally involved through direct benefits, e.g. (i) irrigation by water harvesting, (ii) horticulture, and (iii) the development of water resources.

A.L.D. Mongi: *Eucalyptus globulus* is rated as a good source of litter for the soil. However, experience demonstrates lack of vegetative undergrowth, both in diversity and profusion, in arid and semi-arid areas. What is the explanation?

Tejwani: The absence of undergrowth is more related to moisture limitations rather than to the *Eucalyptus*. For instance, under about 1100 mm rainfall in India, fibre grass (*Eulaliopsis binata*) of considerable quantity and quality has been grown. There is room for more research to determine species characteristics and performance under different rainfall regimes. Currently one needs to exercise caution against generalization on the unsuitability of *Eucalyptus*.

Nyandat: On the east coast of Kenya, cashew, mangoes and coconut are grown with wide spacing. It is our view that the space in between can be put to productive pasture. Does anybody have any experience in this respect?

Tejwani: Yes. We have data in India on the usefulness of this type of exploitation.

Sanchez: Intercropping of these crops and others is being done quite successfully in Latin America.

King: The work of the Indian Central Plantation Crops Research Institute, at Kasaragod, shows much promise for combined systems of production elsewhere and for future agroforestry systems.

LITERATURE CITED


SOIL MYCORRHIZA IN RELATION TO SOIL FERTILITY
AND PRODUCTIVITY

J.F. Redhead

ABSTRACT

All tropical trees that have so far been studied grow in association with mycorrhizal fungi and all important tropical food crops are mycorrhizal. Further studies are needed in savanna types of vegetation. The vascular-arbuscular mycorrhizal association formed by species of Endogonaceae is universal. Apart from the important genus Pinus and some species in the families Myrtaceae (some Eucalyptus spp.), Caesalpiniaceae and Dipterocarpaceae, records of ectotropical mycorrhizal associations are infrequent for tropical plants. The mycorrhizal association is essential for the growth of some genera under field conditions, e.g. Citrus and Pinus, but information is lacking for most other important genera. There is a need to study natural mycorrhizal associations and, through experiment, match the fungi and higher plants most suited to each other under particular ecological environments. Agroforestry research should consider the tripartite relationship soil/plant/fungus rather than only the soil/plant relationship. Selected fungal inocula should be multiplied and tested in crop plants under tropical conditions, both in the nursery and the field. Research is also needed to monitor the effect of soil sterilants and fungicides on the mycorrhizal relationship. Facilities and staff training in these areas should be strengthened so that more emphasis can be given to this work in tropical environments.

It is more than a hundred years since Frank (1885) first coined the term "mycorrhiza" and realized that the association between fungus and tree root was a natural, non-pathogenic relationship. In the same year, Treub (1885) recorded the occurrence of a mycorrhizal association in sugar cane in Java. A few years later, Janse (1896) carried out an extensive survey of the occurrence of mycorrhizal associations, again in Java.

Almost 50 years elapsed before Johnston (1949) studied mycorrhizal association in Trinidad and still more before Redhead (1960, 1968a) surveyed them in the Lowland Rain Forest of Nigeria. Interest was revived because tropical rain forest ecologists, such as Richards, thought that mycorrhizal associations were likely to play an important role in the cycle of nutrients in tropical ecosystems.

* Professor of Forest Biology, Division of Forestry, University of Dar es Salaam, Morogoro, Tanzania.
When mycorrhizal associations were first discussed, some of the leading pathologists believed that the fungus was parasitic: even the famous forester Robert Hartig (1883) was outspoken on this issue. Speculations on the relationship were all based on descriptive observation, and it was only 40 years later that the pioneering efforts of Elias Melin demonstrated through conclusive experiments that the ectotrophic mycorrhizal association was truly symbiotic (Melin, 1923, 1925, 1936). The endotrophic or vesicular-arbuscular mycorrhizal association at that time was still considered parasitic by many mycologists. Gradually experimental evidence accumulated to indicate that even this type of mycorrhizal association had an important beneficial effect and, under certain conditions at least, was essential for the growth of some species (Mosse, 1963; Gerdemann, 1968; Harley, 1968, 1969).

It has since been amply demonstrated that inoculation of forest trees and agricultural plants with mycorrhizal fungi can stimulate their growth in nutritionally poor soils, such as occur in very large areas of the tropics (Bowen, 1978). Future foresters and agriculturists should no longer consider only the soil/plant relationship, complex as that may be, but should think in terms of a soil/plant/fungus relationship, or even in terms of a soil/plant/fungus/bacterium relationship in the case of legumes in symbiosis with nitrogen fixing bacteria.

Scientists have extensive experimental evidence that some fungi are more effective symbiotic partners than others for certain hosts under specific ecological conditions. Both ectotrophic and endotrophic mycorrhizal fungi have been tested under field conditions with great success; and techniques are being perfected that enable inoculation to be carried out under field conditions on a large scale.

This account will review the present state of experience with mycorrhizae under field conditions and suggest priorities for further research in the tropics.

MYCORRHIZAL ASSOCIATIONS IN THE TROPICS

In his extensive survey of the occurrence of the mycorrhizal association in Java, Janse (1896) studied bryophytes, vascular
cryptogams, gymnosperms, monocotyledons and 38 species of woody dicotyledons. Sixty-nine of the 75 species examined, including all the woody dicotyledons, had characteristic endotrophic mycorrhizal associations of the type now generally referred to as vesicular-arbuscular mycorrhizae (VAM). Janse illustrated his account with careful drawings of the morphology of the endophyte and gave the names "vesicle" and "sporangiole" to the special organs he observed. Vesicles were small, round or elongated bladder-like structures formed terminally on hyphae within the root cortex, and sporangioles were clumps of fungal material, cauliflower-like in appearance, formed within the cells some distance from the root tip. Sporangioles are now regarded as a later stage of "arbuscules" which are finely-branched intracellular structures, through which exchange of metabolites takes place between the plant cell and the fungus.

Johnston (1949) surveyed the incidence of mycorrhizal associations in 93 species in Trinidad. Eighty species, including 13 species of forest trees, had endotrophic mycorrhizal associations. It is noteworthy that neither Janse nor Johnston recorded the occurrence of the ectotrophic type of mycorrhizal association.

Redhead (1960, 1968a) carried out a similar survey on the incidence of mycorrhizal associations in 51 tree species indigenous to the lowland rain forest of Nigeria and in 15 exotic trees. Forty-four of the indigenous trees and all the exotics were found to have endotrophic mycorrhizal associations but, in addition, three species of the family Caesalpiniaceae were found to have typical ectotrophic mycorrhizal associations. At the same time as Redhead was examining trees in Nigeria, unknown to each party, a group of Italian botanists were examining the mycoflora of trees in the rain forests of Zaire. They recorded ectotrophic mycorrhizae on eight tree species in the Caesalpiniaceae (Fassi and Fontana, 1961, 1962; Fassi, 1963). These were the first records of the ectotrophic mycorrhizal association in the tropics and for leguminous species.

More recently Thomazini (1974) studied mycorrhizal associations in Brazil and recorded 56 species with endotrophic associations, two ectotrophic and two ecto-endotrophic associations. The rarity of the ectotrophic type of association and universal
frequency of the endotrophic association have been confirmed also from India (Thapar and Khan, 1973), the Philippines (Tupas and Sajise, 1976) and Sri Lanka (de Alwis and Abeynayake, 1978).

All descriptive accounts indicate that the endotrophic mycorrhizal association is remarkably uniform and typically of the vesicular-arbuscular (VA) type. There are numerous records of this type of association on tropical crop plants, notably avocado, cacao, cassava, citrus, coconut, cotton, litchi, maize, paw-paw, sweet potato, sugar cane, rubber, tea, tobacco, tomato, and many different species of timber trees, including cypress and teak.

In contrast, records of the ectotrophic association in natural forest are few: eleven species of Caesalpiniaceae (Redhead, 1960, 1968a; Fassi and Fontana, 1961, 1962; Fassi, 1963; Jenik and Mensah, 1967; Thomazini, 1974), 18 species of Dipterocarpaceae (Singh, 1966; de Alwis and Abeynayake, 1978), one species of Euphorbiaceae (Redhead, 1974), one species of Fagaceae (Singh, 1966) and one species of Myrtaceae (Thomazini, 1974). Although accounts of the ectotrophic mycorrhizal associations of tropical pines from natural forest have not been published, Dr. M.H. Ivory of the Commonwealth Forestry Institute, Oxford, has recently made extensive collections in natural stands of Pinus caribaea and P. oocarpa in Central America and the Bahamas. Several species of Eucalyptus, planted as exotics in many tropical territories, are known to be mycorrhizal in Australia (Chilvers and Pryor, 1965) and may also form ectotrophic associations in the tropics.

The genus Pinus is the only tropical crop genus for which the ectotrophic mycorrhizal association is known to be obligatory for successful growth beyond the nursery stage. Introductions of pines have always failed in the tropics unless mycorrhizal fungi were first introduced. Mikola (1978) gives the following examples: Puerto Rico (Briscoe, 1959), Trinidad (Lamb, 1956), Kenya (Gibson, 1963), Malawi (Clements, 1941), Nigeria (Madu, 1967) and Zambia (Mikola, 1970). Mikola describes his account of the history of the invasion of mycorrhizal infection across the frontiers as a series of detective stories. It is possible that settlers unwittingly introduced mycorrhizal fungi into Australia, New Zealand, South Africa and South America on the roots of potted plants carried from Europe.
The universal distribution of the VA type of mycorrhizal association compared to the rarity of the ectotrophic association in natural vegetation is not easy to explain. Some of the first recorded fossil fungi found in the oldest land plants and illustrated by Kidston and Lang (1921) appear identical to present day fungi in typical VA mycorrhizal associations. Butler (1939) and Nicolson (1975) have discussed the antiquity of the association which must have evolved from a state of parasitism. In many ways, e.g. enlargement of the nucleus and disappearance of starch, the plant cell reacts to the mycorrhizal endophyte as it does to a pathogen such as Pythium. It may have been this similarity that caused some of the confusion and scientific debate on the nature of the association and its causal agents.

It is difficult to account for the world-wide distribution of the VA association on the basis of spore dispersion as the spores of these fungi are very large and subterranean, and consequently not readily dispersed except by small animals (Fogel and Trappe, 1978). In contrast the rare ectotrophic mycorrhizal association has a much more efficient spore dispersal mechanism, normally by basidiospores from aerial sporophores.

No one has so far explained why these fungi are not distributed world-wide as commonly as the VA mycorrhizal fungi. The need for introducing inocula of ecologically suitable fungal species of this type of mycorrhiza has important implications for afforestation with exotic pines.

THE IDENTITY OF TROPICAL MYCORRHIZAL FUNGI

THE ECTOTROPHIC ASSOCIATION

The identity of most of the species of fungi forming ectotrophic associations on naturally occurring tropical trees is not known. Redhead (1974) attempted unsuccessfully to culture fungi from mycorrhizal roots of four species of Caesalpiniaceae: *Afzelia africana*, *A. bella*, *A. bipindensis* and *Brachystegia eurycoma*. It was apparent that several different fungi could form associations on these species because the hyphae were often quite different and some bore clamp connections and were thus Basidiomycetes. If plants raised from surface-sterilized seeds in sterilized soil were left in the open air, a large proportion
developed mycorrhizal associations, often with various types of fungi, presumably from air-born propagules. These species of Caesalpiniaceae seem readily disposed to form associations with a variety of fungi, although they could not be induced to form associations with an inoculum of mycorrhizal pine roots in which the association was formed by *Rhizopogon luteolus*, nor would the fungi from the Caesalpiniaceae trees form associations on pine seedlings.

Sporophores of an *Inocybe* species grew adjacent to experimental mycorrhizal *Afzelia bella* seedlings on four separate occasions (Redhead, 1968b). Hyphae from the base of the stipe appeared identical to hyphae on the mycorrhizal root sheath but attempts to culture from the sporophores were not successful.

Dr. M.H. Ivory made a large collection of fungi associated with *Pinus caribaea* and *P. oocarpa* in the natural forests of Central America and the Bahamas. He confirmed (personal communication) that the fungi shown in Table 1 do form mycorrhizal associations on pines in the laboratory:

<table>
<thead>
<tr>
<th>Fungus</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Gyroporus castaneus</em></td>
<td>Mixed <em>P. caribaea</em> and <em>P. oocarpa</em> forests</td>
</tr>
<tr>
<td><em>Pisolithus tinctorius</em></td>
<td>Both <em>P. caribaea</em> and <em>P. oocarpa</em> forests</td>
</tr>
<tr>
<td><em>Rhizopogon nigrescens</em></td>
<td><em>P. caribaea</em> and <em>P. oocarpa</em> hosts and from the alkaline soils of the Bahamas</td>
</tr>
<tr>
<td><em>Suillus cothurnatus</em></td>
<td><em>P. caribaea</em> on alkaline soils</td>
</tr>
<tr>
<td><em>Suillus cf. Holoeacus</em></td>
<td><em>P. caribaea</em> forest</td>
</tr>
<tr>
<td><em>Scleroderma (geaster)</em>?</td>
<td><em>P. caribaea</em> and mixed pine forests</td>
</tr>
<tr>
<td><em>Tylopius gracilis</em></td>
<td><em>P. caribaea</em> and <em>P. oocarpa</em> forests</td>
</tr>
</tbody>
</table>
It is planned to carry out nursery inoculations with these fungi on *Pinus caribaea* seedlings in the nursery and to test their subsequent performance under Tanzanian conditions. It will then be possible to compare their performance with mycorrhizal pine raised using pine soil inoculum and locally identified fungi.

Many of the fungi identified in exotic pine stands are themselves likely to be exotics because the original inocula were introduced. The transport of living plants and unsterilized soil is usually prohibited by plant quarantine regulations and in some cases mycorrhizal inoculum has been smuggled. As Mikola (1978) comments, "Such cases, of course, have not been well documented".

Fungal sporophores regularly found in association with exotic pines in the tropics, and probably mycorrhizal, include the following:

Table 2: Fungal sporophores commonly found associated with exotic pines in the tropics

<table>
<thead>
<tr>
<th>Fungal sporophore</th>
<th>Territory</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coltricia cinnamomea</td>
<td>West Malaysia</td>
<td>Ivory, 1975</td>
</tr>
<tr>
<td>Hebeloma crustuliniforme</td>
<td>Kenya</td>
<td>Gibson, 1963</td>
</tr>
<tr>
<td>Rhizopogon luteolus</td>
<td>Nigeria</td>
<td>Momoh, 1972</td>
</tr>
<tr>
<td>Scleroderma bovista</td>
<td>Kenya</td>
<td>Gibson, 1963</td>
</tr>
<tr>
<td>Suillus granulatus</td>
<td>Kenya</td>
<td>Pegler, 1977</td>
</tr>
<tr>
<td></td>
<td>Tanzania</td>
<td>Pegler, 1977</td>
</tr>
<tr>
<td></td>
<td>West Malaysia</td>
<td>Ivory, 1975</td>
</tr>
<tr>
<td></td>
<td>Uganda</td>
<td>Chaudhry, 1978</td>
</tr>
<tr>
<td></td>
<td>Zaire</td>
<td>Thoen, 1974</td>
</tr>
<tr>
<td><em>S. luteus (Boletus luteus)</em></td>
<td>Kenya</td>
<td>Gibson, 1963</td>
</tr>
<tr>
<td></td>
<td>Tanzania</td>
<td>Pegler, 1977</td>
</tr>
<tr>
<td><em>S. sibiricus</em></td>
<td>Tanzania</td>
<td>Pegler, 1977; Coll. Redhead, 1979, unpub.</td>
</tr>
</tbody>
</table>
Some fungi may form mycorrhizal associations and apparently grow vigorously but may not produce sporophores under certain ecological conditions. It is expected that studies in progress at the University of Dar es Salaam will shed more light on the ecological requirements of mycorrhizal fungi associations on exotic pines in Tanzania.

THE ENDOTROPHIC ASSOCIATION

If one excludes the endotrophic mycorrhizal associations found in the Orchidaceae, this association is termed vesicular-arbuscular (VA) because of its characteristic morphology within the root cells. The fungi forming VA mycorrhizae are species of the Endogonaceae. This family contains several genera which form the association and Gerdemann and Trappe (1974) attempted a classification of this difficult taxonomic group.

The morphology of the VA mycorrhizal association is remarkably uniform and its variation within the plant cell seems to be controlled by the higher plant at least as much as by the fungus. Identification of specific fungi is based on spores found in the soil. These spores vary in size and are often very large—up to 1050 μ (Old, Nicolson and Redhead, 1973). They also vary in colour, wall structure, content, mode of attachment to the subtending hypha (Mosse and Bowen, 1968), and aggregation, i.e. singly, in naked clusters, or in sporocarps (Redhead, 1977).

It is only during the past few years that attempts have been made to give names to spores found in tropical soils. The principal records are as follows:

Costa Rica: Janos (1975) identified Sclerocystis dussii (Pat.) von Hohn and an Acaulospora species in previously sterilized soil inoculated with mycorrhizal cacao roots.

India: Two new species, Glomus multicaulis and Sclerocystis sinuosa, were found and named by Gerdemann and Bakshi (1976).

Mexico: Three new species, Acaulospora scrobiculata, Glomus constrictus and Sclerocystis clavispora, were found and named by Trappe (1977).
Nigeria: Redhead (1974, 1977) found numerous species, including *Glomus fasciculatus* (Gerdemann and Trappe, 1974), six different kinds of *Gigaspora*, one of which was possibly *G. gilmorei* (Gerdemann and Trappe, 1974), a second was similar to *G. gigantea* (Nicolson and Gerdemann) (Gerdemann and Trappe, 1974) and a third an unnamed species described by Old, Nicolson and Redhead, (1973). Still another was similar to the newly-described species *Acaulospora scrobiculata* Trappe. Spores of a *Scleroxystis* species were also regularly seen. Sanni (1976a,b) has also recorded *Gigaspora gigantea*.

No doubt many other species occur.

THE EFFECT OF MYCORRHIZAL ASSOCIATION ON PLANT GROWTH AND PRODUCTIVITY

EFFECT ON GROWTH

THE ECTOTROPHIC ASSOCIATION

It has been mentioned already that the ectotrophic mycorrhizal association is obligatory for the growth of pine beyond the nursery stage. This is why introduction of pines into new habitats has to be accompanied by the introduction of fungal inoculum and this is well documented for Africa (Mikola, 1970). Less is known about the effects of this type of association on indigenous tropical species. Redhead (1974) grew *Brachystegia eurycome* inoculated with two distinctly different ectotrophic mycorrhizal fungi from naturally growing *B. eurycome*, one with fine, white hyphae and the other with stout, brown hyphae. The mycorrhizal plants produced significantly more dry matter than the non-mycorrhizal controls (Table 3).
Table 3: Mean stem heights and dry weights of *Brachystegia eurycoma* after inoculation with two different mycorrhizal fungi

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Stem height (cm)</th>
<th>Mean dry weight (g)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leaves</td>
<td>Stem</td>
<td>Roots</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>No inoculation</td>
<td>22.4</td>
<td>0.74</td>
<td>1.07</td>
<td>1.10</td>
<td>2.91</td>
</tr>
<tr>
<td>White mycorrhiza</td>
<td>26.3*</td>
<td>1.23**</td>
<td>1.65**</td>
<td>2.05**</td>
<td>4.93**</td>
</tr>
<tr>
<td>Brown mycorrhiza</td>
<td>28.6*</td>
<td>1.54**</td>
<td>1.94**</td>
<td>2.08**</td>
<td>5.56**</td>
</tr>
</tbody>
</table>

* denotes significant at p = 0.05
** denotes significant at p = 0.01

THE ENDOTROPHIC ASSOCIATION

The effect of the VA association on plant growth varies very much with the nature of the higher plant and with the level of soil fertility, particularly soluble phosphate (Hayman and Mosse, 1971; Mosse, 1973). Table 4 gives some examples of growth response of some tropical plants to inoculation with VA mycorrhizal fungi.

Table 4: Some examples of the effect of inoculation with vesicular-arbuscular mycorrhizae on the dry weight of the higher plant

<table>
<thead>
<tr>
<th>Plant</th>
<th>Total dry weight (g)</th>
<th>Control</th>
<th>Inoculated plant</th>
<th>Note</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td></td>
<td>2.367</td>
<td>2.995</td>
<td>Sand culture</td>
<td>Winter and Melch (1958)</td>
</tr>
<tr>
<td>Maize</td>
<td></td>
<td>3.7</td>
<td>13.3</td>
<td>Steam sterilized soil</td>
<td>Gerdemann (1964)</td>
</tr>
<tr>
<td>Maize</td>
<td></td>
<td>6.1</td>
<td>14.4</td>
<td>Steam sterilized soil</td>
<td>Gerdemann (1965)</td>
</tr>
<tr>
<td>Tobacco</td>
<td></td>
<td>1.65</td>
<td>2.72</td>
<td>Subsoil, sand</td>
<td>Peuss (1958)</td>
</tr>
<tr>
<td>Tomato</td>
<td></td>
<td>0.088</td>
<td>0.393</td>
<td>Sand, Low P</td>
<td>Daft and Nicolson (1966)</td>
</tr>
<tr>
<td>Tomato</td>
<td></td>
<td>0.702</td>
<td>0.737</td>
<td>Sand, Very high P</td>
<td></td>
</tr>
<tr>
<td>Podocarpus totara</td>
<td></td>
<td>0.38</td>
<td>2.63</td>
<td>Soil sterilized at 100°C</td>
<td>Baylis <em>et al.</em> (1963)</td>
</tr>
</tbody>
</table>

(Contd.)
(contd.)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Total dry weight (g)</th>
<th>Note</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Inoculated plant</td>
<td></td>
</tr>
<tr>
<td>Khaya grandifoliola</td>
<td>0.91</td>
<td>6.21</td>
<td>Sard</td>
</tr>
<tr>
<td>Inga oerstediana</td>
<td>12.31</td>
<td>19.42</td>
<td></td>
</tr>
<tr>
<td>Sickinga maxonii</td>
<td>13.20</td>
<td>14.37</td>
<td>Sterilized soil</td>
</tr>
<tr>
<td>Vitex cooperi</td>
<td>6.52</td>
<td>16.53</td>
<td></td>
</tr>
<tr>
<td>Unidentified species of Euphorbiaceae</td>
<td>4.82</td>
<td>8.29</td>
<td></td>
</tr>
</tbody>
</table>

Sanni (1976a), using an inoculum similar to Redhead's (1975), found that it increased the growth of cowpea, maize and tomato, especially with the addition of $\text{Ca}_3(\text{PO}_4)_2$.

Perhaps the most striking example of the effect of the association was in the large commercial Citrus nurseries in Florida, U.S.A., seen by the author in 1971. The government had introduced a bonus price for Citrus seedlings guaranteed free from certain diseases and the large nurseries adopted a method whereby the whole area, up to 40 ha, was sterilized by the mechanical injection of methyl bromide through a polythene cover. Seed sown in these nurseries germinated and grew to about three centimetres in height but then remained stunted and chlorotic. Occasionally along the drills there were sections where the seedlings were up to 15 cm tall and a dark, healthy, green colour. Inspection revealed that these plants had somehow developed a VA mycorrhizal association, whereas the others had not because the methyl bromide had destroyed the spores and mycelium occurring naturally in the soil. Plant pathologists continued to look for a pathogen causing this "soil sickness" but research demonstrated without doubt that the lack of growth was due to the absence of the mycorrhizal fungus (Kleinschmidt and Gerdemann, 1972).
It was tempting for early workers to postulate that mycorrhizal fungi obtained nutrients at least partly through an ability to decompose soil organic matter, but there is no evidence that any mycorrhizal fungus has the ability to do this. The fungi obtain carbohydrate material from the higher plant and, unless in partnership with such a plant, the mycorrhizal fungi show weak competitive ability with other soil fungi. Once the partnership is established the fungal hyphae are extremely efficient at absorbing mineral salts from the soil solution and in turn passing them on to the higher plant (Harley, 1969). The work of Gadgil and Gadgil (1975) suggests that ectotrophic mycorrhizal fungi may actually suppress the growth of litter-decomposing organisms by removing nutrients before the micro-organisms involved can make use of them.

There is no evidence that the mycorrhizal fungi possess any special ability to make minerals more soluble, but as long as nutrients are withdrawn from solution, more ions will come into solution to restore the equilibrium. Mycorrhizal fungi are particularly important for the plant in soils deficient in available phosphate (Daft and Nicolson, 1966; Sanders and Tinker, 1971; Barrow et al., 1977).

The great advantage of a mycorrhizal plant over a plant without a fungal associate is that the fungal hyphae spread far and wide in the soil, much farther than root hairs can. A plant with a heavy mycorrhizal association can even bind the soil together in masses, and this is one reason why mycorrhizal seedlings transplant into the field with much higher survival than plants with a weakly developed association.

Ectotrophic mycorrhizal fungi vary a great deal in their growth characteristics. Some form very extensive mycelial strands (Bergstrom, 1976), whilst others remain close to their fungal sheath which is compact with a well-defined surface. It is easy to postulate that a fungus that forms a very extensive mycelium will be more efficient at absorbing nutrients than one that does not. This is an aspect worthy of study.
The VA mycorrhizal fungi also have an extensive phase in the soil, although this can be missed by casual observation as the hyphae easily break off from the root. Sanders and Tinker (1973) measured 80 cm of hyphae/cm of endomycorrhizal roots in onion. In some soils wet-sieving and decanting (Gerdemann and Nicolson, 1963) will reveal masses of typical "Endogone" mycelium. As these fungi are unable to grow saprophytically they do not show up on dilution plate counts of soil fungi. Some texts on soil fungi, e.g. Alexander (1961), do not even mention their existence. The vesicular-arbuscular mycorrhizal fungi do not form strands in the same way as do many of the ectotrophic mycorrhizal fungi, and it is not known whether some species have a more extensive soil phase than others.

Plants vary in their rooting characteristics. Some have low root concentrations and few or no root hairs, designated as "magnolioid" by Baylis (1975), while others, "graminoid" roots, have high root densities, mainly of fine roots with well-developed root hairs. A range of morphology occurs between these two extremes and in many species that do form root hairs they are very irregular in distribution.

Baylis (1975) postulates that, because of their poor rooting intensity and poor production of root hairs, magnolioid roots respond more to mycorrhizal association, and the relative responses of various species tends to decline as roots become more graminoid. There is little quantitative information on rooting in tropical trees. Redhead (1968a) grew mycorrhizal Khaya ivorensis seedlings raised from seed from the same parent tree in wooden tubs under identical conditions, except for different levels of N, P and K. Observations showed that many roots had no hairs at all and no correlation could be demonstrated between the presence or absence of root hairs and either the incidence of an internal fungal associate or the external mycelium. This is in contrast with what might have been expected in the light of Baylis' hypothesis. It appears that many factors may be involved and further studies are required on rooting characteristics in relation to mycorrhizal development in tropical crops.

Rooting habit and mycorrhizal development clearly affect the ability of a plant to absorb moisture and nutrients. In
a monoculture, clean weeding may enable a plant to make use of the soil without competition, but with inter-cropping, as in a taungya farm, the plants with special adaptations to absorb poorly mobile ions such as phosphate will have a competitive advantage. The presence of the most suitable mycorrhizal association would be of major importance.

THE RELATIONSHIP OF THE MYCORRHIZAL ASSOCIATION TO NITROGEN FIXATION

There is no evidence that mycorrhizal fungi can fix nitrogen. Where this has been suggested it has been found that the fixation was by bacteria or blue-green algae, often under rather special circumstances. Giles and Whitesand (1976, 1977) recently incorporated protoplasts of nitrogen-fixing bacteria into the hyphae of the ectotrophic mycorrhizal fungus *Rhizopogon*. This research has very interesting possibilities.

The VA mycorrhizal association appears to be very important for bacterial nodulation and nitrogen fixation by legumes, especially in phosphate-deficient soils. Waidyanatha (1978) studied the leguminous ground cover plants *Pueraria phaseoloides* and *Stylosanthes guianensis* and found that they were dependent on the mycorrhizal association for growth under natural conditions unless given large amounts of rock phosphate. He found that both nodulation and nitrogen fixation were depressed unless the legumes were mycorrhizal, and concluded that there was some evidence that the mycorrhizal association may be more important for nitrogen fixation than for growth *per se*.

Mosse (1978) reports similar responses to inoculation by VA mycorrhizal fungi with *Leucaena leucocephala* (Table 5). Her data show that, as usual, any response to rock phosphate is greatly increased by mycorrhizal inoculation. Nitrogen-fixing legumes are very important components of many agroforestry combinations in the tropics for pasture, fodder trees, cover crops and as food. The interrelationships between the higher plant, mycorrhizal fungus, nitrogen-fixing bacterium and the soil are very complex and deserve special attention in any research programme.
Table 5: Effect of soil and mycorrhiza on growth and nodulation of *Leucaena leucocephala*. (Data from Mosse, 1978)

<table>
<thead>
<tr>
<th>Soil P soluble in:</th>
<th>Dry wt. and No. of nodules</th>
<th>Soil treatments</th>
<th>+ Rock phosphate (7 mg/kg soil)</th>
<th>+ mycorrhizal inoculum</th>
<th>+ Rock phosphate and mycorrhiza</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaCl₂</td>
<td>NaHCO₃</td>
<td>Wt. (mg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>2.4</td>
<td>1,103</td>
<td>1,800</td>
<td>3,947</td>
<td>4,125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nodules</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>4</td>
<td>87</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wt. (mg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>215</td>
<td>254</td>
<td>1,896</td>
<td>1,879</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nodules</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0</td>
<td>35</td>
<td>40</td>
</tr>
</tbody>
</table>

Note: Soils sterilized by irradiation.

DISEASE RESISTANCE

Some ectomycorrhizal fungi produce fungistatic compounds that are antagonistic to root pathogens. Marx (1972) demonstrated that the mycorrhizal fungus *Leucopaxillus cerealis* var. *piceina* produced antibiotics antagonistic to the damping-off fungus *Phytophthora cinnamomi*. A well-developed mycelial sheath is itself a barrier to soil pathogens. The improved nutrition conferred by the association can also contribute to disease resistance, while an extensive growth of mycorrhizal hyphae in the soil can compensate for a degree of root loss from fungal disease.

Damping-off caused by *Phytophthora*, *Pythium* and other fungi are the commonest diseases of pines and eucalypts in tropical forest nurseries. If some mycorrhizal fungi are known to confer a degree of resistance to these pathogens it would be useful to study which mycorrhizal fungi are effective under tropical conditions.

Less is known about whether the VA mycorrhizal fungi protect roots against disease. Studies by Baltruschat and Schonbeck (1972) indicated that the association protected tobacco roots against *Thielaviopsis basicola*, and the work of Schenk et al. (1975) suggested that the fungal associate suppresses root-knot nematodes on soybean. Further studies are needed on these ecological aspects of mycorrhizal associations.
THE SPECIFICITY OF THE FUNGAL ASSOCIATE TO THE HIGHER PLANT

ECTOTROPHIC MYCORRHIZAL FUNGI

It has long been known that certain fungi are specific to certain host genera with which they are frequently associated, e.g. Cortinarius hemitrichus with birch (Betula sp.) (Lange, 1923). Other fungi are more widespread in their relationships, although a fungus may be more physiologically compatible with some higher plants than with others.

As mentioned above, Redhead (1974) found that Rhizopogon luteolus on pine roots would not form an association with Afzelia species or Brachystegia, nor would the naturally occurring mycorrhizal fungi on these species form associations on pine. This was disappointing because the naturally occurring mycorrhizal fungi might have been better adapted to the tropical environment than the exotic Rhizopogon which Momoh (1972) found was unsuited to the prolonged dry season and high temperatures of Northern Nigeria.

Table 1 shows that a brown mycorrhizal fungus improved the dry weight of Brachystegia more than a white mycorrhizal fungus. Trappe (1977) gives data on the effects of four named mycorrhizal fungi on the growth of Tsuga heterophylla (Table 6).

Table 6: Effects of different mycorrhizal fungal inocula on mean oven-dry weight and top/root (T/R) ratio of seedlings of Tsuga heterophylla grown in tube containers for 6 months (from Trappe, 1977)

<table>
<thead>
<tr>
<th>Fungal inoculum</th>
<th>Weight (g)</th>
<th>T/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>No inoculum</td>
<td>0.74</td>
<td>2.89</td>
</tr>
<tr>
<td>Hebeloma crustuliniforme</td>
<td>0.97</td>
<td>2.69</td>
</tr>
<tr>
<td>Laccaria lacta</td>
<td>0.91</td>
<td>2.81</td>
</tr>
<tr>
<td>Pisolithus tinctorius</td>
<td>1.16</td>
<td>2.18</td>
</tr>
<tr>
<td>Thelephora terrestis</td>
<td>1.03</td>
<td>2.49</td>
</tr>
</tbody>
</table>

It seems a general phenomenon that under a given set of environmental conditions different fungi will show different responses on a particular higher plant. A special problem arises
with mycorrhizal fungi in African pine plantations because most, if not all, of these fungi are exotics, originally from Europe. Those that have been tested, e.g. *Rhizopogon luteolus* in Nigeria (Momoh, 1972), have been found to prefer temperatures well below the ambient temperatures of the lowland tropics, although they may be well suited at higher elevations. Research has begun at the University of Dar es Salaam, Morogoro, to identify the fungi forming mycorrhizal associations on pines in Tanzania and to find out which fungi are best suited to their environment. It may be found that other fungi could do much better e.g. some of the fungi from the natural pine forests of Central America.

**ENDOTROPHIC MYCORRHIZAL FUNGI**

The appearance of the VA mycorrhizal fungi within the root cortical cells is so similar over a range of plants and conditions that it was assumed for a long time that the response of the higher plant to the fungal association was the same in all cases. Experimental work by Mosse (1972) demonstrated that fungal strains varied in growth effects according to soil type, especially to pH.

The growth effects of seven different *Endogone* strains were compared using seedlings of onions and the tropical grass *Paspalum notatum* as test plants. Mosse found that the benefit of mycorrhizal infection depended greatly on the particular strain of *Endogone* used. The relative merit of a strain varied according to the soil and whether or not lime had been added.

Further experiments were carried out on rye-grass, using three different *Endogone* strains, with and without added lime. Establishment of two strains appeared to be pH dependent, while the third strain became established in two soils only, irrespective of pH. Mosse concluded that the effect on plant growth may depend more on interaction between a fungal strain and the soil than between a fungal strain and its partner.

There is need to identify the species of the family *Endogonaceae* in tropical soils, to multiply these in pot cultures (Mosse, 1959; Gilmore, 1968), and carry out tests on important crop plants growing in the major soil types. The matching of the most suitable strain to each crop plant and ecological
condition is a prerequisite to the use of inocula to obtain the best plant/fungus response under field conditions.

METHODS OF FUNGAL INOCULATION

ECTOTROPHIC MYCORRHIZAL FUNGI

Two recent review papers (Trappe, 1977; Marx, 1978) give accounts of inoculation methods used with ectotrophic mycorrhizal fungi.

The traditional method in the case of nursery-raised pine has been to add fresh topsoil from an established pine stand: usually a teaspoonful adjacent to the young seedling's roots is adequate. It is not even necessary to do this once a nursery has been used for several years because mycorrhizal root fragments remain in the soil from the previous year's stock. In areas surrounded by old stands the seedlings probably become infected from wind-borne spores also.

This method has the disadvantage that the fungus introduced, or often several different fungi, may not be the most efficient ecological partner. For instance, Marx (1978) reports that in the southern states of the U.S.A., the natural inoculation by wind-borne spores is often of the fungus *Thelephora terrestris*, whereas by *Pisolithus tinctorius* would lead to a much more efficient fungus/pine partnership. On average, *Pisolithus* gives a great improvement in height growth leading to fifteen percent less culls in the nursery. This represents a large financial gain when billions of pine seedlings are raised annually.

The use of soil containing mycorrhizal root fragments has another serious disadvantage in that it might carry pathogens. It is for this reason that plant quarantine regulations usually forbid the transfer of such soil between territories. The use of pure cultures was an attractive alternative and much effort has been put into this by several workers (Moser, 1958; Vozzo, 1966), but with varying success. The technique usually involved multiplication of the fungus in pure culture, either agar, peat moss or liquid culture containing mineral salts and sugars. When these media were used to inoculate pines in soil the results were often disappointing.
It is now known that the reason lay in the mycorrhizal fungi having poor saprophytic properties and poor competitive ability in comparison with a great many soil-inhabiting fungi. When the mycorrhizal fungus plus its food base is added to the soil, the soil saprophytes rapidly colonize the food source and inhibit or destroy the mycorrhizal fungus, possibly through fungistasis.

Marx (1978) has developed a technique for producing inoculum by growing fungi in a vermiculite and peat moss medium. The fungal hyphae ramify throughout this and penetrate between the lamina of the vermiculite.

Before use as an inoculum, the medium plus fungus is thoroughly washed in running water to leach out as much soluble nutrient as possible. The inoculum is not now a "ready meal" for soil saprophytes and the mycorrhizal fungus remains within the lamina of the vermiculite until it comes in close proximity to a pine rootlet, when it grows out and forms a mycorrhizal association.

The inoculum can be prepared in vats on a large scale and incorporated mechanically into the top layer of the seedbed soon after the routine methyl bromide sterilization has taken place. Seeds are then sown and as soon as the young rootlet contacts the vermiculite the association develops. This gives a high chance of inoculation by the culture before this can take place from airborne spores of other fungi.

Another method makes use of a spore inoculum. The basidiospores of many pine ectomycorrhizal fungi only germinate readily when in contact with a pine rootlet and the problem has been to ensure this contact in forestry practice. Marx and his colleagues are perfecting techniques to incorporate spores in a mixture of ground vermiculite and an adhesive, and to pellet seeds in a coating of this mixture. Such pelleted seeds can be sown mechanically and, after heavy irrigation, the adhesive breaks down to release the spores in close proximity to the emerging radicle. The sporophores of some fungi contain vast numbers of spores in a small bulk of material. Donald (1975) found $1.1 \times 10^7$ spores per gram of ground sporophores of *Rhizopogon luteolus* and Marx and Bryan (1975) report approximately $1.1 \times 10^9$ spores of
*Pisolithus tinctorius* per gram of basidiospores. Marx (1975) claims to have extracted twelve kilograms of basidiospores of *P. tinctorius* in less than twelve man-hours. Unfortunately not all spores are so easy to collect in these large numbers. Another serious disadvantage is that it takes several weeks to develop an extensive mycorrhizal association from spores. Use of a mycelial inoculum is usually a much quicker method for mycorrhizal establishment. These techniques are exciting new developments and could be modified for use in tropical nurseries.

**ENDOTROPHIC MYCORRHIZAL INOCULATION**

The VA mycorrhizal fungi will not grow in culture but only when in contact with a plant root. Mosse (1959) developed a method whereby *Endogone* sporocarps could be produced in large numbers and excised spores selected which, after surface sterilization, gave a high percentage of rapid germination. Typical VA mycorrhizal associations were established on seedlings grown aseptically on agar medium and inoculated with these spores. Other workers extracted spores from the soil and used these to produce typical mycorrhizal associations in test seedlings (Gerdemann, 1955, 1961, 1964, 1968; Gerdemann and Nicolson, 1963; Daft and Nicolson, 1966; Nicolson and Gerdemann, 1968). Inoculated seedlings when grown in open pots containing soil that has been previously sterilized, preferably by irradiation, produce masses of spores in the soil (Gilmore, 1968) which can then be used in experiments. Such pot cultures have become a standard procedure for maintaining living spore collections, a new culture being established periodically at intervals of six to twelve months.

The multiplication of specific species and strains of VA mycorrhizal fungi in pot culture permits their use as inocula in field trials. Such trials have been carried out on fumigated soils with crops of *Citrus*, peaches and soybean in the U.S.A. (Ross and Harper, 1970; Kleinschmidt and Gerdemann, 1972; LaRue et al., 1975). Inoculation improved the growth of all these crops. Field trials have also been made in Britain, New Zealand and Pakistan in marginal lands originally deficient in both phosphate and VA mycorrhizal fungi (Khan, 1972, 1975; Saif and Khan, 1977; Powell, 1977; Haymann and Mosse, 1978). The marginal lands in
Britain and New Zealand included hill pastures and in these areas inoculation was found to increase the establishment and growth of white clover. Nodulation of nitrogen-fixing bacteria and phosphate uptake were both enhanced.

Many tropical soils are deficient in phosphate and large growth responses could be expected subsequent to mycorrhizal inoculation with the most suitable mycorrhizal strains. This would also permit the relatively insoluble rock phosphate to be used as a phosphate fertilizer instead of the more expensive superphosphate.

Hayman (1978) lists several possible methods for inoculating field crops:

(i) **Pre-inoculated transplants** - On a practical scale crops normally transplanted to the field, e.g. tree crops, could be grown in containers with selected inoculum and their pre-transplant mycorrhizal status monitored.

(ii) **Soil or sievings from pot cultures incorporated into the drilling furrows** - This inoculum contains spores, hyphae and infected root pieces. It has been especially successful with experiments in fumigated soils where there was no competition from indigenous endophytes.

(iii) **Seed pelletting** - An adhesive such as methyl cellulose can be used to attach inoculum to individual seeds.

(iv) **Fluid drilling** - Germinated seeds and inoculum are suspended in a viscous medium such as dilute methyl cellulose and added to the planting furrows as a slurry.

(v) **Multi-seeded pellets** - Several seeds can be incorporated in a protective carrier material such as lignite mixed with sievings or soil from pot cultures.

(vi) **Highly infective soil** - The vesicular-arbuscular mycorrhizal population can be increased in a field plot by growing a heavily mycorrhizal crop there and using the top soil subsequently as a crude inoculum.

The first five methods involve raising large quantities of inoculum in pot cultures of mycorrhizal stock plants. Hayman (1978) comments that the longevity of these forms of inoculum
and methods of storing them, e.g. refrigerated sievings and lyophilized roots, need further investigation. In some situations infectivity might be increased in situ by pre-cropping with a strongly mycorrhizal crop.

SUMMARY OF RESEARCH RECOMMENDATIONS

Mycorrhizal research has reached the stage of application on a field scale and major benefits can be expected in tropical agriculture and forestry. Some of the priorities for research are as follows:

1. Field surveys
   (a) Surveys are required in savanna vegetation to ascertain which types of mycorrhizal association are represented. For example, in the miombo woodland, one of the world's most extensive plant formations, trees of the family Caesalpiniaceae dominate. Perhaps they have ectotrophic mycorrhizal associations that confer a competitive advantage.
   (b) Surveys of spores of species and strains of the Endogonaceae are needed from which pot cultures can be prepared for experimentation.
   (c) Fungi forming associations on exotic pines and possibly on eucalyptus should be identified and studies carried out on their growth requirements, especially temperature and pH.

2. Evaluation of fungus/plant combinations
   (a) Spores of the Endogonaceae and ectotrophic mycorrhizal fungi, found in the above surveys, should be tested on important crop plants over a range of site conditions.
   (b) Exotic pine mycorrhizal fungi should be selected by homoclinal comparison and evaluated on pines under field conditions.
   (c) Cultures of Eucalyptus mycorrhizal fungi should be obtained from their native Australia and tested on eucalyptus in the field.
3. Root studies

Root studies of important crop plants are needed, especially for crops that form components of agroforestry combinations.

4. Studies of the relationship between mycorrhizal fungi and nitrogen fixing bacteria

Studies are needed on crop plants such as beans and fodder plants such as Leucaena and Acacia.

5. Relationship of mycorrhizal association to disease

The effect of various ectotrophic mycorrhizal fungi on the incidence of damping-off in pine nurseries should be studied.

6. Inoculum preparation and use in field trials

Spore strains and mycorrhizal fungi selected under (2a) should be used in the development of methods suited to the field-scale preparation of inocula under tropical conditions. These inocula should be evaluated in nursery soils subject to fumigation and in lands deficient in available phosphate.

DISCUSSION

Poulsen: Eucalyptus regnans needs inoculation (in Ethiopia) and grows best on soils poor in P.

Redhead: Studies are needed on the mycorrhizal status of Eucalyptus spp. in Africa.

Pereira: Is it true that mycorrhiza can extract P from rock phosphate (fluorapatite)?

Redhead: There is no evidence that the hyphae have any property of dissolving the rock phosphate.

Dommergues: In the nursery, Melaleuca leucadendron is infected by an ectomycorrhiza (white sheath). Have you any idea of the most favourable soil pH for mycorrhizal infection and functioning?

Redhead: Abundant endomycorrhizae are found in soils with pH 4.5-7.0. Spores, if present, are likely to adapt to it.

Sánchez: Endomycorrhizae do not dissolve insoluble P forms but deplete P in soil solutions, causing an increase in soil solution P by shifting the equilibrium to the right. Is it so?


Pratt: Is P the only element involved or is it just the main one?

Redhead: P is most important, but mycorrhizae also absorb N and K efficiently.
LITERATURE CITED


THE EFFECT OF SOIL MICROORGANISMS ON PLANT PRODUCTIVITY

Y.R. Dommergues, H.D. Diem
and F. Ganry

ABSTRACT

Soil microorganisms affect plant productivity favourably or unfavourably either indirectly, by acting upon soil physical or chemical properties, or directly by interaction with plant roots. Beneficial or detrimental effects on soil properties concern structures, coating of particles with water-repellent compounds, redox potential, soil nitrogen status (e.g. gains by N₂ - fixation and losses through denitrification), availability of nutrients (especially N and P) and accumulation or elimination of phytotoxic inorganic and organic compounds. Soil microorganisms directly affect plant growth by improving or reducing nutrient or water uptake (some are well-known, e.g. ecto- or endo-mycorrhizae; others are not even characterized, such as microorganisms inducing proteoid roots). They may also produce growth-regulating substances or protect the plant against certain pathogens. Manipulation of the soil microflora appears to be highly desirable, but it is difficult to accomplish. Some success has already been achieved with direct inoculation, especially in the case of N₂ - fixers and mycorrhizae. Indirect control of soil microflora by methods involving classical means, sterilization or the application of specific compounds, is possible provided some requirements are fulfilled. Altering the soil microflora by acting through the plant is another promising possibility. The processes are discussed with special reference to their importance and occurrence in tropical soils.

Many agronomists today would readily agree that soil microorganisms affect plant productivity, especially in the tropics. Yet this idea took a long time to penetrate, except in the case of Rhizobium, because microbiologists were mainly concerned with the physiology of microorganisms that had been isolated and studied in test-tubes or Petri dishes and were therefore out of their natural environment. Another reason is that the study of the very complex soil-plant-microorganism systems is much more difficult that the study of pure culture.

In this paper, we shall consider some of the mechanisms by which soil microorganisms favorably or unfavorably affect

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plant growth by altering the soil physical or chemical properties, or by directly acting upon the plant itself. Since other contributors have covered the interactions between plants and mycorrhizae, or N\textsubscript{2} - fixing microorganisms, (Kenya, 1979; Redhead, 1979) we shall only briefly mention the role of those microorganisms, focusing our attention upon other groups whose influence is still not always recognized. Two preliminary remarks relate to the unique conditions that prevail in the tropics. First, when soil water content is not limiting tropical temperatures are generally high enough to allow much more vigorous microbial activity than in temperate areas. Second, since the organic materials that originate from the plant debris are only to a slight extent stored as humic compounds and are readily decomposed, most microbial life is located on or around the root system of the plants (rhizosphere).

INFLUENCE OF MICROORGANISMS ON SOIL PROPERTIES

EFFECTS ON SOIL PHYSICAL PROPERTIES

The role of microorganisms in the genesis and maintenance of soil structure has recently been reviewed (Hepper, 1975). Our aim here is to emphasize the importance of this process in the rhizosphere. It has been demonstrated that there are more water-stable aggregates in the rhizosphere than in the non-rhizosphere soil (Harris et al., 1964). Since the number of polysaccharide-producing microorganisms is characteristically higher in the rhizosphere, it can be assumed that soil stabilization around the root can, at least to some extent, be due to the rhizosphere microflora. In tropical soils, where most of the microbial population is concentrated in the root zone, it would be worthwhile to elucidate the relative importance of the root itself and that of associated microorganisms in soil structure stabilization. Such investigations should not be restricted to free-living microorganisms, (such as Azotobacter spp., Beijerinckia indica or Lipomyces starkeyi, which are well-
known polysaccharide producers), but should be extended to mycorrhizae which were reported to be involved in sand aggregation and dune stabilization in colder climates (Koske et al., 1975). In contrast to this beneficial activity, microorganisms can be harmful in two ways: by decomposing the aggregating compounds originating from plants or microorganisms; and by coating soil particles with water-repellent films (Bond, 1964; Bond and Harris, 1964). By altering the advancing contact angle of water with the particles such films disturb the infiltration of water into the soil, inducing a patchy distribution of plants and a marked loss of productivity. Water repellency, which was mostly attributed to basidiomycete hyphae, is thought by Griffin (1969) to be of potentially wide importance, especially in semi-arid conditions.

Microorganisms may also alter the soil redox potential. Thus the growth of aerobic microorganisms, most of which grow at the expense of decaying plant debris, may lead to a reduction in the plant. Alternatively, photosynthetic algae can produce oxygen and raise the redox potential, thus acting directly or indirectly upon the plant.

NITROGEN GAINS AND LOSSES THROUGH BIOLOGICAL PROCESSES

The process of symbiotic N₂ fixation has already been reviewed (Keya, 1979), but mention should be made of the effect of limiting factors, an aspect often overlooked. Besides the possible inadequacy of native N₂-fixing micropopulations and the attacks of pathogens, especially nematodes (Germani, 1979), four major factors can limit symbiotic N₂ fixation in the tropics: moisture stress (especially in semi-arid conditions), soil acidity and associated toxicity, mineral deficiencies and, in some situations, an excess of combined nitrogen in the soil (Table 1). As long as one limiting factor is operating N₂ fixation is low or nil and the input of nitrogen to the ecosystem negligible or non-existent. Two examples will illustrate the unfavourable effect of limiting factors. These examples are related to peanut and result from field experiments.
Table 1. Methods to control the effects of environmental factors limiting symbiotic $N_2$ fixation

<table>
<thead>
<tr>
<th>Limiting factors</th>
<th>Methods of control</th>
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<tbody>
<tr>
<td>1. Moisture stress</td>
<td>- Irrigation</td>
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<td></td>
<td>- Search for drought-resisting cv. of legumes and drought-resisting <em>Rhizobium</em></td>
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<td></td>
<td>- Stimulating VA mycorrhizal infection</td>
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<td>2. Soil acidity and toxicity</td>
<td>- Liming</td>
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<td></td>
<td>- Addition of organic matter</td>
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<tr>
<td>3. Mineral deficiencies, especially phosphorus deficiency</td>
<td>- Addition of phosphorus</td>
</tr>
<tr>
<td></td>
<td>- Stimulating VA mycorrhizal infection</td>
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<tr>
<td>4. Soil inorganic nitrogen</td>
<td>- Split application of nitrogen fertilizers</td>
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<td></td>
<td>- Slow-release nitrogen fertilizers</td>
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<tr>
<td></td>
<td>- Use of compatible fertilizers</td>
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<tr>
<td></td>
<td>- Search for legumes with a lower capacity for nitrate assimilation</td>
</tr>
<tr>
<td>5. Pathogens</td>
<td>- Chemical, biological or integrated control</td>
</tr>
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<td></td>
<td>- Crop rotations</td>
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</table>
carried out at the Bambey Experimental Station in Central Senegal during the last 3 years. The first is illustrated by Fig. 1, which shows that in the arid conditions prevailing in Central Senegal, N\textsubscript{2} fixation (measured by the acetylene assay) is closely related to soil water content. The second example concerns the limiting effect of inorganic nitrogen. Using the A value method, (Ganry, 1976), found that by increasing the rate of application of nitrogen fertilizer from 15 to 60 kg per ha, N\textsubscript{2} fixation by peanut decreased from 52 to 25 kg per ha. In spite of those limitations, some N\textsubscript{2} - fixing systems can remain active. For example, *Casuarina equisetifolia*, a non-leguminous nodule-bearing tree, largely used for reforesting sandy soils on the coast of West Africa, was reported to fix as much as 60 kg N\textsubscript{2}ha\textsuperscript{-1} year\textsuperscript{-1} on the Cap-Vert peninsula (Dommergues, 1963).

Microorganisms can bring about losses through nitrification and denitrification. The activity of nitrifying bacteria varies considerably according to the soil characteristics and to the nature of the vegetation. These bacteria are typically neutrophilic but nitrification is not necessarily restricted to neutral soils, but to the neutral micro-habitats. Since such habitats may occur (e.g. in the vicinity of organic debris) in soils whose overall pH is acid, nitrification can be very active in such soils. Thus acid tropical soils grown with banana, maize, or rain-fed rice exhibit a high nitrifying activity when ammonium fertilizer is applied. (Dommergues et al., 1978; Chabalier, 1978). In forest soils, nitrification may be hindered by antibacterial substances released by the litter; when the forest is cleared, a flush of nitrification usually occurs (Dommergues, 1954). There is increasing agreement that nitrification is a detrimental process since it is responsible for two types of nitrogen loss: through leaching, since nitrate is of an anionic nature, and through denitrification (Focht and Verstraete, 1977). Such losses are highly variable, but they are seldom lower than 20-30 per cent of the nitrogen applied as fertilizer. The increased cost and shortage of fertilizer nitrogen, especially in the tropics, must prompt soil microbiologists to gather more information on factors that could
Fig. 1: Variations of acetylene reducing activity (ARA per plant) of field-grown peanut and of soil water content throughout the peanut growth cycle as observed in 1977 at the Bambey Experimental Station, Central Senegal (Ducerf, 1978)
limit nitrification in soils, since this process is presumably more easily controlled than denitrification. Recent advances in the field of methodology (especially direct detection of bacteria in the soil by the fluorescent-antibody techniques) promise to be most helpful (Schmidt, 1978).

**AVAILABILITY OF NUTRIENTS**

In tropical soils ammonification is usually very active, so that the potential for the release of ammonium from soil organic nitrogen is high. Unfortunately, the organic nitrogen inputs (through N₂ fixation, root and litter deposition) into the soil are often limited, so that ammonium release is not high enough to meet the plant's requirements. It is not clear whether nitrate, which is the end product of nitrification, is more available to plants than the ammonium ion.

Microorganisms, especially those thriving in the rhizosphere, are often thought to be able to increase the phosphate available to plants by dissolving water-insoluble mineral phosphate, or by mineralizing phosphate from soil organic matter. As far as mycorrhizae are concerned, their role as solubilizing agents has not yet been demonstrated. Other soil microorganisms might be involved. *In vitro* experiments have clearly shown that many common microorganisms, including *Pseudomonas*, *Achromobacter*, *Flavobacterium*, *Streptomyces*, and especially *Aspergillus* and *Arthrobacter* can solubilize soil phosphorus (Hayman, 1975; Barber, 1978). However some authors argue that the increased uptake of phosphate may not only result from an increase in the availability of phosphate, but could also be explained by the effect on plant growth of stimulating substances synthesized by the micro-organisms. With regard to organic phosphate, it is readily mineralized by plant phosphates of the root surface. The soil microflora do not seem to increase this process significantly.
Microbially-induced changes of available trace elements have recently been discussed (Bawber, 1978). Since a variety of microorganisms, as well as plants, synthesize some hydroxamic acids known to be powerful chelating agents, it is not surprising that soil microorganisms play a prominent role in the iron metabolism of plants (Waid, 1975). A classical example of the decreased availability of trace elements is that of manganese. Manganese deficiency of oats was shown to occur when the activity of manganese-oxidizing microorganisms was too high. Soil fumigation reduced the population of these microorganisms and eliminated the manganese deficiency symptoms (Timonin, 1946).

SOIL TOXICITY

Phytotoxic compounds that may accumulate in the soils are of microbial or plant origin. A classical example of phytotoxicity induced by microorganisms is that of hydrogen sulphide produced by sulphate-reducing bacteria. The growth and activity of these bacteria is triggered in the rhizosphere when the following environmental conditions exist concurrently: active root exudation, soil sulphate content of the rhizospheric soil above a minimum threshold, and strict anaerobiosis. Accumulation of hydrogen sulphide can be high enough to lead to the death of plants (Dommergues et al., 1976; Jacq and Roger 1978). Manganese toxicity which occurs in acid soils that are relatively rich in manganese may be reinforced by rhizosphere microorganisms capable of reducing manganic sources. Partial sterilization of such soils may prevent toxicity (Barber, 1978).

Phytotoxic compounds of plant origin are responsible for diminishing plant growth when they are not decomposed. Many examples of such toxic effects have been described by Rice (1974). Recently, investigations carried out at the Agronomic Research Center of Bambey in Central Senegal showed that sorghum roots contained phytotoxic compounds which, in some circumstances, could significantly reduce the yield of subsequent crops, especially sorghum. When sorghum is grown once in a two-course rotation (peanut-sorghum) instead of once in a four-course rotation (green manure-peanut-sorghum-peanut) yields are severely depressed.
Such a deleterious effect, (known as "soil sickness") is induced by the accumulation in the soil of a phytotoxic compound after the first crop. The phytotoxic compound, which is specifically inhibitory to sorghum, remains in the soil as long as environmental conditions prevent its biodegradation by soil microorganisms. Since such unfavorable conditions may prevail in sandy soils for seven to eight months, the phytotoxic compounds are still present when sorghum is re-sown too soon after its last cropping. It should be pointed out that while "soil sickness" does occur in sandy soils containing kaolinite-type clays and showing a poor microbial activity, no symptoms are noted in Vertisols, which contain montmorillonite-type clays and where microorganisms are significantly more active. In Vertisols, the sorghum microflora comprising strains that can actively decompose the phytotoxic compound (Dommergues, 1978b).

Another example of phytotoxicity of importance in forestry is related to the failure of Grevillea robusta regeneration in Australia. Seedlings of this species were reported to be killed by some water-transferable factor associated with the roots of parent trees. The resulting regulation of population in G. robusta is thought to explain the maintenance of floristic diversity in complex tropical rain forests (Webb et al., 1967).

DIRECT EFFECTS ON THE PLANT

As the root grows through soil, it encounters diverse components of the soil microflora and it is directly affected by the activity of soil microorganisms. Rhizoplane and rhizosphere populations affect the host plant in many ways, but there is now increasing evidence that the most important effects of microorganisms on plant growth concern the modification of plant nutrition and water uptake, the production of growth-regulating substances and the protection of roots against pathogens.

MODIFICATION OF PLANT NUTRITION AND WATER UPTAKE BY MYCORRHIZAE

The best example of the role of microorganisms as regulating agents of plant nutrition is illustrated by mycorrhizal asso-
citations. The plant's main response to mycorrhizal infection is an increased uptake of nutrients, especially phosphorus. Mineral nutrition of plants as stimulated by ectomycorrhizae has been well treated by Bowen (1973) and the effects of vesicular-arbuscular mycorrhizae (VAM) have been reviewed by Tinker (1975), Redhead (1979) and others.

Many theories have already been proposed to explain the increased uptake of phosphorus by ectomycorrhizal roots (Bowen, 1973). Some of them could apply to VAM since Gerdemann (1968) considers that the function of VAM may also be very similar to that of the ectomycorrhizae.

It includes the formation of more efficient nutrient-absorbing structures than non-mycorrhizal roots. The extensive strands of extramatrical hyphae in VAM may also explore a much greater volume of soil than non-infected roots, as do hyphae of ectomycorrhizal fungi. The possibility of a longer active absorbing life for mycorrhizal as compared with non-mycorrhizal roots, as stated by Bowen and Theodorou (Bowen, 1973) for ectotrophic mycorrhizae, should also apply to VAM (Gerdemann, 1968), although actual evidence is still lacking. Another interesting facet of the biology of mycorrhizae is related to the behaviour of infected roots under low water regimes in the soil. Tropical soils are quite different from one another in water content because there is a wide range of soil textures and climates in the tropics.

In sandy soils, especially in semi-arid regions, plants are often subjected to a relatively long period of water stress. A most interesting question is whether soil water supplies could be improved by mycorrhizae. The physiology of water absorption by mycorrhizae has hardly been studied but some investigations have indicated a greater drought resistance in a number of mycorrhizal seedlings (Bowen, 1973).

In 1971, Safir et al. indicated that VAM could probably decrease the resistance to water transport in soybean. But later (Safir et al., 1972) they concluded that increased plant growth in water-stressed conditions was due to the improvement of phosphorus nutrition. Recently, however, Menge et al. (1978) have reported that mycorrhizal infection enabled avocado plants to resist transplant shock, suggesting that mycorrhizae could
improve water uptake by the host-plant. Drought resistance of mycorrhizal plants may be related to the greater exploitation of soil by extensive hyphal growth, but also to large differences between infected and non-infected roots in their own biology. As stated by Cromer (in Bowen, 1973), mycorrhizal roots of *Pinus radiata* seemed to renew growth more quickly than non-infected roots when they are subjected to severe water stress. Another interesting hypothesis on the relationships between soil-water regime and mycorrhizal infection is given by Sieverding (in Moawad, 1978) who found that the amount of water used to produce 1g of dry matter was much lower in mycorrhizal than in non-mycorrhizal plants growing in dry soil fertilized with Ca₅(PO₄)₃OH (Table 2). According to Moawad, Sieverding's findings may simply be due to the better utilization of water by plants growing in phosphorus-deficient soils. If we wish to explain the greater drought resistance of plants, the theory of water consumption economy as stated above seems to be more plausible and more attractive than the principle of increased uptake or transport of water in plants (Safir *et al.*, 1971).

**MYCORRHIZAE UNDER TROPICAL CONDITIONS**

The impact of mycorrhizal symbiosis in the growth of tropical plants has been recently discussed by Bowen (1978) and Black (1978). Black noticed that the number of tropical plants associated with ectomycorrhizae appears to be very limited as compared to the wide range of ectomycorrhizal plants in the temperate region. The only crop recorded with ectomycorrhizae is *Pinus* (Redhead, 1978). Inventories and other information concerning ectomycorrhizal forest trees are given in Alwis and Abeynayake (1978).

As for endomycorrhizae, although some families such as *Casuarinaceae*, *Chenopodiaceae*, *Urticaceae* are devoid of VAM (Khan, 1974), most tropical plant species of economic importance are infected: cocoa, tobacco, cotton, corn, sweet potato, peanut, sugar cane, sorghum, rubber, tea, citrus and many species of timber trees (Redhead, 1978). Spores of VAM
Table 2. Water consumption (expressed in ml/g dry weight) by *Eupatorium odoratum* L. and *Tagetes erecta* L. at two levels of soil water content (80 and 20% available water) and with two forms of P (after Moawad, 1978).

<table>
<thead>
<tr>
<th>Plant Species</th>
<th>Mycorrhizal treatment</th>
<th>Ca$_2$(H$_2$PO$_4$)$_2$·H$_2$O</th>
<th></th>
<th>Ca$_5$(PO$_4$)$_3$·OH</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>80%</td>
<td>20%</td>
<td>80%</td>
<td>20%</td>
</tr>
<tr>
<td><em>E. odoratum</em></td>
<td>NM</td>
<td>1208</td>
<td>1207</td>
<td>2860</td>
<td>4112</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1237</td>
<td>1177</td>
<td>1574</td>
<td>1436</td>
</tr>
<tr>
<td><em>T. erecta</em></td>
<td>NM</td>
<td>1073</td>
<td>1005</td>
<td>2563</td>
<td>3397</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>923</td>
<td>1060</td>
<td>1180</td>
<td>1424</td>
</tr>
</tbody>
</table>

NM: Not inoculated with VA mycorrhiza
M: Inoculated with VA mycorrhiza
are widely distributed in Nigerian soils from the moist lowland forest to the dry Sahel and Savanna regions (Redhead, 1977). A few olive specimens (e.g. *Olea cuspidata*) may also be infected by both ectomycorrhizal and endomycorrhizal fungi. The significance of mycorrhizal symbiosis in the cultivation of olives in Pakistan has been discussed by Khan and Saif (1973).

In different soils of the arid and semi-arid regions, it is probable that mycorrhizal associations play an important part in the growth and drought-resistance of a number of plants because of their ability to regulate uptake of nutrients and soil water. Unfortunately, little is known about the mycorrhizal response of plants usually growing under dry conditions. Studies of mycorrhizal effects in these regions of the world would be of great practical interest, particularly in the case of afforestation with plant species that usually are transplanted. In our laboratory, observations of the roots of *Azadirachta indica*, a tree whose growth is wide-spread in dry sandy soils in Senegal, indicate that most roots, if not all, are infected with VAM (Fig. 2). It is significant to note that *Azadirachta indica* is able to grow vigorously in non-fertilized soils and in arid conditions.

**EFFECT OF VAM INFECTION ON LEGUME-RHIZOBIUM SYMBIOSIS**

According to a number of papers VAM also occur in many tropical legumes of economic importance e.g. peanuts, cow-pea, *Macroptilium atropurpureum*, *Stylosanthes* spp. (Possingham et al., 1971; Sanni, 1976; Graw and Rehm, 1977). As legumes have been shown to require high levels of phosphate for nodulation, it is likely that mycorrhizal infection may affect the nodulation process and also even N₂-fixation. Many authors have already explored this facet of mycorrhizal response in legumes (Crush, 1974; Islam et al., 1976; Mosse et al., 1976; Smith and Daft, 1977). Recently, in an excellent essay on the role of mycorrhizae in legume nutrition on marginal soils, Mosse (1977) summarized our knowledge on this subject and reported evidence that endomycorrhizal inoculations associated with the supply of rock phosphate stimulated growth and nodulation of many legumes. Although the principal cause of this is undoubtedly
Fig. 2: *Azadirachta indica* roots infected with VA mycorrhizae
increased assimilation of phosphate, Mosse considers that mycorrhizae may have other secondary effects, possibly of a hormonal nature.

MICROBIALLY INDUCED PROTEOID ROOTS

Mycorrhizal associations are not the only process that stimulates the phosphorus nutrition of host plants. Despite resistance of several lupin species to mycorrhizal infections, they are, nevertheless, able to grow in sandy soils that are highly deficient in phosphorus. The ability of lupin to absorb soil phosphate has been attributed to the formation of clusters of rootlets in localized parts of the lupin root system. These clusters of rootlets resemble the dense clusters known as proteoid roots which have been described in the family of Proteaceae by Purnell (in Trinick, 1977). Other proteoid roots have also been recorded by Lamont on Viminaria juncea and by Malajczuk on Kennedia (Trinick; 1977). It has now been shown that proteoid roots play an important role in the phosphorus nutrition of plants due to their increased absorbing ability as compared with normal roots (Jeffrey, 1967; Malajczuk and Bowen, 1974).

According to published literature, very few plant species form proteoid roots. In Senegal, one of the authors (H.G.D.) observed that rootlet clusters similar to proteoid roots can be found in Casuarina equisetifolia usually growing in sandy and deficient soils. In the cluster, lateral rootlets are so numerous that they resemble fingers (Fig. 3). Proteoid roots could therefore provide C. equisetifolia with an alternative system to mycorrhizae for increasing P uptake from deficient soils. Investigations are now in progress in our laboratory to demonstrate the effects of these root formations on the physiology of this species. Although the mechanisms of the initiation of proteoid roots are not clear, some inoculation experiments indicate that proteoid roots may be induced by microorganisms colonizing the root surface (Malajczuk and Bowen, 1974).
Fig. 3: Cluster of rootlets (proteoid roots) of *Casuarina equisetifolia* growing in a sandy soil (Senegal)
EFFECT ON PLANT GROWTH OF PHYTOHORMONE-PRODUCING MICROORGANISMS

As microbial numbers and activity are more intense in the rhizosphere than in soil it hardly seems conceivable that the development of rhizosphere microflora would not directly affect the development of roots. Microbial effects may be detrimental to root growth: for example roots of tomato, subterranean clover and Radiata pine were stunted by the presence of soil microorganisms (Rovira and McDougall, 1967). However, particular attention has been paid to the beneficial effect exerted by rhizosphere inhabitants. Typical rhizosphere bacteria such as *Arthrobacter*, *Pseudomonas* and *Agrobacterium* were found long ago to be able to produce substances promoting plant growth (Krasilnikov, 1958).

Ectomycorrhizal fungi also provide the host plant with phytohormones and growth-regulating B vitamins (Slankis, 1973). Detailed discussion about the direct effects of bacteria on root growth through the production of plant growth-regulating factors can be found in many reviews (Krasilnikov, 1958; Katnelson, 1965; Brown, 1975). The influence of ectomycorrhizal hormones on the development of roots of the host plant has also been amply demonstrated in Slankis (1973). However, instances of increased plant growth resulting from interactions between soil microorganisms and plants show that when plants are artificially inoculated with a particular microorganism known for a determined biological activity (e.g. *N₂* fixation; phosphorus solubilization), stimulation of plant growth often was putatively attributed to the effect of this specific activity, although it may simply be due to the production of phytohormones by the same microorganism. Three examples found in different fields reinforce this point of view: (1) Thirty years ago, Gerretsen (1948) thought that the increased growth of plants in sterilized sand containing insoluble phosphate compounds was due to inoculation with solubilizing phosphate bacteria. This conclusion is now criticized by Brown (1975) who attributes the improved growth reported by Gerretsen to the production of gibberellin-like substances by the bacteria used for inoculation. (2) Increases in plant growth and crop
yields have often been recorded after inoculation with *Azotobacter*, but it is now well known that these effects are caused, not by fixation of significant amounts of N₂, but by the production of small amounts of highly active growth-promoting substances by the bacteria (Brown, 1975). Similarly, inoculation with *Azospirillum brasilense*, a free living N₂-fixing bacterium, can also induce increased plant growth. Table 3 shows that growth of the aerial parts of rice were as actively stimulated by inoculation with a non-N₂-fixing bacterium as with *A. brasilense*, and that root growth was even more actively stimulated. Moreover, since inoculation with *Azospirillum* generally does not significantly improve N₂ fixation, Gaskins and Hubell (1978) and Tien et al. (1979) suggested that the effect of *Azospirillum* inoculation on plant growth could be due to growth-stimulating substances produced by this bacterium, as in the case of *Azotobacter*. (3) In some experiments of biological control, root disease of wheat associated with *Rhizoctonia solani* was reduced and grain yield increased by seed inoculation with bacteria and actinomycetes. Merriman et al. (1974) suggested that the yield increases are primarily due to plant growth-stimulating factors rather than to the biological control of root disease.

**Improvement of Plant Resistance to Infection**

Discussion will be restricted to the control of pathogens through the improvement of plant resistance by symbiotic microorganisms or microorganisms more or less loosely associated with the roots, which is only one aspect of the vast problem of biological control. Two types of mechanisms may be involved in the type of control studied here.

In his review, Marx (1975) indicated that if pine roots were associated with *Leucopaxillus cerealis* var. *piceina* to form ectomycorrhizae, they became resistant to infections caused by such pathogenic fungi as *Phytophthora cinnamomi*. Many mechanisms could be involved to explain the protective role of ectomycorrhizal pine roots. Apart from the explanation that antibiotic production inhibits fungal pathogens (Marx, 1975), the fungal mantle of ectomycorrhizae also creates effective
Table 3. Influence of rice inoculation with *Azospirillum brasilense* (Sp 7), a pectinolytic bacterial strain (Pect.) which did not fix N\(_2\), and a mixture of both strains, upon the dry weight of aerial parts or roots of 17 day-old rice seedlings grown in a sterile alluvial soil (Expt. 1) or a mixture of the same soil and coarse sand (Expt. 2) (Fauthier and Rinaudo, unpublished data, 1979).

<table>
<thead>
<tr>
<th></th>
<th>Dry weight of aerial parts (mg)</th>
<th>Dry weight of roots (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expt. 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>62</td>
<td>125(^{xxx})</td>
</tr>
<tr>
<td>Expt. 2</td>
<td>173</td>
<td>196(^{xxx})</td>
</tr>
</tbody>
</table>

n.d. = non-determined

\(x, xx, xxx\) value significantly different from control, \(P = .05, P = .01, P = .001\), respectively.
mechanical barriers against penetration by *P. cinnamomi*. There was further evidence that fungal mantles formed by non-antibiotic-producing ectomycorrhizal fungi also protected roots from pathogenic root infections. It is also suggested that endophytic mycorrhizae may provide plant protection (Wilhelm, 1973). In this case, there is no physical barrier, but early territorial occupation of living root tissues by the endophyte may promote biological control.

In the presence of saprophytic microflora many plants produce a multitude of compounds, especially the so-called phytoalexins, which can play a role in root disease resistance. Most have been identified in aerial plant parts, but it is likely that the same compounds can also be formed in the root system (Paxton, 1975). For instance, pisatin, the well-known phytoalexin of the pea plant, occurs in the roots as well as in most other parts of the plant and has a wide spectrum of antibiotic activity. Strawberry roots also produce phytoalexins in response to *Phytophthora fragariae* infections (Mussell and Staples, 1971).

**MANIPULATING THE SOIL MICROFLORA**

Since the major part of the soil population in tropical conditions is made up of the rhizosphere microflora, and since the rhizosphere microflora must be viewed as a component of the whole soil-plant-atmosphere system (Dommergues, 1978a), the soil microflora could predictably be manipulated, not only directly by acting upon the microorganisms, but also indirectly by acting upon the soil and the plant. Direct manipulation of the soil microflora can be achieved by inoculation practices, sterilization and the application of specific inhibitors or specific substrates. Indirect manipulation of the soil-plant-atmosphere system can be achieved by classical or non-conventional soil management practices, or by acting upon the plant component itself.
INOCULATION

In spite of the fact that root colonization by non-pathogenic microorganisms is still poorly understood, soil microbiologists and agronomists have been trying for many years to alter the rhizosphere microflora by introducing selected microbial strains, either by coating seeds with an inoculum, or by placing the inoculum into the soil close to the seed or the seedling.

The value of legume inoculation is well recognized, provided that the strain used is highly effective and efficient in its symbiosis with the selected legume cultivar, that it is a good colonizer of the roots and is able to compete with any native root microorganism, and that the proper environmental prerequisites are fulfilled. However, legume inoculation by classical methods is not always fully satisfactory.

The value of ectomycorrhizal inoculation is also generally acknowledged as long as the proper environmental conditions are met (e.g. Hacskaylo, 1972; Marx and Krupa, 1978). Inoculation by endomycorrhizae is currently at the experimental stage except in special situations. Preliminary reports suggest that larger responses are more likely in tropical regions than in temperate regions, because of higher temperatures and the naturally low-phosphorus level of soils (Hayman, 1978).

Recent experiments carried out in the northern coastal area of Senegal have shown that inoculating Casuarina equisetifolia with crushed nodules improved that plant's growth markedly (Dubreuil and Andeque, personal communication). Further investigation on the endophyte of Casuarina is needed in order to improve the current method of inoculation, which is obviously hazardous since crushed nodules used as inoculum may carry pathogens.

Although techniques of inoculation with typically symbiotic microorganisms (e.g. Rhizobium) are already in use in the field, or could be used in the near future (e.g. endomycorrhizae), techniques of inoculation with loosely symbiotic or non-symbiotic microorganisms (e.g. rhizosphere N2 fixers or phosphate-solubilizing bacteria) cannot yet be safely recommended.
The first attempts at using N₂-fixing rhizosphere bacteria to inoculate grasses or cereals were made as early as 1902 (Rubenchick, 1963). Since that date many experiments have been performed, at first with Azotobacter or Beijerinckia and later with Azospirillum (e.g. Smith et al., 1976; Dobereiner, 1977). Yield increases have sometimes been reported but up to now results have generally been inconsistent.

Field experiments with phosphate-solubilizing bacteria (especially Bacillus megaterium) have not shown any consistent effect on plant yield. According to Barber (1978), "this lack of response is not really surprising for two reasons. Firstly, since a considerable proportion of soil phosphorus is present in organic compounds and up to 90% of the rhizosphere microflora are capable of producing phosphatases, the introduction of other organisms, which would have to compete for available carbon sources, is unlikely to cause any increase in the supply of phosphate to plants. Secondly, the inoculum used, Bacillus megaterium var phosphaticum is a spore-forming bacterium and such organisms grow far less readily in the rhizosphere than do other types of bacteria".

When stimulation of plant growth consecutive to inoculation by N₂ fixers or phosphate-solubilizing bacteria has been observed, it could not be explained by N₂ fixation, nor by an increase of phosphate solubilization. The stimulation of plant growth probably has resulted, at least in part, from the effect of growth substances produced by the microorganism's added with inoculum, as already mentioned above. In spite of some recent improvements in the preparation of the inoculum itself (Dommergues et al., 1979) or in the introduction of mixed cultures (Dommergues et al., 1978), there would seem to be no easy solution to the difficulties that arise when attempting to inoculate non-sterile soils.

Soil sickness can result from the presence of plant residues in the soil, especially root litter containing phytotoxic substances. Inoculating such soils with microorganisms that actively decompose the root litter appears to be a promising approach to curing these soils. Thus inoculating a ferrallitic sandy soil that contained phytotoxic root debris with Enterobacter
clos. restored soil fertility (Table 4). Phytotoxic sub-
stances, pre-existing in plant residues or formed during decom-
position, can possess a broad spectrum of effects that are
injurious to the roots and stems of plants (Toussoun and Patrick,
1963). Such a deleterious effect could probably be reduced by
soil inoculation with proper microbial strains.

SOIL STERILIZATION AND APPLICATION OF SPECIFIC COMPOUNDS

In sterilization by heating, irradiation and drying is
used in certain circumstances, sterilization is often achieved
by fumigation with such chemicals as chloroform, carbon-sulfide
methylbromide or chloro-picrin. Such treatments often improve
plant growth even in the absence of pathogens (Wilhelm, 1966;
Rovira, 1976). This beneficial effect can be attributed to
different causes: chemical modifications, especially increase
of NH4 content, flush of organic matter decomposition, including
dead microorganisms (Anderson and Domsch, 1978), elimination of
nitrifying bacteria, which are particularly vulnerable to fumi-
gation (Jenkinson and Powlson, 1976), and re-colonization of soil
by non-pathogenic microorganisms, especially pseudomonads, which
are thought to stimulate plant growth (Ridge, 1976).

Soil sterilization prior to inoculation with mycorrhizae
appears to be most helpful in special situations (Lamb and
Richards, 1978). Among these are fumigated nursery soils where
severe stunting of citrus was reported: inoculation with
vesicular-arbuscular-mycorrhizae appeared to be the best method
to overcome this stunting (Lamb and Richards, 1978; Timmer and

Among the different specific inhibitors that have been studied
(e.g. Anderson and Domsch, 1975), nitrification inhibitors have
received much attention because of their possible use in the field.
Besides the agronomic practices mentioned above, inhibitors such
as 2-chloro-6- (trichloromethyl)-pyridine have been successfully
used to inhibit nitrification, thus increasing the efficiency of
nitrogen-fertilizers by reducing de-nitrification and leaching
of the nitrate ion. Unfortunately, especially in tropical conditions,
the inhibitor is readily decomposed by the soil microflora so
Table 4. Influence of soil inoculation with *Enterobacter cloacae* on the growth and nitrogen content of sorghum grown in either a phytotoxic or a non-phytotoxic soil (Burgos, University Nancy thesis, 1979)

<table>
<thead>
<tr>
<th></th>
<th>Phytotoxic soil</th>
<th>Non-phytotoxic soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No inoculation</td>
<td>With inoculation</td>
</tr>
<tr>
<td><strong>Aerial parts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>30</td>
<td>65</td>
</tr>
<tr>
<td>Dry weight (g per plant)</td>
<td>0.5</td>
<td>3.9</td>
</tr>
<tr>
<td>Total N content (mg per plant)</td>
<td>13.9</td>
<td>48.7</td>
</tr>
<tr>
<td><strong>Roots</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry weight (g per plant)</td>
<td>0.6</td>
<td>8.2</td>
</tr>
</tbody>
</table>
that nitrification occurs before plant requirements for nitrogen are at their peak. Another reason for the restricted use of nitrification inhibitors is their price. However some inexpensive substitutes have been proposed, such as neem cake (made of the seeds of Azadirachta indica), but this material is not as effective as 2-chloro-6 (trichloromethyl)-pyridine (Prasad and de Datta, 1978).

The stimulation of a given component of the microflora can be achieved by adding a specific substrate to the soil. A classical example is that of the selective multiplication of actinomycetes in a soil amended by chitin, Streptomycetes, and to a lesser extent Nocardia, constituting the bulk of the chitin-decomposing microflora (Alexander, 1961).

Another example is that of the solubilization of rock-phosphate by Thiobacilli. These chemoautotrophic bacteria are introduced into the soil together with sulphur which is oxidized to sulphuric acid, thus dissolving the phosphate (Swaby, 1975).

FERTILIZATION AND SOIL MANAGEMENT

Inoculation even with specific microorganisms, especially Rhizobium, is unsuccessful when one of the limiting environmental factors listed in Table 1 is still operating. Therefore, improvement of environmental conditions is a pre-requisite that can be achieved by different soil management practices, such as irrigation, liming, application of organic amendments or slow-release fertilizers. The beneficial effect of liming is illustrated by Table 5 (Expt. 1) which reports on a study of soybean nodulation in a ferrallitic acid soil from Casamance, Senegal. The increased nodulation was attributed to the elimination of Mn and Al toxicity of liming. Table 5 (Expt. 2), shows that the application of organic matter even at low rates (400 kg of peat per ha) favourably affected the growth and nodulation of soybean. This last result confirms those obtained by Dart et al., 1973 with Vigna mungo and V. radiata. Neither species grew well in a nitrogen-free sand-grit mixture. But adding 10% of Kettering loam by volume improved growth and nodulation. When added loam had been previously ignited at 450°C for 4 h to remove soil organic matter, plant growth was
Table 5. Effect of addition of CaCO₃, or sterile peat, on nodulation and dry weight of aerial parts of soybean cv. Chippewa (Boureau, unpublished data, 1979)

<table>
<thead>
<tr>
<th>Expt.</th>
<th>pH</th>
<th>Nodule number (per plant)</th>
<th>Nodule dry weight (mg per plant)</th>
<th>Dry weight of aerial parts (mg per plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0 a</td>
<td>14 a</td>
<td>42 a</td>
<td>3.38 a</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₃ (2500 kg per ha)</td>
<td>7.0 b</td>
<td>39 b</td>
<td>112 b</td>
<td>3.78 a</td>
</tr>
<tr>
<td>2</td>
<td>4.0 a</td>
<td>28 a</td>
<td>44 a</td>
<td>2.16 a</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat (400 kg per ha)</td>
<td>4.0 a</td>
<td>41 b</td>
<td>88 b</td>
<td>3.03 b</td>
</tr>
</tbody>
</table>

One plant per pot containing 5 kg of soil from Sefa Research Station, Senegal. All plants were inoculated with 1 ml of a 3-day old culture of *Rhizobium japonicum* G2Sp (10⁸ bacteria per ml). Observations were made when plants were 6 weeks old. In each experiment, numbers in columns not having the same letter are statistically different (P = .05).
poor and the plants eventually died.

A combination of liming, ploughing and the application of farm-yard manure was reported significantly to increase peanut yields in Central Senegal, probably through increasing N$_2$ fixation (Wey and Obaton, 1978).

Since N$_2$ fixation is not always active enough to meet the legume's requirements, it is necessary to use nitrogen fertilizers. But it is known that such applications inhibit N$_2$ fixation. To prevent this inhibition in legumes, Hardy et al. (1973) suggested the use of other form of nitrogen fertilizers that do not inhibit N$_2$ fixation, while providing the plants with the complementary nitrogen required for their growth. Such new forms of chemical fertilizers, which they designated as compatible fertilizers, could also be recommended for use. The possibility, though promising, has not yet been seriously explored.

Nitrification can be controlled by such classical methods as split application of ammonium fertilizers, localization in mud balls (International Rice Research Institute, 1978), or banding, which inhibits nitrification due to the effect of the high concentration of fertilizer on nitrifying bacteria (Wetselaar et al., 1972; Myers, 1978). The use of slow-release fertilizers is also recommended to avoid the harmful effects of nitrification (Fochts and Verstraete, 1977).

MANIPULATION OF THE PLANT COMPONENT OF THE SOIL-PLANT-MICROORGANISMS SYSTEM

Introducing a specific crop in the rotation system has been used successfully as a basis for the biological control of some pests. Thus in Florida, soils infested by nematodes pathogenic to tomato, are cured by growing a grass, Digitaria decumbens, after the tomato crop (Salette, personal communication). Crop rotation is often the best method of controlling soil-borne phytopathogenic fungi in cereals (see Baker and Cook, 1974). The possibility of increasing populations of microorganisms beneficial to plants through proper crop rotation was suggested by Krasilnikov (1958) but the method has not yet been exploited.
Though manipulation of the microbiological balance through crop rotation is a promising approach, investigations in that field will probably be difficult to initiate and develop because of the large variability of climate and soil conditions.

Genetic variability in plants responding to *Rhizobium* infection is well known. This variability could be used as a basis for the breeding programmes of legumes. The future of this approach was envisioned as follows by Holl and La Rue (1974). 

"Plant genes controlling fixation do occur, and experience shows that we can obtain informative and useful variants. There is no obvious reason why symbiotic fixation cannot be increased by genetic means. We can envisage cultivars which nodulate early in harsh soil conditions, fix dinitrogen, even in the presence of high soil nitrate levels, and continue fixing throughout their life. It appears that fixation may be limited by the supply of photosynthate to the roots. Increased fixation may then require greater photosynthesis, decreased photorespiration, delayed lodging, or less pod-nodule competition for carbon".

Two examples may serve as an illustration for such a promising approach, which has not yet been seriously exploited. The first concerns the nodulation of peanut. Comparing the time course of nodule dry weight of three peanut cultivars grown in 1977 at the same time in identical conditions (Dior soil, Central Senegal), Germani (1979) found that the maximum nodule weight of two of them was much higher than that of the third (Fig. 4). However, such results should be interpreted with caution since differences in nodule weight are also observed from one year to another. Thus the maximum nodule weight of cv. 55-437, which was only 70 mg in 1977, could reach 100 mg in the same soil during more humid years (1973 and 1975) and even more than 200 mg during an even more humid year (1974) (Wey and Obaton, 1978).

The other example is related to soybean. In West African soils, certain soybean cultivars, such as Malayan, are readily nodulated by native *Rhizobium* of the cow-pea group, whereas other cultivars, such as Bossier, a high yielding cv. from the USA, require inoculation with the specific *Rhizobium japonicum* strains. Selection of high-yielding soybean that could nodulate with native *Rhizobium* of the cow-pea group would allow the development of this crop in Africa without requiring any
Fig. 4. Time course of nodule dry weight of peanut expressed as mg per plant. A: cv. 28-206 and GH 119-20; B: cv. 55-437. All data are mean values for collections in 1977 at Patar, Central Senegal (Germani, 1979).
inoculation, since native *Rhizobia* of the cow-pea group are common in most African soils (International Institute of Tropical Agriculture, 1977).

**CONCLUSIONS**

This paper has summarized the numerous ways in which soil microorganisms can affect the fertility of soil and it has noted, with examples, how in some cases they can be manipulated in order to benefit the growth of plants. Up to now practically all work done has been with agricultural, horticultural or forestry land-use systems. There is clearly a very urgent need now to relate specific areas of soil microbiological research to agroforestry systems in which woody and herbaceous plants will be grown either mixed together or in some sequential manner.

The many possible ways in which the activities of soil microorganisms in the soil-plant association of one of these groups of plants can affect the other is an almost untouched field of research. In particular, the effects on microorganisms of soil management, inoculation and nitrogen fixation and transformation, and the consequent influence on soil fertility in agroforestry systems might be given early attention.

**DISCUSSION**

**Keya:** Nitrification inhibitors are produced in the roots of many grasses. The neem (*Azadirachta indica*) plant also produces such an inhibitor, which might have some prospects in agroforestry.

**Sánchez:** In North Queensland, Australia, they have observed a competitive relationship between *Eucalyptus* and grass pasture for N, but not in legume pasture.

**Pereira:** The reason for all crops doing poorly after sorghum in dry conditions is that the stubble continues to utilize water from the 2-m deep subsoil for many weeks.

**Dommergues:** A reduction in soil water content may also reduce the microbiological activity responsible for decomposing phytotoxic compounds added by sorghum roots.

**Ahn:** Some grasses are known to inhibit nitrification in West African savanna soils. Thus, yams (*Dioscorea* spp.) which demand less N, are grown in the first season followed by grain crops.
Dommergues: Probably N immobilized in the grass root system is not readily mineralized and it is only progressively decomposed. In contrast, crop residues are easily mineralized.

Ahn: Does the phytotoxic effect of sorghum on a succeeding crop apply to a succeeding crop of sorghum also?

Dommergues: Yes. However, the phytotoxic effect is only on soils with low biological activity and water reserve.

Poulsen: Does grass exude nitrification inhibitors, thereby reducing growth of Eucalyptus?

Dommergues: Yes. But there is no published reference for the inhibition of Eucalyptus growth.

Pratt: Citrus and peach produce toxic materials in their roots which inhibit the development of new trees. Some seeds of desert annuals have growth inhibitors that prevent germination until these water-soluble inhibitors are leached away or changed chemically.

LITERATURE CITED


Biological nitrogen fixation accounts for 40-70% of the global nitrogen input. It occurs under a wide range of habitats and is mediated by free-living and symbiotic microorganisms endowed with the enzyme nitrogenase. Non-symbiotic and symbiotic fixation respectively account for about 4-20 and 20-300 kg N ha\(^{-1}\) y\(^{-1}\). Thus, the contribution of free-living nitrogen fixers is small. *Rhizobium*-legume symbiosis is estimated to contribute 40 x 10\(^6\) metric tons of N, which is approximately 20% of the N\(_2\) fixed annually. Legume-based symbiosis offers much scope for increasing N inputs to food production and conditions essential for optimum N\(_2\) fixation merit more study. Careful manipulation of plant, microorganism, soil and environmental parameters are critical for optimum biological nitrogen fixation. Many of the best N\(_2\) fixers are multipurpose woody plants which should be exploited in the development of agroforestry systems. Strategies for the optimization of the N\(_2\) - fixing capacities of plants under agroforestry conditions are indicated.

Vigorous growth of plants in agriculture and forestry is frequently limited by adequate supply of assimilable soil nitrogen. Although the plant is surrounded by an atmosphere containing about 80 percent gaseous nitrogen (N\(_2\)), this form is not immediately available. Therefore nitrogen must be furnished to the plant from soil organic matter, inorganic N forms in the soil, added fertilizer or from N\(_2\) fixation by biological processes. Most soils show moderate to acute deficiencies in nitrogen, yet fertilizer sources require energy in their manufacture and transport. Through biological nitrogen fixation the inert molecular dinitrogen can be converted into compounds useful to living organisms. Not only is the nitrogen fixed accumulated in the system but higher plants can recycle this nitrogen near the soil surface for the growth of non-nitrogen-fixing species.

Global gains of biological nitrogen-fixation have been estimated at about 175 x 10\(^6\) t N/yr (Postgate, 1978).
This is approximately 40-70% of the annual global nitrogen requirement. Nitrogen can also be fixed chemically or industrially and nearly all fertilizers today are produced this way. In general, most estimates concur that biological fixation systems are responsible for about half of the world's need. Hardy and Havelka (1975) reported that production and consumption of fertilizer nitrogen in 1974 was $40 \times 10^6$ t. They further projected that by the year 2000 the consumption would be $200 \times 10^6$ t if there are no other alternative techniques for producing fixed nitrogen. Unfortunately, industrially-fixed nitrogen is currently used more in developed countries. Yet a bigger increase in food production is urgently needed in the developing world. With increasing scarcity of petroleum-based nitrogenous fertilizers, agroforestry practice will depend more on an integrated systems approach where-in nitrogen-fixing species are planted concomitantly with non-nitrogen fixing crops.

Due to its advantages and relative magnitude this paper will review the scope and potential of biological nitrogen fixation in agroforestry. Some research strategies need to harness this system will also be considered.

NITROGEN FIXING ORGANISMS

The ability to fix atmospheric nitrogen is confined to the simplest and presumably the most primitive organism, being distinguished by the absence of cell nuclei. The nitrogen-fixing organisms include several genera of bacteria and cyanobacteria, or blue-green algae. Whether the microorganisms are autotrophic or heterotrophic, the energy required for nitrogen fixation is obtained from photosynthesis or preformed intracellular carbohydrate. The higher plants and animals have not demonstrated the capability to fix nitrogen, although several participate indirectly by forming symbiotic associations with the nitrogen-fixing eukaryotes. The best known of these relations is the one between leguminous plants and various bacteria of the genus
Rhizobium. Recently Dilworth (1974) showed that rhizobia can fix small amounts of nitrogen while living freely in the soil. However, higher amounts are fixed in symbiosis with nodulated legumes. Many other genera of free-living bacteria and algae fix nitrogen in soil and water. A few are photosynthetic, some are obligate anaerobes while others require oxygen for growth. Table 1 summarizes information on some of the nitrogen-fixing organisms.

All the nitrogen-fixing organisms possess a unique enzyme, nitrogenase, which catalyses nitrogen fixation. Also, the organisms apparently share a common mechanism for nitrogen fixation in that the initial product is ammonia. The overall chemical reaction of nitrogen fixation is the same whether it is performed by the Haber process or takes place in the living cell. Initially the triple bond of the N₂ molecule must be broken, then three hydrogen atoms are bound to each nitrogen atom. The chemistry and biochemistry of nitrogen fixation has been reviewed by Postgate (1971). The fact that nitrogen-fixing organisms possess nif genes suggests there may be prospects for genetic manipulation. The transfer of genes from a nitrogen-fixing bacterium to some other organism, such as a crop plant, offers the most spectacular means of increasing the world's supply of fixed nitrogen. Postgate (1978) has been able to transfer the nif genes from Klebsiella pneumoniae into a plasmid of Escherichia coli, a bacterium that has no nitrogenase. However, successful transfer of nif genes to the higher plants, with concomitant nitrogen fixation by cereal plants still remains a remote possibility.

METHODOLOGY FOR BIOLOGICAL NITROGEN FIXATION

A number of methods exist for the determination of nitrogen fixation. However, a breakthrough in nitrogen fixation research came with the discovery that nitrogenase can reduce acetylene to ethylene (Schollhorn and Burris, 1966; Koch and Evans, 1966). Later Stewart, Fitzgerald and Burris (1967), and Hardy et al. (1968) refined this technique, making it possible to assay for
### Table 1: Nitrogen fixing organisms

<table>
<thead>
<tr>
<th>Free living or symbiotic systems</th>
<th>Nitrogen fixing organism</th>
<th>Associated organism</th>
<th>Natural habitat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free living bacteria and algae</td>
<td><em>Azotobacter vinelandii</em></td>
<td>None</td>
<td>Aerobic soils (temperate)</td>
</tr>
<tr>
<td></td>
<td><em>Beijerinckia</em></td>
<td>None</td>
<td>Aerobic soils (tropical)</td>
</tr>
<tr>
<td></td>
<td><em>Acronobacter, Aerobaeter, Pseudomonas</em></td>
<td>None</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Clostridium pasteurianum</em></td>
<td>None</td>
<td>Anaerobic soils</td>
</tr>
<tr>
<td></td>
<td><em>Klebsiella pneumoniae</em></td>
<td>Various</td>
<td>Anaerobic and aerobic soils, water, also in association with plants and man</td>
</tr>
<tr>
<td></td>
<td><em>Rhodospirillum rubrum</em></td>
<td>None</td>
<td>Photosynthetic bacteria found in surface of polluted ponds and waters</td>
</tr>
<tr>
<td></td>
<td><em>Chlorobium, Chromatium</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Rhodopseudomonas</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Anabaena, Nostoc</em></td>
<td>None</td>
<td>Paddy (rice) fields, alkaline lakes</td>
</tr>
<tr>
<td></td>
<td><em>Tolyphorhiz</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Anabaenopsis, Cylindrospermum</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Spirillum lipoferum</em></td>
<td>Roots of cereals &amp; grasses</td>
<td>Rhizosphere of grasses and other cereals</td>
</tr>
</tbody>
</table>

#### (a) NON-LEGUMES:

- *Citrobacter freundii* - Termite - Termite gut
- *Frankia alni* - Alder - Root nodules of the alder tree
- *Nostoc muscorum* - Gunnera macrophylla (tropical herb) - In stems (a cyanobacterium)
- *Anabaena asciata* - *Azolla* (Aquatic fern) - In leaf pores: A cyanobacterium

#### (b) LEGUMES

- *Rhizobium trifolii* - Clover - Nodule form on roots
- *R. meliloti* - Alfalfa (lucerne) - " " "
- *R. phaseoli* - Beans - " " "
- *R. lupin* - Lupines - " " "
- *R. japonicum* - Soybeans - " " "
- *R. leguminosarum* - Peas - " " "
- *Cowpea group* - Cowpeas - Groundnuts, etc.
nitrogenase activity. The method has several advantages in that as little as $10^{-12}$ moles of ethylene can be detected (Hardy et al., 1973). Hardy et al. (1973) reviewed the factors that affect acetylene reduction in various systems. Some of these factors must be borne in mind. For instance, one should not forget the fact that acetylene reduction is an indirect method of nitrogen fixation. This is why Kjeldahl nitrogen determination is still preferred as the reference method (Vincent, 1970). Other methods such as $^{15}$N$_2$ depletion have gained increasing acceptance but, as with acetylene reduction, the equipment needed is rather expensive and usually not available in developing countries.

Apart from fixation, additions to soil nitrogen from the atmosphere may be in the form of settling dust, soluble nitrogen compounds brought down in precipitation, or plant absorption of combined nitrogen. When conducting field experiments, therefore, it is important to take these sources of nitrogen into account, otherwise there is a danger of overestimating biological nitrogen fixation by as much as 10 kg ha$^{-1}$ (Allison, 1965). Data obtained by Kjeldahl determinations do not distinguish nitrogen fixed by free-living organisms and those derived from other possible sources (Parker, 1957). The Kjeldahl technique only provides net gains that are usually lower than the gross amounts of nitrogen fixed under field conditions. Similarly losses due to leaching, volatilization, denitrification and other processes will not be measured.

Both the acetylene reduction and heavy isotope$^{15}$N$_2$ methods provide instantaneous assessment of fixation rate. Consequently data obtained represent maximum potential rates of fixation which should only cautiously be equated with gross nitrogen fixation.

**NITROGEN FIXATION IN VARIOUS HABITATS**

**SOILS IN GENERAL**

A wealth of information exists on nitrogen fixation in the soil (Stewart, 1976). Soils possess many agents capable of
dinitrogen fixation. The organisms range from heterotrophic to photosynthetic bacteria to blue-green algae. Nitrogen-fixing blue-green algae are usually found in moist soils low in combined nitrogen. In arid desert soils, blue-green algae constitute an important part of the microbial flora. Generally they occur beneath pebbles and stones where light still penetrates but where the desiccating effects of the sun are less severe. More recently, blue-green algae have been observed to play a role in the nitrogen economy of bare soils. In algal crusts, species of *Anabaena*, *Cylindrospermum* and *Nostoc* are common. Nitrogen contents of soils that exhibit algal and lichen crust are considerably higher than those of soils without crusts.

Algal fixation is confined to the surface of the soil and is dependent on light, moisture and low soil nitrogen. The maximum algal fixation rates vary from 2.5 to 51 kg ha⁻¹ y⁻¹. Much of the nitrogen fixed becomes available for the growth of other plants upon decomposition of algal biomass (Stewart, 1970). The amounts of nitrogen fixed by blue-green algae are generally lower than those of bacterial fixation, probably due to the factors limiting algal growth. Algal fixation of nitrogen occurs under quite diverse habitats (Table 2) ranging from agricultural soils in Sweden (Henriksson, 1971, 1972) to forest and savannah soils of Africa (Greenland and Nye, 1959).

Many free-living bacteria capable of fixing nitrogen have been isolated from soil (Dalton, 1974) and numerous laboratory experiments with non-sterile soil have shown that gains equivalent to 100 - 160 kg N ha⁻¹ y⁻¹ are possible (Moore, 1966). Although laboratory data indicate that soil has a potential for non-symbiotic fixation, the gains recorded vary from zero to over 200 kg N ha⁻¹ y⁻¹. The highest values were obtainable only when soils were amended with a carbon (energy) source. Generally the proportion of the accretion due to autotrophic versus heterotrophic microorganisms is not known. The contribution of the genus *Azotobacteraceae* and *Beijerinckia* in aerobic soils, and *Clostridium* in anaerobic soils, was at one time thought to be quite significant. The list of nitrogen-fixing organisms in
<table>
<thead>
<tr>
<th>LOCATION</th>
<th>HABITAT</th>
<th>MICROORGANISM(S)</th>
<th>RATE OF N$_2$-FIXATION (kg ha$^{-1}$ y$^{-1}$)</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghana</td>
<td>Fallow land (from forests)</td>
<td>Bacteria and blue-green algae*</td>
<td>22 - 56</td>
<td>Greenland and Nye (1959)</td>
</tr>
<tr>
<td>Ghana</td>
<td>Fallow land (from savanna)</td>
<td>Bacteria and blue-green algae</td>
<td>4 - 11</td>
<td>-----------</td>
</tr>
<tr>
<td>Arizona (USA)</td>
<td>Desert algal crusts</td>
<td>Anabaena spp. Scytonema spp.</td>
<td>10.9</td>
<td>Mayland, McIntosh and Fuller (1966)</td>
</tr>
<tr>
<td>Saskatoon (Canada)</td>
<td>Chernosemic</td>
<td>Clostridium butyricum</td>
<td>42 - 52</td>
<td>Rice, Paul and Wetter (1967)</td>
</tr>
<tr>
<td>Quebec (Canada)</td>
<td>Agricultural soils</td>
<td>Azotobacter (pH 6.5)</td>
<td>1.7-226</td>
<td>Brouzes, Lasik and Knowles (1969)</td>
</tr>
<tr>
<td>Sweden</td>
<td>Agricultural fields</td>
<td>Nostoc spp.</td>
<td>15 - 51</td>
<td>Henriksson (1971) and 1972</td>
</tr>
<tr>
<td>Artic</td>
<td>Tundra</td>
<td>Blue-green algae (in lichens)</td>
<td>2.5</td>
<td>Fogg et al. (1973)</td>
</tr>
</tbody>
</table>

* Identity of organism questionable
soil has been expanding. Isolates of *Spirillum*, *Bacillus*, *Denzia* spp. and some members of the genus *Enterobacteriaceae*, such as *Klebsiella*, have been shown to fix nitrogen in soils. Although non-symbiotic nitrogen fixation is small in temperate regions, the contribution of non-symbionts in tropical soils may be quite significant.

**FOREST SOILS**

Soils under forest constitute a habitat where combined nitrogen could be high enough to inhibit fixation. Due to low light conditions the bacteria have a competitive advantage over the blue-green algae. Nitrogen accumulation under pine forest is usually ascribed to the heterotrophic bacteria in the rhizosphere (Bjorkman, 1976). The forest floor is rich in organic carbon which furnishes energy for the majority of heterotrophs. The other environmental conditions, such as moisture and darkness, favour bacterial growth under forest conditions and both aerobic and anaerobic nitrogen fixers have been reported (Jones, King and Eastlick, 1974).

The information shown in Table 3 originates mainly from the temperate North. However, Greenland and Kowal (1960) have shown that a tropical forest in Ghana, containing 4 - 8% legumes, added about 40 kg N ha\(^{-1}\) y\(^{-1}\) to the vegetation. The measured net fixed nitrogen input into the system accounted for 31% of the total nitrogen. Rates of fixation obtained have ranged from as low as 0.10 kg N ha\(^{-1}\) y\(^{-1}\) in litter under some German forests to 476 kg N ha\(^{-1}\) y\(^{-1}\) under Ukrainian forests, giving an average of about 50 kg N ha\(^{-1}\) y\(^{-1}\). At this rate approximately 50% of the plant community's requirement can be met from biological nitrogen fixation. Little information is available in tropical forests. In addition, more information is needed on seasonal fluctuations in \(N_2\) - fixation rates under forest conditions.

**GRASSLAND SOILS**

Grasslands form an important interface between forest and cleared land and nitrogen fixed in such communities as could
<table>
<thead>
<tr>
<th>LOCATION</th>
<th>HABITAT</th>
<th>N$_2$-FIXATION</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scotland (U.K.)</td>
<td>Soil under <em>Pinus sylvestris</em></td>
<td>50</td>
<td>Ovington (1951)</td>
</tr>
<tr>
<td>California (USA)</td>
<td><em>Pinus ponderosa</em> forest floor</td>
<td>63</td>
<td>Dickson and Crocker (1953)</td>
</tr>
<tr>
<td>Glacier Bay (Alaska)</td>
<td>Deglaciated shore (soil and forest floor under <em>Alnus tenuifolia</em>)</td>
<td>60</td>
<td>Crocker and Major (1965)</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Forest trees in monoculture</td>
<td>58</td>
<td>Ovington (1956)</td>
</tr>
<tr>
<td>New Zealand</td>
<td><em>Pinus radiata</em> forest</td>
<td>36</td>
<td>Stevenson (1959)</td>
</tr>
<tr>
<td>Kade (Ghana)</td>
<td>Tropical rain forest (4 - 8% legumes)</td>
<td>40</td>
<td>Greenland and Kowal (1960)</td>
</tr>
<tr>
<td>Ukrainia (U.S.S.R.)</td>
<td>Soil under pine forest</td>
<td>476</td>
<td>Terent' yeva (1962)</td>
</tr>
<tr>
<td>Munich (Germany)</td>
<td>Forest-litter</td>
<td>0.10</td>
<td>Huser (1965)</td>
</tr>
<tr>
<td></td>
<td>Forest-mull</td>
<td>0.32</td>
<td>.........................</td>
</tr>
</tbody>
</table>
influence N-status of sylvo-pastoral systems. The data accumulated in this field and shown in Table 4, indicates that fixation rates of about 160 kg N ha\(^{-1}\) y\(^{-1}\) are possible in grassland. Dobereiner, Day and Bulow (1975) have reviewed nitrogen fixation in grasses and they have pointed out the plant-soil and environmental factors that may influence their nitrogen fixation. Other work by Dobereiner et al. (1978) seems to indicate that nitrogen fixation generally occurs in the rhizosphere of grasses but associated bacteria of the genus *Spirillum* have been found in intracellular locations. Since nearly all grasses that have been shown to fix nitrogen possess the \(\text{C}_4\)-photosynthetic pathway, Dobereiner maintains that their potential is greater than that of the legumes with the \(\text{C}_3\)-photosynthetic pathway.

It seems, therefore, that non-symbiotic nitrogen fixation is extremely important to the productivity of grasslands. The grassland soils, being low in combined nitrogen, are able to support their vegetation through nitrogen fixation since yields of 10-20 tons ha\(^{-1}\) y\(^{-1}\) are easily attainable with tropical grasses (Hutton, 1970). Some questions still need to be answered. What is the basis for the predominance of \(\text{C}_4\) plants among \(\text{C}_3\) nitrogen-fixing associations? What are the relationships between the bacteria and the plant? What is the mode of transfer of nutrients between the plant and the bacteria, and how can the efficiency of this hitherto unexploited system be improved?

**FLOODED SOILS**

Cultivation of rice is prevalent on soils subjected to periodic flooding. Under such conditions, where moisture and light are less limiting, the responsible organisms that fix nitrogen are blue-green algae and photosynthetic bacteria. The blue-green algae commonly isolated include *Anabaena*, *Calothrix*, *Cylindrospermum*, *Nostoc*, and *Tolypothrix*. Fixation of nitrogen by algae and photosynthetic bacteria in tropical soils have been reported by Watanabe and Yamamoto (1971). These organisms must play a crucial role in the nitrogen economy of paddy soils as shown by Table 5. Value as high as 276 kg N ha\(^{-1}\) y\(^{-1}\) (Willis and Green, 1948) and as low as 55 kg N ha\(^{-1}\) y\(^{-1}\) (McRae and Castro
<table>
<thead>
<tr>
<th>LOCATION</th>
<th>HABITAT</th>
<th>MICROORGANISM(S)</th>
<th>$N_2$-FIXATION (kg ha$^{-1}$ y$^{-1}$)</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas (U.S.A.)</td>
<td>Native grass sod on desurfaced soil</td>
<td>?</td>
<td>22</td>
<td>Smith et al. (1954)</td>
</tr>
<tr>
<td>Merredin (Western Australia)</td>
<td>Soil under <em>Lolium rigidum</em></td>
<td>?</td>
<td>60</td>
<td>Parker (1957)</td>
</tr>
<tr>
<td>Saskatchewan (Canada)</td>
<td>Grassland (cultivated soil)</td>
<td><em>Clostridium</em> spp.</td>
<td>0.6</td>
<td>Paul et al. (1971)</td>
</tr>
<tr>
<td></td>
<td>(virgin soil)</td>
<td><em>Azotobacter</em> spp.</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Rio de Janeiro (Brazil)</td>
<td>Lawns and pastures: rhizosphere of <em>Paspalum notatum</em></td>
<td><em>Azotobacter</em> paspali</td>
<td>15-117</td>
<td>Dobereiner, Day and Dart (1972a; 1973)</td>
</tr>
<tr>
<td></td>
<td>Rhizosphere and roots: <em>Beijerinckia indica</em> of <em>Saccharum</em> spp.</td>
<td></td>
<td>70</td>
<td>Dobereiner, Day and Dart (1972b); see also Ruschel, Henis and Saleeti (1975)</td>
</tr>
<tr>
<td>Rio de Janeiro (Brazil)</td>
<td>Maize plots rhizosphere of <em>Zea mays</em></td>
<td><em>Spirillum</em> in the rhizosphere of <em>Zea mays</em></td>
<td>38-874</td>
<td>Von Bulow and Dobereiner (1975)</td>
</tr>
</tbody>
</table>
### Table 5: Nitrogen fixation in some waterlogged soils

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>HABITAT</th>
<th>MICROORGANISM(S)</th>
<th>$\text{N}_2$-FIXATION $\text{kg ha}^{-1} \text{y}^{-1}$</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dacca (Bangladesh)</td>
<td>Paddy soil (pot experiments)</td>
<td>Blue-green algae</td>
<td>13-98</td>
<td>De and Sulaiman (1950)</td>
</tr>
<tr>
<td>Japan</td>
<td>Paddy field</td>
<td>Tolypothrix tenuis</td>
<td>68</td>
<td>Watanabe, Nishigaki and Konishi (1951)</td>
</tr>
<tr>
<td>Laguna (Philippines)</td>
<td>Paddy soil</td>
<td>Photosynthetic microorganisms</td>
<td>10-55</td>
<td>MacRae and Castro (1967)</td>
</tr>
<tr>
<td>Sweden</td>
<td>Lakeside meadow</td>
<td>Anabeana spp.</td>
<td>4-44</td>
<td>Henriksson (1971; 1972)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calothrix spp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cylindrospermum spp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nostoc spp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>Alluvial paddy soils</td>
<td>Blue-green algae</td>
<td>180-240</td>
<td>Rinaudo et al. (1971)</td>
</tr>
<tr>
<td>Laguna (Philippines)</td>
<td>Paddy soil</td>
<td>Photosynthetic microorganisms</td>
<td>40-80</td>
<td>Yoshida et al. (1973)</td>
</tr>
</tbody>
</table>
1967) have been reported for paddy soils.

Such large inputs of nitrogen into the paddy environment explain the well-known observation that rice fields can be continuously cultivated without addition of nitrogenous fertilizers (Watanabe et al., 1971).

Additionally, aquatic vascular plants associated with other organisms contribute nitrogen to various flooded ecosystems. Floating plants such as *Salvinia*, *Hydrilla*, *Eichhornia*, *Colocasia*, *Monorchia*, *Lemma*, and *Azolla* are common constituents of the flora of paddy fields.

**OTHER HABITATS**

That nitrogen fixation is known to occur in lakes and seas (Postgate, 1974), decaying wood (Siedler et al. 1972), and even in the mammalian gastro-intestinal tract (Bergersen and Hipsley, 1970) is worth noting because these sources could influence global nitrogen cycles. It also illustrates that nitrogen-fixing organisms are widely distributed in aquatic and terrestrial habitats. The apparent universality of these organisms should interest the soil biologist because the habitats represent extremes of nutrient locale.

**SYMBIOTIC NITROGEN FIXATION**

**NON-LEGUMES**

The major aspects of non-symbiotic nitrogen fixation have been considered in the preceding sections. Symbiotic nitrogen fixation is used to imply fixation of atmospheric nitrogen when two partners can be distinguished. The larger partner, the macrosymbiont, is usually incapable of fixing nitrogen and may include all higher plants and fungi. On the other hand, the smaller associate is generally a bacterium, an alga or actinomycete endowed with nif genes. It should be noted that symbiosis is not essential for these smaller organisms to fix nitrogen Stewart (1970). Many of these associations, such as those of fungi and blue-green algae to form lichens, are common and
interesting examples. Nitrogen fixed in this type of symbiosis may make only a very slight contribution to the general soil economy. However, since lichens are common on the bark of forest trees, it serves to illustrate the potential, albeit small, contribution to this particular ecosystem.

A case in which an alga of the *Anabaena* species forms an association with the water fern, *Azolla*, is a symbiosis that results in the fixation of appreciable quantities of nitrogen. In Vietnam and China successful cultivation of rice is partly attributed to this source of nitrogen. Prior to planting rice, the field is seeded with *Azolla* which grows and serves as green manure. The crop is harvested almost ten times in a period of 3 to 4 months. During this period about 160 tons ha\(^{-1}\) of dry matter containing 425 kg N is obtained. At this rate *Azolla* is said to fix more nitrogen than the most efficient legume (Chu, 1978).

Other kinds of algal symbiosis have been discussed by Clarke and Paul (1970) and this reference describes some of the associations involving non-legumes and certain microorganisms. It is apparent that many genera of gymnosperms are associated with blue-green algae whereas only one case of an angiosperm-algal combination has been found.

Since nitrogen-fixing non-legumes are widely distributed in nature (Stewart, 1976) they must also make an important contribution to the nitrogen budget of the world. Some of these species, their distribution and habitat are shown in Table 6. However, only limited data on nitrogen fixation is available and what is presented in Table 7 provides only the estimates that have been reported.

For example, *Casuarina* species are probably very important to the nitrogen economy of the poorer sandy soils of the tropics and subtropics. Yet the only quantitative account of their nitrogen fixation comes from Dommergues (1963). He has suggested that *Casuarina* is capable of fixing about 60 kg N ha\(^{-1}\) y\(^{-1}\) in the sand dunes of Cap Vert in western Africa.
Table 6: Distribution and habitats of nitrogen-fixing non-legumes

<table>
<thead>
<tr>
<th>GENUS</th>
<th>DISTRIBUTION</th>
<th>HABITAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alnus</td>
<td>Northern temperate and arctic regions; S. America, Japan</td>
<td>River banks, mountain slopes</td>
</tr>
<tr>
<td>Casuarina</td>
<td>Tropical Asia, Australia, Pacific Islands</td>
<td>Coastal soils and dune systems</td>
</tr>
<tr>
<td>Ceanothus</td>
<td>N. America</td>
<td>Forest soils, particularly newly cleared areas</td>
</tr>
<tr>
<td>Comptonia</td>
<td>N. America</td>
<td>Undergrowth of forests</td>
</tr>
<tr>
<td>Coriaria</td>
<td>S. Europe, S. Asia, N. Africa, S. America, New Zealand</td>
<td>Pioneer plants on eroded and newly cleared soils</td>
</tr>
<tr>
<td>Discaria</td>
<td>Australasia, S. America</td>
<td>Stony plains</td>
</tr>
<tr>
<td>Elaeagnus</td>
<td>Asia, Europe, N. America</td>
<td>Eroded slopes, over-grazed pastures</td>
</tr>
<tr>
<td>Hippophae</td>
<td>Temperate to arctic regions of Asia and Europe</td>
<td>Coastal areas near inland waters</td>
</tr>
<tr>
<td>Myrica</td>
<td>Tropical to sub-arctic regions</td>
<td>Acid bogs, mountains in the tropics</td>
</tr>
<tr>
<td>Shepherdia</td>
<td>N. America</td>
<td>Sandy soils, eroded slopes, near water courses</td>
</tr>
</tbody>
</table>

Source: Stewart, 1966
<table>
<thead>
<tr>
<th>LOCATION</th>
<th>HABITAT</th>
<th>PLANTS</th>
<th>RATE OF $N_2$-FIXATION (kg ha$^{-1}$ y$^{-1}$)</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap Vert</td>
<td>Sand dune</td>
<td>Casuarina equisetifolia</td>
<td>59</td>
<td>Dommergues (1963)</td>
</tr>
<tr>
<td>Helsinki</td>
<td>Pot experiments</td>
<td>Alnus glutinosa</td>
<td>125 - 625</td>
<td>Virtanen and Miettinen (1963)</td>
</tr>
<tr>
<td>(Norway)</td>
<td></td>
<td>Hippophae rhamnoides</td>
<td>1.5 - 57.5</td>
<td>Stewart and Pearson (1967)</td>
</tr>
<tr>
<td>Gibraltar</td>
<td>Embryonic to mature sand</td>
<td>Gunnera dentata</td>
<td>72</td>
<td>Silvester and Smith (1969)</td>
</tr>
<tr>
<td>point (U.K.)</td>
<td>dune system</td>
<td>(leaf nodules with Nostoc punctiforme)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canterbury</td>
<td>Sand culture</td>
<td>Myrica cerifera</td>
<td>3.4</td>
<td>Silver and Mague (1970)</td>
</tr>
<tr>
<td>(New Zealand)</td>
<td></td>
<td>Alnus rubra</td>
<td>160</td>
<td>Taraht and Trappe (1971)</td>
</tr>
<tr>
<td>Texas (U.S.A.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oregon (U.S.A.)</td>
<td>Forest</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Non-leguminous species generally occur in greater abundance in soils containing low levels of combined nitrogen. Often these plants are pioneering tree species in nutrient-poor environments. This may mean that the amount of nitrogen fixed through symbiosis goes a long way to meeting the plant's requirements. The site for nitrogen fixation in a non-legume symbiosis, especially in trees, is the nodule. These are formed as a result of microsymbiont infection through the root hair. In the host cells the endophytes exist in three forms: hyphae, vesicles and bacteria-like cells. The endophyte is an *Actinomyces* sp. which is an obligate symbiont. Aspects of non-leguminous nitrogen fixation have been reviewed by Date (1973), Quispel (1974), and Burns and Hardy (1975).

**LEGUMINOUS PLANTS**

Due to the part these play in improving soil fertility and in food production, nodulated legumes have been studied intensively over a long period of time. There is a vast amount of literature in this field. In more recent times many detailed and highly informative reviews have become available (Broughton, 1977; Hardy and Havelka, 1975). The Leguminosae constitutes one of the largest families of flowering plants, with some 690 genera and about 18,000 species of herbs, shrubs, trees and climbers (Pursglove, 1968). Many species of legumes have nodules on their roots containing the bacteria *Rhizobium* which fix nitrogen. Some of the fixed nitrogen becomes available to the plant.

In many developing countries plant sources provide some 90% of food protein, of which 18.5% is derived from grain legumes (Rachie, 1977). Well-nodulated grain legumes are important not only as a source of food but also as an independent source of nitrogenous fertilizer. Among the important grain legumes in the tropics are cowpeas, beans, pigeon peas, peas, grams, mung-bean and wingbean. The role of legumes in pasture productivity has long been recognized. Many species have been selected and successfully incorporated in pasture management. A few of these are *Centrosema, Stylosanthes, Desmodium* and *Medicago*. Data from Australia (Henzell, 1968), Malaysia (Broughton, 1977) and elsewhere clearly suggest that symbiotic nitrogen fixation is capable
of supplying from 75% to 90% of the plant community's net nitrogen requirements. This is why the majority of current research is directed towards legumes for fodder, grains, and plantation crops. Consequently, much information on nitrogen fixation by tropical pasture and grain legumes is available. Selected examples of these data are given in Table 8.

**SOME NODULATED LEGUMINOUS TREES AND SHRUBS**

Hitherto efforts have been directed towards selecting, adapting and managing pasture and grain legumes yet work on leguminous trees for fuel, timber, forage and soil reclamation has been minimal. One of these legumes is *Acacia mearnsii*, commonly known as the black wattle, which serves as an excellent example of a multipurpose tree. The plant possesses a high growth rate and its soil-improving qualities as a nodulated legume have been exploited in anti-erosion and soil conservation projects, with good results, in many parts of the world. Its bark provides one of the richest known sources of vegetable tannin. Its wood, apart from its value as fuel or as construction timber, has been found to be suitable as a raw material for the production of parquet blocks, charcoal, hardboard, rayon, and certain types of paper. Considering its status as a pioneer species, it exhibits amazing versatility as a commercial tree. Its success as an agroforestry crop, especially outside its native Australia, is shown by its adoption in many parts of the world. Black wattle is capable of fixing atmospheric nitrogen in the soil with the aid of *Rhizobium*. Derby, cited by Sherry (1971), calculated that 160 kg N ha⁻¹ y⁻¹ was fixed. Sherry further states that a single 10-year rotation of wattle can rehabilitate degraded arable land and render it capable of yielding normal crops of grain and hay because the nitrogen status of the soil was adequate without the addition of nitrogenous fertilizers. In Kenya, the author has observed black wattle growing on murrum pits and extremely duned soils.

Another multipurpose agroforestry legume is *Leucaena leucocephala*, a versatile legume whose full potential is yet to be
Table 8: Agronomic efficiencies of some nitrogen-fixing systems

<table>
<thead>
<tr>
<th>AGRONOMIC SYSTEM</th>
<th>MICROORGANISM(S)</th>
<th>NITROGEN FIXED (kg ha(^{-1}) y(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lucerne</td>
<td><em>Medicago</em> with <em>Rhizobium</em></td>
<td>300 - 600</td>
</tr>
<tr>
<td>Clover</td>
<td><em>Trifolium</em> with <em>Rhizobium</em></td>
<td>150 - 300</td>
</tr>
<tr>
<td>Lupin</td>
<td><em>Lupinus</em> with <em>Rhizobium</em></td>
<td>150</td>
</tr>
<tr>
<td>Pulse legumes</td>
<td>Legume with Rhizobia</td>
<td>60</td>
</tr>
<tr>
<td>Paddy fields</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-leguminous trees</td>
<td><em>Alnus, Casuarina</em>, etc., with <em>Actinomycetes</em>?</td>
<td>60 - 140</td>
</tr>
<tr>
<td>Soil under wheat</td>
<td><em>Azotobacter</em></td>
<td>0.25 - 0.37</td>
</tr>
</tbody>
</table>

After: Mishustin and Shilnikova (1971) and Postgate (1974)
tapped. Its many uses include firewood, timber, forage, windbreak, firebreak, shade, ornamentation and soil improvement. *Leucaena* has been neglected despite its fast growth rate and in some areas it has been referred to as a weed. Effectively nodulated, *Leucaena* will form a symbiosis with *Rhizobium*, thereby fixing adequate nitrogen for normal plant growth. This permits the plant to thrive in some soils where nitrogen levels are inadequate to sustain the growth of most other crops. Under good rainfall and soil conditions, *Leucaena* bushes can provide foliage containing up to 500 - 600 kg N ha$^{-1}$y$^{-1}$ (N.A.S., 1977).

Within the *Acacia* family there are many trees and shrubs of importance to farmers in savannah, forest and rangeland ecosystems. Among these are *Acacia senegal*, the major producer of gum arabic. The potential for nitrogen fixation of several species of *Acacia* found in tropical grasslands has not yet been determined. A more neglected group are the nodulated leguminous weeds and shrubs. These may include *Indigofera*, *Aeschynomene*, *Crotalaria*, *Stilosobium*, *Pueraria*, *Cajanus*, and *Vigna* species. These can form dominant or significant plant communities in rangelands and some of them are secondary colonizers when a forest is cleared, or during the fallow period.

**THE PLACE OF LEGUMES IN MULTIPLE CROPPING**

In the tropics legumes are seldom used in monoculture. However, they are often an integral part of various multiple cropping systems. Legumes are grown in mixtures with grasses in pastures and with cereals. They are also used as a cover crop under cocoa, oil palm and rubber. At one time, tree legumes were grown to provide shade, as in the case of *Leucaena* with coffee in some estates in Tanzania and Kenya, and black wattle with tea in Sri Lanka. Where a legume is employed as a shade plant, nurse crop or ground cover, nitrogen fixation is only a secondary function. In such situations fixation of nitrogen per unit area will not be as great as when the legume is grown by itself, since the grass or tree crop occupies much of the land. Often the benefit of providing nitrogen to the soil and to the non-nitrogen fixing plant is either ignored or not quantified.
By far the best studied in this regard is the rubber-cover crop system found in Malaysia and described below.

Before planting rubber the ground is cleared of all vegetation. The rubber seedlings are planted to give 450 trees ha\(^{-1}\). Concurrently a mixture of three legumes, *Calopogonium mucunoides*, *Centrosema pubescens* and *Pueraria phaseoloides* are sown in rows between the trees. In order to promote initial establishment, an appropriate fertilizer is applied to both trees and cover crop. Both the trees and legumes are protected from weeds until the legumes cover the ground. Twelve to 18 months later the legumes cover the soil (Broughton, 1976). Rubber trees with a legume undercover become tappable about four years after planting. On the other hand, the rubber plantations managed by applying fertilizers but with no legume undercover take 6 years. Although the legumes decline and die after six years due to overshadowing by the rubber trees, the net amount of nitrogen added has been estimated by Broughton at 900 kg N ha\(^{-1}\). Furthermore, the yield benefit that accrues from having planted legumes lasts for 20 years after they have been completely shaded out (Mainstone, 1969; Broughton, 1976). This practice described for Malaysia, can also be found in Cameroon, Nigeria and other tropical countries.

**STRATEGIES TO MAXIMIZE BIOLOGICAL NITROGEN FIXATION UNDER AGROFORESTRY**

Research approaches required to optimize nitrogen fixation have been developed and successfully utilized in temperate agriculture. However, these methodologies have yet to be extended to developing countries, where the need is now greatest. Biological nitrogen fixation entails effective manipulation of three major components: the plant, the microorganism, and the environment. This section will consider each component.

There is a need for the assessment of the grain and biomass yield levels of nitrogen-fixing plants in various agroforestry systems and how the yields fluctuate with soil fertility status.
and environmental variables. Equally important is the need to determine the amounts of nitrogen fixed by nodulated leguminous and non-leguminous species. Also the amounts of nitrogen that become available for the subsequent or associated crop need to be quantified. The introduction of nitrogen-fixing plants should take into account varieties that are compatible with agroforestry requirements. Selection, breeding and improvement of such plants ought to incorporate disease and pest resistance, high rates of photosynthesis, and matching current rotations and intercropping practices. The plant species selected should positively contribute to soil fertility in addition to being adapted to the local environment. Above all, preservation and management of these plants to achieve the desired objectives should form part of an integrated research and extension programme.

Microbiological facets should include collection, selection, testing and preservation of valuable genetic resources among the known nitrogen-fixing microorganisms. Where cultures already exist, dissemination and exchange of a microbial gene pool ought to be encouraged in order to facilitate the deployment of these organisms for sound environmental management. Development of appropriate technology for handling already known and effective microsymbionts, such as *Rhizobium* and *Anabaena* spp., requires urgent priority. In the case of *Rhizobium*, determining the need and response to inoculation of legumes is required. Where inoculation is successful, facilities for the preparation of inoculants and their distribution within the local area is essential. In developing areas the inoculants must be supplied in a form and package commensurate with the technological level of the small-scale farmer. Successful use of inoculants should be supported by quality control of inoculants. Backstopping laboratory and field studies should furnish information on the survival of *Rhizobium* in local soils, competition with indigenous strains, adaptation to stresses like low phosphorus, acid soils and high ambient soil temperatures.

Experimental evidence supporting inoculation with non-symbiotic nitrogen-fixing organisms is rare. Immediately, what can be done is to authenticate the microorganisms involved, to
ascertain their ecological amplitude and to discover what characteristics are amenable to management for increased nitrogen fixation. In the case of the blue-green algae determination is still needed of the amount of nitrogen fixed and the effects on this of some agronomic practices. The other endogens, such as mycorrhiza, that might indirectly enhance nitrogen fixation by supplying extra phosphorus, ought to be investigated.

Soil as a medium provides most of the nutrients necessary for plant and microbial growth. The highly-leached acid soils found in warm, humid tropical regions are generally low in phosphorus and calcium. In these soils manganese and aluminium toxicity coupled with soil acidity often limit plant growth and nitrogen fixation. High soil temperatures and fluctuating soil stress reduce the longevity of nitrogen-fixing organisms in soil, besides influencing the fixation process per se. That high levels of inorganic forms of native soil nitrogen retard $N_2$-fixation ought to be borne in mind when selecting microbial strains. Changes in the ability of a microorganism to fix nitrogen may occur in the presence of pesticides applied for crop protection purposes. These and other environmental variables must be carefully manipulated in the search for viable biological nitrogen-fixing systems.

SUMMARY AND CONCLUSIONS

There is little widespread and deliberate use of nitrogen-fixing plants with their associated micro-symbionts for agroforestry production systems. In the highly developed areas of the world biological $N_2$-fixation is widely exploited in the farming systems extant. Despite the fact that certain legume-Rhizobium associations in the tropics can fix large amounts of dinitrogen per unit area of land, the use of legume nitrogen is still only a fraction of its potential, especially in developing countries. Similarly, although legumes are important components in many crop production systems, grain legume yields in most tropical countries are low, being in the order of 700 kg ha$^{-1}$ compared to over 2000 kg ha$^{-1}$ attainable at research stations. Therefore, the means of realizing some of the potential for $N_2$-fixation by plant-microorganism associations in increasing crop yields must be considered against a background of known factors limiting
biological nitrogen fixation. In order to maximize biological nitrogen fixation an interdisciplinary approach is needed since the plant, the microorganism and the environment have to be matched properly. This requires an integration of knowledge. The use of multipurpose woody plants that are associated with high levels of $N_2$-fixation, as well as short duration $N_2$-fixing plants in agroforestry systems offers much scope for the economic viability of these farming systems. The potential plant species will, however, need to be selected for their suitability in particular agroforestry systems and environments.

DISCUSSION

Fried: Associative $N_2$ fixation is much lower than shown in the slide. The shorter-term goal is to select for use the organisms already in the soil, while the longer-term goal is to inoculate with "super strains".

Keya: Agreed. The super strain might vary from legume to legume. Super strains can hardly be universal.

Sánchez: At CIAT, Date and Halliday found differential tolerance of Rhizobium strains to acidity. Can it be screened by using agar medium buffered at pH about 4.5?

Keya: Yes. But acid-tolerant organisms cannot grow on neutral or alkaline soils.

Dommergues: Could you comment about Azolla in Kenya? Is A. nilotica found in Kenya?

Keya: Azolla grows naturally in Kenya, especially around Lake Victoria and in rice growing areas in the Kano plains. The Azolla in Kenya, suspected to be A. nilotica, is considered to fix more $N_2$ than that in China or Vietnam.

Dommergues: In your soybean inoculation trials what were the cultivars used and the Rhizobium strain used in the inoculation?

Keya: The cultivars used were American (Hill, Williams) which do not nodulate at our Kabete Field Station. The seed was inoculated with R. japonicum.

LITERATURE CITED


National Academy of Science, Washington, D.C.


Termites live in soil nests in the warmer regions of the world. They are wood-feeding scolyphagous organisms. Lower termites possess symbiotic protozoans in the hindgut on which they depend for cellulose digestion. Higher termites possess, in addition to symbiotic protozoans, symbiotic cellulolytic bacteria and also nitrogen-fixing bacteria in the paunch. Some termites are fungus-cultivating. The foraging termites collect leaves. Humivores are higher termites and probably consume vegetable remains contained in humus. The nests within wood are excavated to form galleries and chambers which serve as shelter and a food source. The subterranean nest in its simplest form consists of passages extending into the ground, enlarged in places into chambers. All phases of intermediate structures exist between the diffuse nest and the concentrated nests which occupy an area distinct from the surrounding soil. Epigean nests are built with earth or a mixture of earth and excrement. Some have an earthy wall surrounding a central portion of "pasteboard". Arboreal nests are constructed on trees and are connected to the ground by passages that run along the trunk. Water requirements are high, especially for building mounds and to humidify nests. Termites can acquire water from deep phreatic sheets. Rain water penetrates the ground quickly and easily through the numerous galleries. This water can accumulate in the subterranean portion of the mound. The numerous galleries aerate the soil. Evaporation of water, important in humidifying and cooling the mound, causes a deposition of dissolved substances, especially bases. The large quantities of humus passed through the alimentary canal of humivores and bits of organic materials fed on by termites on the soil surface, are of considerable importance in the nitrogen cycle. To build large earth mounds, termites excavate deep into the soil. Through rain erosion, the materials of large earth mounds are spread around the site. Lime is also known to accumulate below living or dead mounds, a phenomenon not well understood. Mound erosion may also affect soil fertility depending on composition of mound material, the termite species and the state of erosion. Because of their activities, termites will greatly influence the viability of agroforestry systems.

Termites are social insects that build and live in nests. They are found mainly in the warmer parts of the world, most species either excavating their nests within the soil or building them from soil particles and other materials. Underground passages are used by termites when looking for nest-building

*Maître de Conferences, Faculté des Sciences, Université de Dakar, B.P. Dakar, Senegal.
material, food and water.

The activities of termites have been reviewed by Bachelier (1963) and Lee and Wood (1971). This paper is therefore not an exhaustive study of these insects but a review of the principal effects they have on the soil, with illustrations from studies in western and central Africa. They are treated here in view of their importance to soil-plant systems, especially in relation to their effects in the establishment and management of viable and sustained agroforestry systems.

TERMITES AND THEIR BIOLOGY

Termites eat wood and other cellulose materials. They are divided into two groups according to the process of cellulose digestion. Lower termites have symbiotic flagellate protozoans in their posterior gut, on which cellulose digestion depends. These include: (i) Mastotermitidae (e.g. Mastotermes), (ii) Termopsidae (e.g. Zootermopsis), (iii) Hodotermitidae (e.g. Hodotermes), (iv) Kalotermitidae (e.g. Kalotermes and Cryptotermes), and (v) Rhinotermitidae (e.g. Psammotermes and Coptotermes).

Higher termites have no symbiotic flagellates. Cellulose digestion is accomplished by symbiotic bacteria (Grasse and Noirot, 1959). These higher termites belong to the Termitidae family which is composed of: (i) Amitermiteinae (e.g. Amitermes and Macrotermes), (ii) Termitinae (e.g. Cubitermes), (iii) Apicotermitinae (e.g. Apicotermes), (iv) Macrotermiteinae (e.g. Macrotermes*, Bellicositermes and Odontotermes), and (v) Nasutitermitinae (e.g. Nasutitermes, Trinervitermes).

TERMITE DIETS

The diets of termites vary according to species and castes (workers, soldiers, larvae and reproductives). Only workers, and in species without workers old larvae and nymphs, eat crude

*Some authors divide the genus Macrotermes into Macrotermes s.s. and Bellicositermes. Ruelle (1970) wrote a revision of the genus Macrotermes. To avoid possible confusion the name given by every author is given followed by the name given by Ruelle in brackets.
nutrients. Soldiers, young larvae and reproductives are fed by the workers with food that is provided at the mouth level (saliva and stomodeal food regurgitated from the crop), or at the anus level (proctodeal food from the paunch, with many flagellates, and different from excrements).

The xylophagous termites gnaw wood. They are found among both the lower and higher termites (most of the Macrotermiteinae, numerous Nasutitermiteinae and Amitermiteinae). These termites can either attack living wood, in which case they may cause damage in plantations, or sound dead wood (Roy-Noël, 1971, 1974, 1977). However, many termites prefer wood that has been more or less altered by fungi. Macrotermiteinae are fungus-growing termites. They construct fungus combs with faecal material (Sands, 1969). Grasse and Noirot (1961) believe, however, that combs are built with masticated plant material. The fungi attack the wood and the workers eat the oldest parts of these fungus-gardens whilst building up the other side with new material.

Foraging termites, or harvesters, (e.g. Trinervitermes) cut leaves. They bring these into their nests as fragments, which are either soon utilized or stored. Some termites have a mixed nutrition, gnawing wood or cutting leaves according to circumstances. The humivore termites eat humus. Remains of plants are assimilated as they pass through the alimentary canal. These termites occur only among the Termitidae.

DINITROGEN FIXATION

Recent studies using the acetylene/ethylene reduction technique have shown the important place of termites in nitrogen fixation. Workers of Coptotermes formosanus were placed in a sealed vial containing acetylene and the formation of ethylene was found to be proportional to the number of termites used. The experiment lasted for 1 h at 30°C. Beyond this time the rate of ethylene formation decreased, perhaps owing to toxicity of acetylene for the termites (Breznak, 1973). The hindgut of
this termite species contains many bacteria and protozoa and it appears, therefore, that these organisms might be responsible for nitrogen fixation.

FACTORS AFFECTING N₂ FIXATION

N₂ fixation in termites could depend on a number of different factors, for example on their food intake. Worker termites fed with wood show a far lower acetylene-reducing activity than those fed with cellulose filter paper. The addition of NH₄⁻ or NO₃⁻-N to paper diminishes acetylene reduction and it can then fall below that of termites fed on wood (Breznak, 1973). It would appear, therefore, that the N₂-fixing activity of termites can be modulated by the amount of N contained in the diet. Soldier termites and reproductives do not fix nitrogen, or may do so only to a small extent (Benneman, 1973). Benneman also observed that Cryptotermes brevis and Zootermopsis angusticollis do not fix N₂ as well as Kalotermes minor, indicating that N₂-fixing capacity may vary between species.

N₂-FIXING ORGANISMS

When workers of Coptotermes formosanus were fed with filter disks containing antibacterial antibiotics, all detectable acetylene-reducing activity ceased and their gut protozoa disappeared after 3 weeks or longer (Breznak, 1973). There would, therefore, appear to be a relationship between the vitality of the protozoa and the presence of bacteria, the latter acting to fix nitrogen.

When a diet of filter paper (cellulose) was given, bacterial numbers increased by 31% and nitrogenase activity nearly ten-fold (Breznak, 1973). Many different bacteria have been isolated from the gut of termites. For example, Breznak and Pankratz (1977) isolated 13 kinds of bacteria from the gut of Reticulitermes flavipes and Coptotermes formosanus, both wood-eating termites. Three bacteria out of 13 were common to both termite species. Potrikus and Breznak (1977) isolated one N₂-fixing bacterium, Enterobacter agglomerans, from the gut of C. formosanus and showed that its activity was inhibited by oxygen.
Table 1 shows the results of a study by Eutick (1978) on the bacterial flora of nine Australian termite species. These results were irrespective of the geographical localization of the termites in Australia. There was a close relationship between the major bacterium and the termite family and seven species out of nine had N$_2$-fixing Enterobacter. For Nasutitermes exitiosus, which have no Enterobacter, French et al. (1976) found nitrogen fixation when the diet was filter paper and no fixation when the food was wood, although no explanation was offered for this finding. The function of the other bacteria was not discovered but it does not appear that they were involved in cellulose digestion (Eutick et al., 1978).

Table 1: Bacteria associated with some Australian termites (Eutick et al., 1978)

<table>
<thead>
<tr>
<th>Termite species</th>
<th>Major bacterium</th>
<th>Minor bacterium</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASTOTERMIDAE:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mastotermes darwiniensis</td>
<td>Streptococcus</td>
<td>Enterobacter, Flavobacterium</td>
</tr>
<tr>
<td>KALOTERMIDAE:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryptotermes primus</td>
<td>Streptococcus</td>
<td>Enterobacter</td>
</tr>
<tr>
<td>RHINOTERMIDAE:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heterotermes ferox</td>
<td>Enterobacter</td>
<td>Streptococcus</td>
</tr>
<tr>
<td>Coptotermes acinaciformis</td>
<td>Enterobacter</td>
<td>Bacillus</td>
</tr>
<tr>
<td>C. lacteus</td>
<td>Enterobacter</td>
<td>Streptococcus, Bacillus</td>
</tr>
<tr>
<td>Schedorhinotermes</td>
<td>Enterobacter</td>
<td>Streptococcus, Bacillus</td>
</tr>
<tr>
<td>intermedius</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TERMIDAE:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nasutitermes exitiosus</td>
<td>Staphylococcus</td>
<td>Streptococcus</td>
</tr>
<tr>
<td>N. graveolus</td>
<td>Straphylococcus</td>
<td>Enterobacter</td>
</tr>
<tr>
<td>N. walkeri</td>
<td>Straphylococcus</td>
<td>Enterobacter</td>
</tr>
</tbody>
</table>

TERMITE NESTS

Termite nests have many chambers connected by passageways. These chambers are either directly excavated or surrounded by
a mound. The building materials used are particles of earth, wood, saliva and excrement. The form and position of the nests are quite variable (Noirot, 1969).

NESTS WITHIN WOOD

This type of nest, in its simplest form, is composed of chambers connected by passageways dug within wood, dry wood for Kalotermitidae, wet wood for Termopsidae. In a more elaborated shape, passageways connect the nest to the ground (some Rhinotermitidae and Termitidae).

HYPOGEOUS OR SUBTERRANEAN NESTS

The simplest type is the diffuse nest. It has scattered chambers at different levels connected by passageways. The most complex type is the concentrated nest containing a paraecie (an empty place). The nest occupies a reduced and well-defined volume and is separated from the ground by the paraecie. Many intermediate types exist between these two extremes. Subterranean nests are built by Hodotermitidae, some Rhinotermitidae (nests made of sand agglomerated probably by excrement for Psammotermes, concentrated nests made of cellulosic material, probably stercoral, for some Coptotermes) and in some Termitidae. For this last family there are great variations: for example the concentrated and remarkably-structured nests of Apicotermes and the large diffuse nests of Odontotermes.

EPIGEOUS NESTS OR MOUNDS

These nests emerge above ground level, making a more-or-less large mound, with gently or steeply sloping sides according to species. A great number of the Termitidae and some Rhinotermitidae (e.g. some Coptotermes) build these kinds of nests, which can be divided into two types. In an homogeneously-structured nest (Fig. 1), there are no important differences between the centre and the periphery; chambers are connected by passageways. In a heterogeneously-structured nest there is an external part (wall) that is more compact than the central part (habitacle), which contains larvae, reproductives and fungus gardens (Fig. 2).

Some Amitermes have a homogeneous nest made of a mixture of earth and excrement, as do termitidae such as Termes and
Fig. 1: *Macrotermes subhyalinus* mound (Botanical garden of Dakar University). Fig. 2: Section in *Macrotermes subhyalinus* mound: structured central part with fungus-gardens and compact wall. Fig. 3: *Macrotermes subhyalinus* mound around an *Eucalyptus* trunk (Dakar University). Fig. 4: *Macrotermes subhyalinus* mound with several new constructions (Dakar University). Fig. 5: *Macrotermes subhyalinus* mound with a single large construction built during one night (40 km from Dakar). Fig. 6: *Macrotermes subhyalinus* mound without vegetation (40 km from Dakar). Fig. 7: *Macrotermes bellicosus* mound (Parc National du Niokolo-Koba, Eastern Senegal). Fig. 8: *Macrotermes bellicosus* mound with much vegetation (45 km from Dakar). Fig. 9: *Macrotermes bellicosus* veneerings around food near Dakar. Fig. 10: Section in *Trinervitermes* mound: homogeneous structure (Parc National du Niokolo-Koba, Eastern Senegal). Fig. 11: *Cubitermes* mushroom mounds (Parc National du Niokolo-Koba, Eastern Senegal).
Cubitermes (Fig. 1) and Trinervitermes (almost an underground nest, Fig. 2). Coptotermes have an heterogeneous type nest (with a clay wall, and a cellulosic habitacle). The Australian Nasutitermes and some Macrotermiteinae also have this kind of habitacle. The mounds of Macrotermes are among the largest and these are built with partly masticated material cemented with saliva.

The species Bellicositermes bellicosus (M. subhyalinus) has domed nests with a massive outside wall and a curiously structured habitacle that, in Senegal, is concentrated in form (Roy-Noël, 1971; Lepage, 1974) and diffuse at Zinder Place (Grasse and Noirot, 1961). The habitacle is linked with the wall and the underground parts.

Bellicositermes natalensis (M. bellicosus) has "cathedral-like" nests (Figs. 7-8). The habitacle lies on a pillar base. In the wall are large longitudinal corridors connected to the cavity under the base and a smaller corridor system (Ruelle, 1964).

ARBOREAL NESTS

These nests are built on trees often several metres above ground. They are connected to the ground by covered corridors along the trunk. This type of nest is built by Termitidae and Nasutitermitidae. In a Nasutitermes nest the structure is homogeneous and the construction is of cellulosic material. It is the same for Microcerotermes nests. Some species build nests of different types, according to their biotypes.

WATER NEEDS

Termites (except a few, e.g. Trinervitermes), never live in the open air. The nest is connected to the food source by underground passages or covered outside corridors. Food is surrounded (Fig. 9), or partly covered, by earthy veneers. Hollow parts are filled up with different materials according to species, e.g. soil, cellulosic material, etc.

Water is important, especially for Macrotermiteinae with
large mounds. Termites need water for their biological processes and for maintaining viable structures (e.g., permeable integuments) for producing abundant saliva for nest building and for maintaining the micro-environment of the habitacle at a suitable humidity.

Bodot (1966) estimated the quantity of water in a *Bellicositermes natalensis* (*M. bellicosus*) nest at 200 l/m³ and Lepage (1974) at 400 l for a *Bellicositermes bellicosus* (*M. subhyalinus*) half-spherical nest of 1.50 m. radius. The necessary degree of humidity changes both according to the age of the termite mound and throughout its different parts. Some species will abandon dry parts of their nest (Lepage, 1974), a situation I also noticed among *Macrotermes bellicosus* in Senegal at the end of the dry season after the low rainfall of 1970 to 1973.

Termites obtain their water supplies from surface sources. If there are none, or if they disappear during the year, the insects will go deeper in the soil to find a water supply: 40 m in the Sahara for *Psammotermes* (Grasse and Noirot, 1948), probably 40-50 m in Northern Senegal for *Psammotermes* and *Bellicositermes bellicosus* (*M. subhyalinus*) (Lepage, 1974). Recently, Leprun (1976) observed water accumulation in spongy cavities built by termites along underground corridors in Upper-Volta soils.

**ACTION OF TERMITES ON THE SOIL**

In this respect those that build large mounds in tropical regions are the most important termite groups to consider.

**EFFECTS ON WATER CIRCULATION IN THE GROUND**

Termites act in various ways on water circulation in the soil. Some authors mention a better draining of rain water at the termitories level owing to the system of underground or walled passageways. However, in *Bellicositermes natalensis* (*M. bellicosus*) nests, whose habitacles rest on pile foundations, water can temporarily accumulate in the underground hole without disturbing the nest (Boyer, 1966).

Under large mounds of *Bellicositermes bellicosus rex* (*M. subhyalinus*) in the Central African Republic, Boyer (1966) found
"artesian" water. The inflexion of the soil horizons under the mounds was the cause of a rise in hydraulic water pressure during the rainy season which forced water up through the termite galleries.

Due to their position, large epigeous nests have a relatively large surface for evaporation and this can cause a rise in subadjacent soil water by capillary action (Boyer, 1966). This author mentions it in respect to Bellicositermes natalensis (M. bellicosus) and B. bellicosus rex (M. subhyalinus) mounds. This rise in water level is very important for termites and also for the vegetation around termitories. Water moving in this way can also modify the chemical properties of the soil because of dissolved substances.

EFFECTS ON THE SOIL

This relates, essentially, to the building of epigeous nests. Termites use soil material for building and modifying their mounds and quite large amounts of soil can be moved. Meyer (1960) in the Congo area calculated that mounds of several Macrotermiteinae involved some 2,400 tons/hectare of soil. In Northern Senegal Lepage (1974) calculated, for Bellicositermes bellicosus (M. subhyalinus) 13 m$^3$/ha with an increase in weight of 1 t/ha yr.

The increase in size of the nest is not regular (see Figs. 4-5). It varies during the year according to rain, dew and the consequent changes in soil water status. Material for big mounds comes from the deeper layers. On the other hand small mounds are generally built with topsoil materials. The Cubitermes mounds in Eastern Senegal, for instance, have a few centimetres of loose topsoil laid on above a thick lateritic crust. Samples of different levels are made according to species and within a species according to the growth of the nest. For example Bellicositermes natalensis (M. bellicosus), samples will be made to 2 m depth over a surface area of 10 to 15 m$^2$. For B. bellicosus rex (M. subhyalinus) they will be deeper, up to 12 m depth, and over a surface area of 1,500 to 2,000 m$^2$ (Boyer, 1971). Indeed Lepage (1974), for B. bellicosus (M. subhyalinus) in Northern Senegal, indicates a maximum depth of 3.20 m for sample levels.
Under the very large mounds made by *B. bellicosus rex* (*M. subhyalinus*) in Central Africa, Boyer (1966) observed an inflexion of the soil layers in proportion to the underground activity of termites. Inflexion was maximum under the mound's centre and it still existed under the periphery. This kind of soil movement was so marked that Boyer used the word "puits" (a well or hole) to describe its effects. Lepage (1974) also mentioned such a movement of soil under the mounds of *B. bellicosus* (*M. subhyalinus*) in Northern Senegal, but to a smaller extent than in Central Africa.

**NATURE OF TERMITARIA MATERIALS**

The nature of Termitaria materials can change with species and, within species, between the different parts of the termitarium.

The main material is clay. Analyses made with different termite biotypes around Dakar (Senegal) showed that *Macrotermes* need soils with a minimum of 5 to 10 percent clay content (Roy-Noël, 1971).

Mineralogical analysis showed that the disposition of the two *Macrotermes* species in this area on various soils depended on clay structure (Leprun and Roy-Noël, 1976). *M. bellicosus* only occupied ferruginous and ferralitic soils containing kaolinic clay whereas *M. subhyalinus* was located on both montmorillonitic and kaolinitic clay soils. In this case this termite species included a small quantity of expanding clay into its nest by mineralogical transformations (Laprun and Roy-Noël, 1967).

In Central Africa Boyer (1966) mentions that the clayey part of mounds of *B. natalensis* (*M. bellicosus*) and of *B. bellicosus rex* (*M. subhyalinus*) mainly consists of fire-clay type kaolinic products. In large mounds of *B. bellicosus rex* (*M. subhyalinus*) he observed other silicates of aluminium from deeper horizons (illite) or from neoformation, that is artificial illite resulting from the grinding and trituration of micas by termites to form montmorillonite and hydrobiotite, these not being present in the substratum.
Other materials used by termites are sands, which may be pure quartz, ferruginous pseudo-sands, very hard ferruginous concretions or other heavy minerals (Boyer, 1966). Termites make their own choice, this varying with species, the part of the nest being built (Table 2) and the area.

Table 2: Mechanical analysis of soil from mounds of some termite species (after Maldague, 1959)

<table>
<thead>
<tr>
<th>Termite species and source of sample</th>
<th>fine elements, % (silt and clay)</th>
<th>sands, % fine</th>
<th>coarse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellicositermes bellicosus (M. subhyalinus)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEST: wall</td>
<td>70.6</td>
<td>11.6</td>
<td>17.9</td>
</tr>
<tr>
<td>centre</td>
<td>82.0</td>
<td>11.1</td>
<td>8.8</td>
</tr>
<tr>
<td>SOIL: 10 cm</td>
<td>31.8</td>
<td>29.7</td>
<td>38.4</td>
</tr>
<tr>
<td>50 cm</td>
<td>20.1</td>
<td>29.9</td>
<td>50.0</td>
</tr>
<tr>
<td>Bellicositermes natalensis (M. bellicosus)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEST WALL</td>
<td>69.7</td>
<td>15.1</td>
<td>15.2</td>
</tr>
<tr>
<td>TOPSOIL</td>
<td>56.5</td>
<td>20.2</td>
<td>23.3</td>
</tr>
<tr>
<td>Amitermes unidentatus (evuncifer)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEST: wall</td>
<td>63.5</td>
<td>12.1</td>
<td>24.4</td>
</tr>
<tr>
<td>centre</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TOPSOIL</td>
<td>59.0</td>
<td>18.8</td>
<td>22.1</td>
</tr>
<tr>
<td>Nasutitermes ueleensis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEST</td>
<td>55.0</td>
<td>29.5</td>
<td>15.5</td>
</tr>
<tr>
<td>TOPSOIL</td>
<td>40.4</td>
<td>24.7</td>
<td>34.9</td>
</tr>
</tbody>
</table>

For domed nests of B. bellicosus (M. subhyalinus) Lepage (1974) mentions a 1.5-3.0 cm thickness of deposit on the surrounding soil per year. Boyer (1966) noted only a small amount of erosion for "cathedral" nests of B. natalensis (M. bellicosus) but a greater amount for the large mounds of B. bellicosus rex (M. subhyalinus). The "cathedral" nests have a wall microstructure (with pectinized elements) that resists
erosion. The microstructure of the large mounds is such that the superficial material can easily be swept away.

Spread around a mound, therefore, will be material more or less from various soil horizons, with neo-formation materials and other substances that result from the action of termites on soil chemistry. The nature of these materials depends on the species. It also changes with the stage of erosion because the materials used in the wall and the habitacle appear in different proportions.

Lepage (1974) observed that the cone of erosion of the mound of *B. bellicosus* (*M. subhyalinus*) makes a relatively impermeable layer, consisting as it does of cohesive, fine material with a low porosity. Clos-Arceduc (1956) has also mentioned this as occurring around "cathedral" mounds of *M. bellicosus* and I have observed it for many *M. bellicosus* and *M. subhyalinus* mounds.

As far back as 1931 in Angola, Nazaroff (1931) related these tunnel formations in "laterite" to termite activity and later Erhart (1951) again repeated the hypothesis. Tessier (1959) also discovered fossil termitaria in laterite at Dakar. By making a size analysis and thin sections he was able to distinguish deep habitacles, passageways, and at the surface, spongy areas. The effects of termites in the genesis of some ferruginous crusts is no longer accepted, but it is possible that old termitaria may become ferruginous (Bachelier, 1963).

**EFFECTS OF TERMITES ON PHYSICAL PROPERTIES OF THE SOIL**

Termites looking for building material, food and water dig many passageways which aerate the soil. Indeed Drummond (1888, mentioned by Boyer, 1966) and Grasse (1950) maintain that termites are more important in this respect than earthworms. Tricart (1957) identifies their importance in breaking up lateritic crusts and they can decrease soil bulk density. For example, with *B. bellicosus rex* (*M. subhyalinus*) (Boyer, 1971) nest materials are less rich in coarse sand than sample horizons but for *B. bellicosus* (*M. subhyalinus*), Lepage (1974) found that the proportion of coarse sand in non-altered soil decreased from the surface down although it was the contrary for the eroded nest.
EFFECTS ON CHEMICAL CHARACTERISTICS OF THE SOIL

Several authors have observed an increase in pH in termitaria compared with the surrounding soil. For example for *M. bellicosus* (*M. subhyalinus*) and *Cubitermes* (Stoops, 1964) and for *B. bellicosus* (*M. subhyalinus*) (Lepage, 1974), soil pH of 5.5 to 6, increased to pH 7.4 in the mound. Indeed the mound material can reach 8.6 when there is a calcareous level underneath and Lee and Wood (1971) found that an increase in pH is often connected with an accumulation of carbonates. On the other hand Maldegue (1959) found a lower pH in nests (5.5) than in the surrounding soil (6.7-7.0) with *B. bellicosus* (*M. subhyalinus*) and little change (5.3 and 5.9) with *B. natalensis* (*M. bellicosus*).

The effects of termites are both negative and positive; they feed on soil organic matter but they return some of it to the soil in a changed form through their saliva and excrements and dead bodies.

For example, humivore termites digest some part of the soil humus and Meyer and Maldague (1956 mentioned by Boyer, 1966) and Maldague (1959) found only thin layers of humus in Belgian Congo (Zaire) forests that they attributed to termite action. Foraging termites, and those that feed on dead wood, will tend to decrease the quantity of organic matter which otherwise would be incorporated in the soil by the action of other organisms, or some components of it.

Organic matter is added to the nest materials but there are important differences according to the building method used. Nests built with mineral material agglomerated with saliva (*e.g.* *Macrotermes*) have less organic matter than nests built with early excrements (*e.g.* *Cubitermes*) or stercoraceous material (containing faeces) (*e.g.* in the central part of *Amitermes* mounds). There can also be an organic matter reserve in the form of combs in the nests of fungus-growing termites. Some examples of C and N enrichment are given in Table 3. Generally, percent C and N, and C/N are lower in the mounds of *Macrotermes* sp. than in the surrounding soil.
Table 3: Differences in soil C and N (%) and C/N between termite mounds and surrounding soil (0-5 cm depth)

<table>
<thead>
<tr>
<th>Soil type</th>
<th>C%</th>
<th>N%</th>
<th>C/N</th>
<th>Mound type</th>
<th>C%</th>
<th>N%</th>
<th>C/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. ZAIRE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy 1</td>
<td>1.13</td>
<td>0.082</td>
<td>13.6</td>
<td>Cubitermes</td>
<td>1.40</td>
<td>0.112</td>
<td>12.5</td>
</tr>
<tr>
<td>Lateritic crust</td>
<td>2.77</td>
<td>0.306</td>
<td>9.1</td>
<td>Cubitermes</td>
<td>3.81</td>
<td>0.358</td>
<td>10.6</td>
</tr>
<tr>
<td>Sandy 1</td>
<td>2.29</td>
<td>0.247</td>
<td>9.27</td>
<td>Amitermes: Centre</td>
<td>14.00</td>
<td>0.750</td>
<td>18.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wall</td>
<td>4.18</td>
<td>0.222</td>
<td>18.82</td>
</tr>
<tr>
<td>Sandy 2</td>
<td>1.17</td>
<td>0.122</td>
<td>9.59</td>
<td>B. natalensis</td>
<td>0.76</td>
<td>0.081</td>
<td>9.38</td>
</tr>
<tr>
<td>Sandy 2</td>
<td>0.48-2.60</td>
<td>0.051-0.264</td>
<td>9.41-11.84</td>
<td>B. bellicosus: Centre</td>
<td>0.52</td>
<td>0.057</td>
<td>9.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wall</td>
<td>0.61</td>
<td>0.066</td>
<td>9.24</td>
</tr>
<tr>
<td>B. SENEGAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy 3</td>
<td>0.84</td>
<td>0.115</td>
<td>6.53</td>
<td>M. bellicosus: Wall</td>
<td>0.62</td>
<td>0.095</td>
<td>6.23</td>
</tr>
<tr>
<td>Sandy 3</td>
<td>1.47</td>
<td>0.118</td>
<td>7.89</td>
<td>M. subhyalinus: Wall</td>
<td>0.665</td>
<td>0.096</td>
<td>6.84</td>
</tr>
</tbody>
</table>


In several countries, some authors have pointed out that there is an increase of bases in termitories (especially exchangeable bases) and often CaCO₃ accumulation under large mounds, as indicated by the rise in pH mentioned previously, e.g. Indonesia (Kalshoven, 1936 and 1941; Indenberg, 1937), Tanzania (Milne, 1936), Thailand (Pendleton, 1942), Uganda (Griffith, 1938), Belgian Zaire (Sys, 1957, mentioned by Boyer (1966); Stoops, 1964), C.A.E. (Boyer, 1966), Senegal (Lepage, 1974; Leprun and Roy-Noël, 1977), Nigeria (Kang, 1978). On the other hand Hesse (1955) found no chemical differences between termitories of Macrotermes and surrounding soils in Eastern Africa.
Tables 4 and 5 give examples of proportions of exchangeable bases found in termite mounds under particular conditions. The clear increase of bases in termitaries can have several origins. For example, water rising from underground contains dissolved bases and its evaporation at the termitarium level brings dissolved salts into the nests. Furthermore, there is a direct action of termites on soil materials by salivary trituration, liberating ions (Boyer, 1966).

Table 4: Exchangeable bases in *Macrotermes subhyalinus* mounds

<table>
<thead>
<tr>
<th>Source of soil sample</th>
<th>Sampling depth, cm</th>
<th>Exchangeable bases, me/100 g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ca</td>
</tr>
<tr>
<td><strong>B. BELLICOSUS REX</strong> (Boyer, 1966):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil surrounding mound</td>
<td>5</td>
<td>4.38</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>4.08</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2.78</td>
</tr>
<tr>
<td>Soil from centre of mound</td>
<td>2</td>
<td>6.35</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>6.05</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>16.14</td>
</tr>
<tr>
<td><strong>B. BELLICOSUS</strong> (Boulet and Leprun, 1970; Lepage, 1974):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil surrounding mound</td>
<td>0-10</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>70-80</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>2.66</td>
</tr>
<tr>
<td>Soil of eroded mound (without CaCO₃)</td>
<td>0-10</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>4.14</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>3.47</td>
</tr>
<tr>
<td>Soil of eroded mound (with CaCO₃)</td>
<td>0-10</td>
<td>7.74</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>4.96</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>27.85</td>
</tr>
</tbody>
</table>

**EFFECTS ON SOIL FERTILITY**

The fertility of mounds and the surrounding soils will obviously depend on the various factors mentioned above. As these
Table 5: Exchangeable bases in *Macrotermes bellicosus* and *Cubitermes sankurensis* mounds

<table>
<thead>
<tr>
<th>Source of soil sample</th>
<th>Sampling depth, cm</th>
<th>Exchangeable bases, me/100 g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ca</td>
<td>Mg</td>
</tr>
<tr>
<td><strong>B. NATALENSIS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Boyer, 1966):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil under spread</td>
<td>20</td>
<td>2.05</td>
</tr>
<tr>
<td>material</td>
<td>40</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1.12</td>
</tr>
<tr>
<td>Soil from inhabited</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td>2.28</td>
<td>2.12</td>
</tr>
<tr>
<td>Habitacle</td>
<td>4.93</td>
<td>2.32</td>
</tr>
<tr>
<td><strong>B. NATALENSIS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Stoops, 1964):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil surrounding</td>
<td>0-15</td>
<td>0.05</td>
</tr>
<tr>
<td>mound</td>
<td>45-55</td>
<td>0.05</td>
</tr>
<tr>
<td>Soil from uninhabited</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td>0.27</td>
<td>0.12</td>
</tr>
<tr>
<td>Centre</td>
<td>0.31</td>
<td>0.37</td>
</tr>
<tr>
<td>Soil from inhabited</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td>0.13</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>CUBITERMES SANKURENSIS</strong> (Stoops, 1964):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil surrounding</td>
<td>0-12</td>
<td>0.65</td>
</tr>
<tr>
<td>mound</td>
<td>30-50</td>
<td>0.08</td>
</tr>
<tr>
<td>Soil from top of mound</td>
<td>1.60</td>
<td>0.60</td>
</tr>
</tbody>
</table>

will change with species, erosion stage and soil composition, it is easy to understand why many authors give different and sometimes contradictory results.

Water movement under and around large mounds will develop a wet area that can be advantageous for vegetation (*e.g.* Boyer, 1966). Indeed this author explains the "savanes tigrées"
formation in some dry areas in tropical Africa as "l'emplacement des anciennes termitières souvent totalement arasées offre une vegetation arbustive et herbacée plus dense que celle du reste de la savane et restant verte longtemps en saison sèche". On the other hand Clos-Arceduc (1956) observed that the soil of B. natalensis (M. bellicosus) nests was "tout à fait imperméable se comporte comme un parapluie asséchant le sous-sol à son aplomb" and there was no vegetation actually on the eroded termitaria. Certainly, in undisturbed soil, all termite passageways make for easier water circulation. Robinson (1958) in Kenya observed the good effect of Odontotermes badius on coffee-shrub plantations.

In Cubitermes, Amitermes and Nasutitermes mounds the per­centages of organic matter and exchangeable bases are higher than in the surrounding topsoil. These accumulations become very important in improving soil fertility when the mound is finally destroyed. However, for Cubitermes nests, in particular, there is the adverse factor relating to the compactness of the mound materials. Indeed, these mounds were formerly used for surfacing tracks in Africa (Harris, 1961).

As has already been mentioned, Macrotermes nests are less rich in organic matter but richer in bases surrounding topsoil. The fertility of these mounds has been discussed by various authors. For instance, Harris (1961) states that "... in Africa, the spread of woodland ... into areas where man has obliterated the original cover is preceded by the development of large termite mounds" and that "crops grown on a large scale, such as sisal, cotton and tobacco, indicate by increased growth and intensified green colour and the presence of termite mounds ... (that the) peasant(s)... cultivate only the top and sides of a mound ....". Then, again, Sillians (1959) and Thomas (1941), both mentioned by Harris (1961) describe mound vegetation in Oubangi-Chari (C.A.E.) and Uganda, respectively, and Troll (1936) commented on the vegetation formations, consisting of grass and limited islands of woodland, that are found based on large termite mounds in both Africa and South America.

Some authors, however, such as Clos-Arceduc (1956) describing the erosion stages of M. bellicosus mounds; Lepage (1974)
commenting on *M. subhyalinus* mounds, as well as others before them, have stressed that vegetation does not grow on these termite mounds and that crops are less vigorous in association with them. The last author specifies that "farmers generally avoid cultivating mounds".

In Western Senegal the following personal observations are relevant. For *M. subhyalinus*, nests may sometimes have vegetation (grass and bush) on them or at their base and sometimes they may not (Fig. 6). In the first case nest materials are not so compact and sorghum growing close by is more vigorous than near the second type of mound. The two nest types may, however, be separated by only several metres. This seems to indicate that there are very specific conditions, varying according to micro-location (surface soil more or less sandy, topsoil slope, pH, etc.) moderating the structural composition of these pests and term their efforts in selecting soil fertility.

For *M. bellicosus*, nests are generally surrounded at their base by compacted material without any vegetation, but some nests have vegetation on and/or near them (Fig. 8). Farmers do not destroy the mounds of either of these two species (Roy-Noël, 1976) and crops are generally taller around such termitaria even if there is no vegetation at their base. Trees (e.g. *Eucalyptus*, *Prosopis*, and palm trees) which have *M. subhyalinus* nests around or near their trunks are more vigorous (Fig. 3).

I have observed, that *M. subhyalinus* and *M. bellicosus* do not attack living trees and crops as they eat only dead wood (Roy-Noël, 1971). The authors mentioned above have made the same observation, although some authors consider these two termite species as forestry pests in Africa (see Harris, 1961).

From all these various observations we must conclude that the situation is complex. In order to make use of material from termitaria, or in order to improve the material disseminated around the base, it is necessary for each area or site not only to know what termite species are involved, but also to study the mound material, the topsoil material and the related crop. Thus the results obtained for any particular species cannot be used for other areas without further information.
TERMITES AND AGROFORESTRY

The effects of termites are an important consideration in land-use systems involving mixtures of perennial and herbaceous species. However, from what has been said above it is clear that no simple guidelines can be provided at this stage. The presence of increased amounts of woody debris and/or humus will undoubtedly provide a greater food supply for termites, but whether or not they use it will depend on the way it is disposed, its manner and rate of decomposition and also on soil conditions and other environmental factors; in addition, of course, on the species of termites originally present and those which will eventually flourish.

If termite populations are encouraged then the possibility has to be borne in mind of damage by xylophagous species to woody crop plants, including even such crops as maize and sorghum. But here, again, the extent to which this may or may not happen will depend on a whole range of factors, including the availability of other alternative food sources from adjacent trees and shrubs.

Thus a close examination of any agroforestry system is needed so as to monitor what is happening and to evaluate carefully the balance of beneficial and detrimental termite activities in any particular situation.

**Discussion**

*Singh:* Termite nests are very common in the tobacco growing areas in Tanzania, especially in Iringa region.

*Sánchez:* Should one clear the termite mounds?

*Roy-Noël:* In Senegal, *M. bellicosus* mounds are left because Macrotermes control the Odontotermes which eat the crop.

*Redhead:* The best growth in a plantation crop was commonly found around termitaria in N. Nigeria. In this area, *Tamarindus indica* was never found growing naturally except on old termitaria. Has the speaker observed this?

*Roy-Noël:* No.

*Ahn:* In the Accra plains (Ghana) short grass savanna vegetation is suppressed by thicker clumps – which grow on old termitaria.

*Redhead:* Termite damage to *Eucalyptus* spp. is overcome by adding Aldrin or Dieldrin to the potting mixture or applying the chemical around the planting hole. Do you know any other such chemicals?
H.O. Mongi: In view of the disadvantages of *M. bellicosus* in eating leaf litter and of *Odontotermes* spp. in eating crops raised in much of East and Central Africa, what advice do you have to offer for raising viable agroforestry systems? For example, some tree species seem to escape some of the termite effects.

Roy-Noël: No concrete information is available on this. It is impossible to indicate the tree species that escape termite effects because they vary according to specific conditions. Some authors have written that *Casuarina* spp. are not attacked by termites in Africa. But they are in several areas, especially in Senegal.

Near Dakar, on live dunes (sandy soils) tree plantations with *Casuarina equisetifolia* are attacked by "within-wood" nest termites and arboreal nest termites. On the Northern Plantations which are exposed to the winds these termites are not so frequent. On fixed dunes (sandy clay soils) there are tree plantations with *Anacardium occidentalis*, *Eucalyptus* spp. and *C. equisetifolia*. The first species is the tree most attacked by termites. Here termites species are more numerous because there are also subterranean nest termites.

When planting *Eucalyptus*, chemical insecticides are applied in the plantation holes. It is necessary to destroy arboreal nests and to burn dead trees that have "within-wood" nests before the rainy season.

**LITERATURE CITED**


The disastrous effects of nematodes on the productivity of crop plants are often not recognized but they can be demonstrated under different farming systems, soil and climatic conditions by the use of nematicides. For example, two types of positive yield responses to DBCP (nematicide) have been observed with: (1) soybeans (infected by *Pratylenchus sefaensis* and *Aphasmastylelenchus stratoratus*) and groundnuts (infected by *A. stratoratus* and *Scutellonema cavenessi*), and (2) groundnuts affected by clump disease caused by a virus transmitted by a fungus sensitive to the nematicide. DBCP treatment of a groundnuts chlorosis thought to be due to nematodes had, however, no effect on the disease or yields and it was subsequently established that the symptoms were due to K⁺, Na⁺, Cl⁻ toxicities resulting from the large amount of ash accumulating on the spots where plant residues were burnt at the time of land preparation.

Relatively few nematological studies have been carried out in vast areas of Africa, with its diversity of geographical and climatic regions. Many of the studies have been restricted to faunistic surveys. Investigations of fauna rarely suffice in themselves for the detection of agricultural problems due to nematodes. This is especially true in the case of cultivated crops in Africa, which are often grown on recently-cleared land where nematode populations are often very varied and contain new species.

High populations of polyphagous, pathogenic nematodes (*viz.*, *Meloidogyne*, *Rotylenchulus* and *Pratylenchus* spp) and the presence of species specific to certain crops (*viz.*, *Radopholus similis* on banana and *Tylenchulus semipenetrans* on citrus) are almost always associated with crop damage. This is not always the case with other species whose pathogenicity is unknown because of their recent discovery and a lack of information on their biology. Crop damage due to nematodes is often difficult, if not impossible, to discern through observation of the plants alone. Nematicide treatments are generally of great use in

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B.P. 1388, Dakar, Senegal*
the detection of plant disease by nematodes.

There are two types of situation in which nematicidal applications are useful for the detection of disease problems in Africa. The first situation is where the nematodes found in a particular area are already known to be pathogenic in other areas of the world. Then nematicide treatments allow for the confirmation of pathogenicity and of the efficacy of the nematicide applied in the new situation. This is the case with banana infected by *Radopholus similis* in the Ivory Coast (Luc and Vilardebo, 1961) and of soybean in Senegal, infected by *Pratylenchus setaensis* (Fortuner, 1973).

The second situation is where the nematodes infesting a given crop are not known or are only suspected of parasitism, and nematicide treatments restore or improve crop yield. The resulting benefits may be attributable to the control of nematodes. This is the case, for example, of a disease, "Upper-Volta chlorosis of legumes" (Germani, 1972) which was discovered almost at the same time as the possible causal agent *Aphasmatylenchus straturatus* (Germani, 1970). If nematicidal trials had not been carried out, it is likely that investigation of the nematode would have merely remained a taxonomic study because of its limited distribution and the relatively low level of its population in the soil.

Sometimes, however, yield increases resulting from nematicide application cannot be attributed directly to nematicidal activity. Most nematicides are rather general biocides and they can therefore affect some other pathogenic agents. If crop improvement does not occur with nematicidal treatment, however, it can be concluded that nematode pathogenicity is not a factor and attention can be directed to other causes. One case in point is where we were able to show that a specific chlorosis of peanut was due to soil physical factors and not to nematodes or other pathogens.
NEMATICIDE USE IN PLANT DISEASE DETECTION AND CONTROL

The following examples from our experiments and studies in West Africa will illustrate the use of nematicides for the detection or elimination of nematodes as causal agents of plant disease problems.

SOYBEAN INFECTED BY Pratylenchus sefaensis

A trial of nematicidal treatment with Nemagon (ibromochloropropane) was included in an experiment carried out at Sefã (Casamance) by ISRA* in the study of inoculation techniques of *Rhizobium* on soybean (cv. 44A73). In this experiment, six plots were treated with nematicide and six untreated served as controls. Each of the twelve plots received the same inoculation of *Rhizobium japonicum* G2Sp embedded in a polyacrylamide gel (Dommergues et al., 1979). Three series of measurements were performed during the plant's life-cycle on the treated and control plots, viz. (1) the number and (2) dry weight of root nodules after 51, 67, and 88 days' plant growth; and (3) nematode count after 60 days of plant growth (Table 1). Data showed a considerable beneficial effect of the nematicide application on the nematode population and particularly on *P. sefaensis*, which had been reduced to 27 per 100 g of roots as against an average of 200,000 for the control. The favourable effect of the nematicide was also apparent on the aerial parts of the plants. The root systems of plants in the control plots were less developed, had fewer nodules, and had a great deal of necrosis in comparison with the roots in the treated plots. The increase in yield of beans obtained on the treated plots was 206% that of the control plots (Table 1).

CHLOROSIS OF PEANUT AND SOYBEAN PLANTS IN UPPER-VOLTA INFECTED BY Aphanomyces straturatus

At the beginning of the 1960s, a chlorosis of peanuts had been noted in the village of Niangoloko in south-west Upper-Volta, but the cause was unknown. Observations carried out in 1968 had proved a consistent coincidence between the chlorosis

*Institute Sénégalais de Recherche Agronomique
Table 1. Effect of soil fumigation with DBCP on number and weight of nodules and yield of field-grown soybean infected with *Pratylenchus semifolius*

<table>
<thead>
<tr>
<th>Time</th>
<th>Number (a)</th>
<th>Dry weight (a)</th>
<th>Number (b)</th>
<th>Dry weight (b)</th>
<th>Yield (kg/beans ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51 Days</td>
<td>27</td>
<td>181</td>
<td>14</td>
<td>174</td>
<td>2207</td>
</tr>
<tr>
<td>67 Days</td>
<td>31</td>
<td>407</td>
<td>21</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>88 Days</td>
<td>33</td>
<td>276</td>
<td>21</td>
<td>291</td>
<td></td>
</tr>
<tr>
<td>a/b %</td>
<td>191</td>
<td>104</td>
<td>150</td>
<td>122</td>
<td>1072</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>206</td>
</tr>
</tbody>
</table>
and the presence of a new species of plant pathogenic nematode, *Aphasmatylenchus straturatus*, in the soil. It became evident later that not only peanuts but also other legumes growing in the same region showed similar symptoms, *via* soybean, *Cajanus cajan*, *Tephrosia* sp., *Voandzia subterranea*, *Vigna sinensis* and *Stylosanthes gracilis*. A survey on the extent and severity of the disease in peanut and *Cajanus cajan*, in 1974, showed roughly 25% of the fields were afflicted with chlorosis and infested by *A. straturatus*. The affected areas comprised 1.7% of the total area observed.

The nematicide treatments performed on diseased peanuts always significantly decreased the numbers of nematodes, simultaneously suppressed the chlorosis (Plate 1, Fig. 3) and increased pod yields (Dhery et al., 1975 and Dhery, 1973). Foliar analysis showed that diseased plants were very deficient in nitrogen, the nitrogen level in healthy plants being 225% that of chlorotic plants. It was shown (unpublished data) that chlorosis of the legumes resulted from N deficiency and was correlated with reduced nodulation (Plate 1, Fig. 1, 2) due to the parasitic action of *A. straturatus*. Another field experiment was made on soybean infected by *A. straturatus* in a field near the village of Koutoua (s.w. Upper-Volta). Four treatments were compared in this experiment (Fisher blocs design) (Table 4).

The calculation of the number and weight of the nodules and the measurement of ARAP (acetylene reduction per plant), carried out after 63 days' growth of the plants, and bean yield are shown in Table 2. The nematicide treatment had a greater influence on the yield than the *Rhizobium* inoculation. As noted previously in peanuts, infection of soybean by nematodes caused a significantly reduced nodulation, N2-fixation and crop yield.

The application of nematicide on areas infected by *A. straturatus* has thus shown that a species belonging to a genus that was considered as a mere taxonomic curiosity could be a most serious pathogen. According to inoculation experiments carried out in the greenhouse, there is now evidence that *A. straturatus* is responsible for the chlorosis of legumes in Upper-Volta.
Fig. 1: Upper-Volta chlorosis of groundnuts: profuse nodulation in root system uninfected by nematodes. Fig. 2: Upper-Volta chlorosis of groundnuts: poor nodulation in root system infected by A. straturatus. Fig. 3: Upper-Volta chlorosis of groundnuts: experimental alternate plots fumigated with DBCP show growth improvement while unfumigated ones do not. Fig. 4: Upper-Volta groundnuts clump-disease: experimental plots fumigated with DBCP show growth improvement (left) while unfumigated ones do not. Fig. 5: Growth improvement in groundnuts infested by Scutellonema cavenessi at Patar, Senegal, following fumigation with DBCP. The plants in the foreground (stunted) were not fumigated.
Table 2. Effect of soil fumigation with DBCP and inoculation with *Rhizobium japonicum* on nodulation, N\textsubscript{2}-fixation (ARAP*) and yield of field-grown soybean infested with *A. straturatus* (Upper-Volta).

<table>
<thead>
<tr>
<th></th>
<th>Rhizobium inoculated</th>
<th></th>
<th>Uninoculated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nodules</td>
<td>ARAP micromoles per plant</td>
<td>Yield kg/beans/ha</td>
</tr>
<tr>
<td>Number Dry weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fumigated (a)</td>
<td>19 678 5.59 777 9</td>
<td>410 3.07 872</td>
<td>Unfumigated (b)</td>
</tr>
<tr>
<td>a/b, % 298</td>
<td>272 203</td>
<td>186 185 400 786</td>
<td>176</td>
</tr>
</tbody>
</table>

*ARAP: Acetylene reducing activity per plant (micromoles/hour)*
A nematological survey in the traditional groundnuts-growing area in Senegal revealed that there was apparently no nematode specific only to groundnuts and generally nematodes associated with them were the same as those infecting millet and sorghum, which are frequently grown in rotation with groundnuts. However, the high population and widespread distribution of *Sautellonema avenessi* (Sher, 1963) peanut fields indicated it may be an important parasite.

Two experiments were carried out at Patar (Plate 1, Fig. 5), Central Senegal, in order to: (1) estimate the impact of nematode infection on the growth and yield of peanut, (2) estimate the residual effect of nematicides on peanut and millet production and (3) compare responses of some peanut cultivars.

The first experiment was placed in a field where crop rotation was as follows: peanut (1974), peanut (1975), millet (1976), peanut (1977) and millet (1978). The experiment was set up according to a Fisher Block design. More details about experimental procedures are reported in another paper (Germani and Gautreau, 1977). Yield data (Table 3) showed that DBCP fumigation significantly increased peanut and millet yield. Moreover it was interesting to note that this treatment enhanced mycorrhizal infection of peanut variety 28-206 (Germani, *et al.*, 1979).

In the second experiment, a nematicide application was made, before sowing, in 1978 on groundnuts (cv 55-437) in a field contiguous to that of the first experiment (latin square design with four treatments). Tested chemicals were: Mocap 10 G at 100 kg/ha (10% a.i. as Ethoprofos) spread over the field surface; (2) Furadan 10 G at 6 g/m (10% a.i. as Carbofuran) spread in the rows; (3) Nemagon (liquid, 75% a.i. as DBCP) applied by infection into the soil at 15 l/ha; and (4) Control (no soil treatment).

All the treatments were performed the same day as the sowing. None of the nematicides used were phytotoxic to groundnuts. In previous experiments with Nemagon, a higher rate of 25 l/ha was
Table 3. Yields of groundnuts (cv 28-206) and millet (cv Sanic) observed in the year of fumigation with DBCP and one or two years later.

<table>
<thead>
<tr>
<th>Year of fumigation</th>
<th>Year of crop</th>
<th>Yield (kg pods per/ha)</th>
<th>increase a/b, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fumigated (a)</td>
<td>Unfumigated (b)</td>
</tr>
<tr>
<td>Groundnuts</td>
<td>1974</td>
<td>3630</td>
<td>2545</td>
</tr>
<tr>
<td></td>
<td>1974</td>
<td>2680</td>
<td>1920</td>
</tr>
<tr>
<td></td>
<td>1975</td>
<td>2950</td>
<td>1015</td>
</tr>
<tr>
<td>Millet</td>
<td>1976</td>
<td>1805</td>
<td>1523</td>
</tr>
<tr>
<td>Groundnuts</td>
<td>1976</td>
<td>1469</td>
<td>641</td>
</tr>
<tr>
<td></td>
<td>1977</td>
<td>1893</td>
<td>793</td>
</tr>
<tr>
<td>Millet</td>
<td>1976</td>
<td>1153</td>
<td>936</td>
</tr>
<tr>
<td></td>
<td>1977</td>
<td>1469</td>
<td>1272</td>
</tr>
</tbody>
</table>
used. As the nematicide is phytotoxic when used at this rate, it had to be applied one week before sowing. Since it is not possible to apply nematicides before the beginning of the rainy season in the Sahel, the treatments were made at the first rainfall and sowing was made at the second rainfall, thus avoiding any phytotoxic effect. Since it has been shown that a delay of 8 days in sowing causes yield losses up to 85% (Germani and Gautreau, 1977), the fact that a lower rate of Nemagon (15 l/ha) used at the time of sowing is not toxic seems to be of interest because it avoids the planting delay, and the cost of the treatments is much lower and a widespread application of these treatments can be considered.

Nematodes were enumerated in the different treatments after 34 days of growth of the groundnuts, i.e. the time when the number of nematodes in the roots was increasing (see Fig. 6). Table 4 shows data on yields (pods and straws). The effects of Nemagon and Furadan on nematode numbers are not similar, while their effects on groundnuts yield is quite similar. This is due to the fact that the first compound is a fumigant acting by contact and the latter has a systematic action.

In conclusion, although these results of nematicide treatments cannot be positively attributed to the mere killing of nematodes, this hypothesis cannot be rejected and it should be confirmed by further experiments. In any case, the application of nematicides appears to be economically feasible, the profitability being increased by the residual effect of Nemagon, which may last for two consecutive years in groundnuts and millet fields. The effect of nematicide treatments varied from year to year (Tables 3 and 4), probably along with rainfall which, in Senegal, is the major limiting factor in groundnuts production.

CHLOROSIS OF GROUNDNUTS IN SENEGAL

During our survey on groundnuts in Senegal, a number of chlorotic areas were recorded. A nematicide treatment was performed in two areas, each area having four plots. Two of the plots were treated while the other two untreated plots were considered as controls. Two types of chlorosis were discovered.
Fig. 6. Variations in the number of *Sutellonema cavensis* per 100 g roots (A) or per litre of soil (B) during the growth of groundnuts (*Arachis hypogea*) cv. 55-437 at Bambey Experimental Station, 1974.
Table 4. Effect of soil treatment with three nematicides on the number of *Sceletionema cavenessi* present in soil after treatment and on peanut yields (kg pods or straw per ha).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of <em>S. cavenessi</em> per 100g soil</th>
<th>No. of <em>S. cavenessi</em> per 100g roots</th>
<th>Wt. of pods kg/ha</th>
<th>Wt. of straw kg/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>3248</td>
<td>27567</td>
<td>2103</td>
<td>2768</td>
</tr>
<tr>
<td>Nocap</td>
<td>3504</td>
<td>2145</td>
<td>2252 (7)*</td>
<td>3156 (14)</td>
</tr>
<tr>
<td>Nemagon</td>
<td>14</td>
<td>26</td>
<td>2504 (19)</td>
<td>3589 (30)</td>
</tr>
<tr>
<td>Furadan</td>
<td>3288</td>
<td>1250</td>
<td>2753 (31)</td>
<td>3579 (30)</td>
</tr>
</tbody>
</table>

* Numbers in brackets represent % yield increase
Chlorosis attributed to a nematode (*S. aavenessi*)

The nematicide treatment was performed in the area where peanut (cv 55-437) regularly showed symptoms of chlorosis. These areas were heavily infested by *S. aavenessi*. Plants from plots treated with Nemagon showed a homogeneous green appearance; in contrast to the chlorotic plants in the control plots (Germani and Gautreau, 1977). No pathogenic nematodes were observed in treated plots whereas high numbers of *S. aavenessi* were found in the control plots (30,000 ± nematodes per 100 g of groundnuts roots). Plants from treated plots were 3.5 times higher in ARAP and had well-developed nodules. Yields from treated plots were 140% higher than those of controls. These results were similar to those obtained in Upper-Volta with *A. straturatus*.

Chlorosis attributed to a soil defect

This type of chlorosis was associated with the reduction of the root system and of nodulation. In this case, the nematicide treatment had no effect on the chlorosis. Nematological analysis of soil and roots showed that nematode populations were low even in control plots. It was noted that soil from the chlorotic areas contained a large number of charred plant fragments and ash. This suggested previous on-the-spot burning of bush or crop residue, a common practice during the inter-season in Senegal, a factor which was most probably responsible for the groundnuts chlorosis. This hypothesis was confirmed by experiments in the laboratory which showed that addition of ashes to the soil increased the pH up to 9.0 and simultaneously increased the Cl⁻, K⁺ and Na⁺ content and induced chlorosis symptoms in groundnuts (Germani, 1975).

CLUMP-DISEASE OF GROUNDNUTS

Clump-disease of groundnuts has been known since 1931 but its cause was discovered only in 1974, following nematicide treatment of diseased areas in Upper-Volta (Dhery *et al.*, 1975; Germani and Dhery, 1973) and in Senegal (Menry and Mauboussin, 1973). Although the soil treatment with DBCP suppressed the
disease (Plate I, Fig. 4) and increased groundnut yields (Dhery et al., 1975; Germani and Dhery, 1973), the responsibility of nematodes for this disease was not demonstrated. No nematode appeared to be clearly associated with the disease, and symptoms of clump-disease did not resemble those generally caused by nematodes. Therefore investigations were initiated to determine whether the disease could be induced by a virus.

There is now evidence that clump-disease is virus-induced, as shown by graft transmission experiments and by electron microscopy (Germani et al., 1975; Thouvenel et al., 1974). Although positive results were obtained with nematicide treatments, they did not elucidate the nature of the pathogen (which was a tubular virus). They did, however, establish that the vector was in the soil and also indicate that it was sensitive to DBCP. Attempts to study Trichodorus sp., the only nematode genus able to transport tubular virus in the rhizosphere, were not successful. It is now suggested that the vector may be a fungus of the group Plasmopodiophorales (Thouvenel, pers. comm.) whose spores are sensitive to Nemagon. The clump virus may also be transmitted by seeds (Thouvenel et al., 1978), which may explain its geographic dispersion.

Therefore experiments using nematicide treatments carried out in Senegal and in Upper-Volta on legumes and especially on peanut have led to some results of practical importance: viz. (1) the possibility of increasing groundnut yields by applying a nematicide at the time of sowing, (2) the suppression of Upper-Volta chlorosis of groundnuts (a disease affecting many legumes), (3) establishment of the nature of clump-disease and its control, (4) confirmation of the unfavourable effects of crop-residue burning on groundnut growth, and (5) better understanding of relationships between the host plant, Rhizobium, endomycorrhizae and pathogenic nematodes.

These studies have only been concerned with the traditional Sahel groundnut growing areas in Senegal and in Upper-Volta. Further field experiments should be initiated in other Sahel zones to confirm the above data and possibly discover other diseases caused by nematodes and ways to effect their control.
**DISCUSSION**

Pereira: Is there any sharp evidence for the suppression of nematodes by maize?

Germani: Maize is not a suitable host for *Meloidogyne* spp.

Bradley: How do nematodes affect nodulation?

Germani: Possibly the nematode injects a toxin into the plant which inhibits nodulation or root hair formation. Preliminary experiments in which a nematode extract was injected into peanuts induced chlorosis.

Keya: Do you have any nematode-resistant variety of groundnuts?

Germani: Not in the strict sense.

Ahn: The African marigold (*Tagetes* spp.) is known to suppress nematodes and is sometimes grown in a rotation for this purpose. How important could this be and what is the mechanism?

Keya: But *T. minuta* is a very bad weed.

H.O. Mongi: *Tagetes minuta* need no longer be regarded only as a pernicious weed! It is now the basis of a very lucrative perfume industry in southern Africa. Its cultivation in the areas affected by nematodes may, therefore, be exploited in that way.

Germani: The nematicidal effect of *Tagetes* spp. can be attributed to toxic compounds exuded by the root. Sesame is another interesting crop that seems to have similar properties.

Ial: Are some tree species that are recommended for planted fallows and for soil and water conservation, affected by nematodes? If so, how do you control the nematodes?

Germani: In Senegal, *Azadirachta indica* (Neem) is resistant to root-knot nematodes. Chemical control of tree nematodes is known. *Tagetes* spp. can be grown as a cover crop.

Ial: How do tree species grown in association with food crops affect the incidence of nematode infection?

Germani: In the presence of polyphagous nematodes, which are infrequent in Africa, tree roots may harbour pathogenic nematode species and thus act as reservoirs of inoculum. For example, papaya and baobab are good hosts for root-knot nematodes and *Rotylenchulus* spp.
LITERATURE CITED


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HYDROLOGICAL AND SOIL CONSERVATION ASPECTS OF AGROFORESTRY

Sir Charles Pereira, F.R.S.*

ABSTRACT

Soil conservation is an integral part of agroforestry (limited here to planting of trees in tropical subsistence agriculture). Work from developed countries has shown that planted trees can improve streamflow regulation but reduce water yield. Evidence from tropical/sub-tropical regions is much more scanty. Watershed experiments in India have demonstrated how soil conservation methods can control runoff and soil movement. In Kenya the hydrological effects of two types of plantations involving agroforestry have been evaluated by large-scale watershed experiments over 20 years. In one of them relative water use of softwood plantations (established by the "taungya" or "shamba" system using vegetable gardens) and of indigenous bamboo forest indicated an unchanged streamflow pattern. In the other, replacement of tall rain-forest by tea has shown similar water-use and, with sound erosion control methods higher, but not damaging peak flows. In semi-arid regions agroforestry depends even more critically on sound soil conservation. Livestock can cause severe damage on an immense scale because the inevitable year-to-year fluctuations in rainfall are also an intrinsic cause of overgrazing. Soil conservation earthworks do not succeed unless both cropping practices and livestock management are improved. Tree planting in agroforestry schemes has a useful role but rainfall reception, storage and disposal have to be organized on a watershed scale.

The term "agroforestry" is so broad that it is necessary to start by defining the scope of a paper on the subject. I believe that this meeting is concerned with the effects of planting trees for economic purposes in the less-developed countries, in a context of subsistence agriculture, with particular emphasis on the stabilization of "fragile ecologies" such as steep slopes, rocky hillsides or harsh climates with long dry seasons. Soil conservation practices are, therefore, an integral part of these operations. Our concern is mainly with the tropics and subtropics and, in these environments, quantitative evidence on the physical effect of the planting of trees is very sparse indeed.

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QUANTITATIVE EVIDENCE FOR THE EFFECTS OF TREES

Most of the quantitative evidence for the effects of trees on water resources has come from experiments in the temperate zone. In the USA the classical "paired-valley" experiments were developed. Streamflows from comparable valleys were calibrated by regression and one of the valleys was then clearfelled. These experiments have demonstrated unequivocally that both natural and planted forests beneficially regulate streamflow while evaporating substantially greater quantities of water than pastures or seasonal crops (Sopper and Lull, 1967). The most detailed analytical studies yet attempted on a watershed scale are currently examining the mechanisms of the water-balance of trees and of pastures on steep mountain catchments in Britain (McCulloch et al., 1977).

Quantitative studies of the restoration of misused land are much more difficult where they introduce the farmer as the unpredictable variable. Such evidence also comes mainly from the USA, where the Soil Conservation Service laid the foundations of much of the present worldwide conservation practices. The most thoroughly measured and documented large-scale study was made by the Tennessee Valley Authority, which integrated hydropower, water transport, irrigation and land reclamation over a watershed of some 90,000 km². An extremely relevant experiment was reported from a valley severely eroded by over-grazing and burning. After calibration the valley was restored by construction of cut-off drains and grased waterways. Ravines were stabilized by the planting of black locust trees while the valley was reforested with pine trees planted on the contour. Peak flows were reduced by 90% and sedimentation by 94%; but the total yield of water was halved. In the USSR a century of experience and some experimentation was summarized by Molchanov (1960). He concluded that the planting of 6% of the area of an agricultural watershed by contoured strips of forest was sufficient to increase the infiltration and to reduce surface runoff by one-half.

Quantitative evidence for tropical watersheds is very scarce indeed. Four sets of experiments were begun in the decade 1955-1965 in East Africa, West Africa, India and Indonesia. Those in West Africa and Indonesia lapsed during the 1960s but data relevant to this meeting are still being generated by the work
in India and in Kenya. These are the watershed experiments begun in India in 1963 by the General Soils and Water Conservation Research and Training Institute (Tejwani, Gupta and Mathur, 1975; Patnaik, 1978) and those begun in Kenya in 1955 by the East African Agricultural and Forestry Research Organisation (Pereira, 1959; Pereira, McCulloch, Dagg et al., 1962; Blackie, 1972; Pereira, 1973).

EVIDENCE FROM INDIA

In India the land-pressure is so severe that even the forest reservations are invaded and over-grazed; very large areas are eroded and in need of soil conservation. Watershed experiments by the Soil Conservation Research Institute and the Forest Research Institute at Dehra Dun, reviewed by Patnaik (1973), demonstrated that under high rainfall conditions of between 1000 mm and 2500 mm the restoration of land management discipline, with basic measures of soil conservation, successfully controlled both runoff and soil movement, while continuing to sustain regulated grazing. In a large-scale restoration programme aimed at reducing sedimentation of reservoirs by standard soil conservation treatments (cut-off drains, gulley-stopping and contour bunding) sediment yield measurements made on 16 sub-catchments of the Damodar Valley showed a 90% reduction. A review of 16 years of ravine reclamation by reforestation on the borders of Uttar Pradesh and Rajasthan showed that, in addition to successful erosion control, production of fuel and timber had more than repaid the original expenditure, with a cost-benefit ration calculated at 1.9.

Thus the Indian research and large-scale operational experience has shown that the standard soil conservation practices originating from the USA could be adapted successfully to tropical and subtropical environments and could be operated in the context of subsistence farming. The measures include tree planting for gully stopping and for soil stabilization as an essential component, while in a fuel-hungry countryside the yield of the planted trees has proved to be profitable. In West Africa, in the humid tropics, new techniques such as zero tillage are being evolved by research to stabilize the arable phase of shifting cultivation.
WATERSHED CONVERSION BY "SHAMBA" (TAUNGYA) AGROFORESTRY

In East Africa the Kenya experiments include the first, and I believe, the only watershed hydrology study of the "taungya" or "shamba" system of agroforestry, in which young trees are planted among agricultural crops grown by small-scale farmers. Nairobi city draws its water-supply from mountain watersheds protected by dense indigenous bamboo forests of *Arundinaria alpina*. The Kenya Forest Department established observation plots of pines and cypress in the bamboo forest. These grew successfully and a large-scale programme of softwood planting by the shamba system was planned. The water-supply engineers opposed these plans strongly since they feared that the pines would evaporate more water. Data were quoted from experiments with other tree species in temperate climates, but data for the tropics were not available. This presented an opportunity to tackle a research problem with wide interest and support from both sides of the dispute.

Simple methodologies were used in these studies. As a first step to establish some facts, pits were dug in the small plantations and in the adjacent bamboo. Roots were washed out (using Forest Department fire-equipment) and measured. Soil observations of the depth and duration of available moisture throughout the 3-metre root range were made with very simple apparatus. Gypsum-block tensiometers were made in the laboratory and read in the forest with a rugged hand-cranked insulation testing meter to avoid problems with batteries and delicate instruments. Under the sharply seasonal rainfall this equipment gave clear records of duration of available water at each depth and indicated the times at which a soil sampling would give most information. Only three or four well-replicated samplings a year were needed. (The neutron soil moisture meter is more accurate but only while it has the time and care of specialist staff. In the volcanic soils of these catchments a separate calibration curve has been found necessary for every half-metre depth of soil). The results showed that under complete canopies of *Pinus radiata*, *Cupressus macrocarpa* and bamboo about the same amounts of water were drawn from the soil. An earlier experiment on these plots had established that the different canopies intercepted about the same
proportion from storms of different amounts. The pines were 25 years old and the cypresses 16 years old, while the Forest Department proposed short 25-year rotations. These simple experiments indicated that neither rainfall acceptance nor water use would be seriously altered by replacement of the bamboo forest by softwood plantations. Only measurements on a complete watershed, however, could provide confirmation on a scale appropriate to the gravity of the decision to be made.

Detailed studies of water and energy balances of two adjacent watersheds were made, one of which was cleared and planted with vegetables and maize by small-scale farmers. The pines were planted between vegetables, which grew for 3 years before the shade of the tree canopy became too great. The results were conclusive. The shamba system successfully avoided both significant soil erosion and loss of streamflow regulations. Today, with the pines 22 years old and nearly ready for harvesting, the water use of the two species remains equal and the Forest Department has gone ahead with the pine plantation programme in which agroforestry plays an integral part. A computer model has been built by the Institute of Hydrology on the results. This will enable short-term measurements to be assembled from other watersheds where long-term experiments are not possible.

TEA PLANTATION IN A FORESTED WATERSHED

A second hydrology study of another tree crop was also begun in Kenya in 1954. This concerns tea, which is of direct and growing importance to small-scale farmers in agroforestry. Land pressure has resulted in the cultivation of very steep slopes for subsistence food crops in the forested highlands. On such slopes, of 25% or more, only tree crops can be grown without serious annual losses of soil. Tea was grown, however, mainly at the "agribusiness" level on very large and highly capitalized estates; the leaf is processed by heavy equipment in large estate factories. Adaptation to growing on scattered small hillside plots has been difficult, but has been successfully accomplished by the Kenya government, with strong backing of the Commonwealth Development Corporation; the C.D.C. has invested £10 million in a series of 21 new factories, each of which has been developed
with a tea plantation large enough to supply only part of its capacity. The rest is supplied by small-scale growers. These number more than 115,000, all having plots of from 1 to 2 ha of tea. Tea grows best in the high-rainfall areas, where the small remaining areas of Kenya's original tall "rainforest" still protect vital watersheds. The new factories have involved much forest clearing; the hydrological consequences of this change could only be adequately assessed on a watershed scale.

The experiment tests the effect on soil water resources of the clear-felling of an 810 ha valley in the South-West Mau Forest, a large area of dense forest, for comparison with an adjacent unchanged control valley. The planting of a tea estate, with a full network of roads, tea factory, housing for labour, nurseries, etc., was carried out with detailed measurements and very meticulous soil-conservation planning. In spite of the traumatic damage of tree-felling and deep root-ripping by heavy machinery, the rapid establishment of full soil-conservation methods was successful, with roads and tea on the contour, grass sown or planted on all banks and cuttings and a cover crop of oats sown as the tea was planted. The 2000 mm rainfall severely tested these precautions, but there was negligible soil erosion. However, the roads and drainage ways accelerated runoff, so that initial streamflows showed a serious loss of the regulating effect of the forest. Storm peaks were four times as high as those from the forested valley. As the tea and shade trees developed, the peak flows were reduced, but they are still double the storm flows from the forested catchment. Erosion control remains successful and the water use of the tea and shade trees is effectively the same as that of the forest. Thus the establishment of the new tea factories and plantations need not seriously damage soil and water resources, if they are planned with good soil conservation technology and are well managed. The high peak flows may require extra detention-storage construction if large areas are converted. Again, the results have been successfully built into a computer model (Blackie, 1972).
SOIL CONSERVATION UNDER TREE CROPS

Soil conservation on the plots of the "out-growers" is readily ensured for the tree component of their agroforestry, since the plots are inspected and the tea trees are not issued until terracing or bunding and grass-mulching are completed. I am, however, concerned at the lack of soil conservation among the associated food crops and small livestock on these steep lands, which will need constant attention from extension staff to retain their soil and hence their productivity, in spite of the stability of the "Kikuyu friable clays" (Ahn, 1977).

Although tree crops bind the soil with their roots, shade it and shower organic matter on it, their attendants trample footpaths as they pluck and prune tea, pick, spray and prune coffee or tap rubber on steep slopes. These footpaths channel rainfall and rapidly produce gullying unless there is track discipline to keep the paths on the contour. In some of the older plantations, even on a small-holder scale, the contours have been ignored and the trees are planted "on the square". Soil conservation techniques have been developed to meet this problem. Contour bunds or, better, narrow-based terraces with carefully-laid drainage gradients, are built to convey surplus water to natural rocky drainage ways or to prepared waterways stabilized with grass. These narrow terraces can be built through the trees ignoring the tree rows with only a very few trees per hectare to be transplanted out of the way. This is standard practice in the older Arabic coffee plantations of East Africa and the older tea and rubber plantations in Sri Lanka and Malaysia. Fortunately the plant breeders have made so much progress with new varieties that replanting is usually profitable and the new plantations are being set out on the contour.

As tree crops are planted in successively drier conditions, (tea, rubber, coffee, tanbark acacia and eucalyptus or other species for poles and fuel), soil cover becomes sparser and soil conservation becomes more difficult. The provision of advice and help with drainage patterns and the fielding of teams of "contour peggers" should be a high priority for extension services. This does not always need trained surveyors with accurate levelling
instruments. The Kenya Line Level, which is essentially a carpenter's spirit level suspended between two sticks on 10 metres of string, is a practical substitute for a theodolite and staff (Layzell, 1968). I have had the personal experience of teaching three intelligent but illiterate labourers in two hours to use this device. By securing the string to one stick 25 cm higher than to the other a 1 in 400 drainage grade was established. They subsequently set out a hillside and dug narrow-based terraces which survived the following rainy seasons with complete success.

**SOIL STABILITY IN DRYLAND AGRICULTURE**

Some of the most difficult land to protect from erosion is in the semi-arid 500 mm rainfall zone, where this has been over-grazed and over-exploited by subsistence agriculture. The staple crops are usually sorghums and millets in the tropics with barley in the subtropics. Dry seasons are characteristically long and the rains erratic, with a distribution that is often unfavourable to agriculture. Here the well-tried physical soil conservation methods can fail unless the cropping and livestock husbandry are also improved. A well-documented study of this type of environment has been made at Machakos in Kenya. More than 200 km² of badly eroded land was thoroughly repaired in 1948, using heavy equipment to construct cut-off drains and terraces. Erosion was checked, but not enough improvements were achieved in the farming practice. Thin crops without fertilizer gave poor soil protection, while all plant residues were consumed by livestock, with much trampling of the soil surface. A set of aerial photographs taken in 1972 was systematically measured and compared with an earlier set from 1948 (Thomas, 1975). The total area of severe erosion had increased from 26% to 37% in the course of the 24 years.

Hudson (1971, 1976) has shown that crop population density and the physical protection the crop provides were of critical importance in reducing soil erosion in a similar environment. Vigorous crop responses to small dressings of cattle manure and phosphates had been demonstrated on some Machakos terraces (Pereira and Thomas, 1961). Only the provision of nutrients
can secure a crop or a grass cover capable of protecting this soil. Livestock can contribute to the maintenance of soil fertility on the arable areas in this environment, since they forage widely in areas too rough for cultivation and concentrate the nutrients in the manure deposited in the night bomas (cattle enclosures). The cultivators must, however, make the effort to spread the manure on the land and to dig or plough it under. There is such a wealth of experimental evidence on the beneficial crop effects of cattle manure that there is no need to review it here. Planting of trees can make a direct contribution by the supply of leguminous fodder, and an indirect input by supply of firewood so that cattle dung is not burned for fuel (Vietmeyer, Cottom and Ruskin, 1977).

**LIVESTOCK AND TREES**

The physical aspects of the combination of livestock with trees planted for fuel, shelter and shade can be very satisfactory in flat land (or become so as soon as the trees grow beyond browsing height). In hilly land, however, the lack of ground cover under tree plantations leaves the soil vulnerable to trampling. This can lead to very severe soil erosion; many will have seen examples of such damage under eucalypts or wattle in East Africa, Ethiopia or Australia. In these conditions very wide tree-spacing is needed, unless the livestock can be kept out of the plantations. Planting at wide spacing on the contour, with contour bunding, can control the erosion if livestock pressure is not excessive. The bunds must deliver the surplus water into protected drainage ways, which lead into the natural drainage lines of the watershed.

**GOVERNMENT ROLES IN WATERSHED PLANNING**

Such work requires organization and technical supervision by a responsible authority. The random decisions of thousands of small-scale farmers cannot be expected to achieve watershed protection. The help of trained staff is needed in the field to adapt improved techniques to the local soils and climates. This combination of operational research and development is the essential engine of change. Such changes will not be adopted widely by the small-scale farmer unless they are seen to lead to economic
benefits. For the more expensive terracing and crop-structures, direct financial subsidy is inescapable. Provision of staff and finances depends primarily on the priority allotted by governments to their own programmes of rural development, but where these priorities are high there is much scope for international reinforcement of the essential operational research and development. Conservation of soil and water is not an "optional extra" for any government, but a basic condition for population survival. The low priorities allotted to such work over the past three decades in many developing countries have already caused the loss of natural resources that are sorely needed to ensure that Malthus was wrong.

**DISCUSSION**

**Keya:** What would be the effect of removing shade trees in tea areas?

**Pereira:** The tea crop yields from vegetative growth and in East Africa respond directly to radiation input. This was shown by direct measurements at Limuru. Tea is grown mainly in high rainfall and therefore cloudy climates, so that the results may apply elsewhere. However, I believe the shelter belts are necessary since tea is also sensitive to wind. In a few areas where hail is common, shade trees are needed for protection.

**Lundgren:** To what extent can the comparison between bamboo, a monospecific one-storied vegetation, and *Pinus* spp., be used to draw conclusions about the hydrological effects of replacing a mixed-multi-storied forest by monocultures?

**Pereira:** Clearly to study the effects of removing a multi-storey forest we should look at the Kericho experiment where tall multi-storey rain forest was felled. But the hydrological effects of replacing one continuous tree canopy with another were found to be slight in both cases. The stream regulation effects depend on the presence of people in the watershed. In the case of pines there was no change in the regulation. With tea it was less good.

**Germani:** Usually replacing a complex vegetation by a monoculture induces an increase in some components of the soil fauna (e.g. insects, rodents, etc.) or soil microflora (e.g. fungi). Do you have any data about such an effect in the case of forest clearing followed by a tree crop? Did the replacement of bamboo by pines change these biotic components?

**Pereira:** Only that the volume of the leaf litter was greatly reduced, and from the change in pH under pine plantations I would expect a change of physical measurements.
LITERATURE CITED


EFFECTS OF CULTURAL AND HARVESTING PRACTICES ON SOIL PHYSICAL CONDITIONS

R. Lal*

ABSTRACT

The cultivable arable land area in tropical regions is increasing rapidly: 6 to 10 million hectares per annum. Deforestation and the use of heavy equipment results in degradation of soil structure and water acceptance, and causes unfavourable soil temperature and moisture regimes. Methods of seedbed preparation also affect soil physical and chemical properties. A majority of soils in the tropics respond favourably to reduced tillage systems. Crop residue mulches and planted fallow improve soil physical and chemical properties. Continuous farming and sustained crop yields are obtainable from soils currently under shifting cultivation and related bush fallow systems, provided soil disturbance is kept to minimum and residue mulches and cover crops are used frequently and generously.

The encroachment of arable farming into the forest regions of the humid tropics is inevitable. The question is no longer whether to stop this encroachment, but how to transform the forest ecology to arable farming with minimum damage to soils and the environment. The problem is rather complex and the solution has to be based on thorough investigations of basic aspects of soil and micro-climate in the forest ecosystem, alterations thereto by deforestation and subsequent production practices under different systems of soil and crop management. This baseline information is essential both for the planning of land development and the establishment of appropriate cultural practices that will keep soil degradation to a minimum while sustaining productivity.

PHYSICAL CHARACTERISTICS OF SOILS IN THE TROPICS

Soil structure in the forest ecosystem is generally good.

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because the vegetative cover protects the soil against raindrop impact and because it has a relatively high organic matter content due to a continuous litter fall (Ewel, 1976) and the activity of soil macro- and micro-organisms. This is evidenced by the soil's bulk density, relatively large proportions of macro-pores, high infiltration rate, and aggregate stability (Lundgren, 1971; Lal and Cummings, 1979). However, the sub-soil horizon, with its low organic matter content may have an unstable structure even under the forest ecosystem (Volkoff, 1976).

Except in organic soils and soils derived from volcanic ash, the available moisture retention capacity of the majority of Alfisols, Ultisols, and Exisols is generally low compared with soils in temperate areas. Coarse texture and a high proportion of gravel (Clayton, 1975; Campus and Perecin, 1976; Olivin and Ochs, 1978a, b) contribute to this, though the formation of micro-aggregates of clay-sized particles, permitting free drainage, can be another factor (Wolf, 1975; Ahn, 1979). The field capacity of some of these soils is better approximated at 1/10 or 1/20 bar rather than at the conventionally-used 1/3 bar suction (Maclean, 1970; Maclean and Yager, 1972; Wolf, 1975; Wolf and Drosdoff, 1976b, d; Freire et al., 1976; Maglinao and Briones, 1977). Most of the available water may be released between tensions of 0.05 and 1.0 bar (Maclean, 1970; Wolf, 1975), though levelling-off the moisture tension curves may occur at suctions ranging between 2 and 5 bars (Oliveira and Querioz, 1975). The available water-holding capacity is related to the nature and amount of colloid complex, soil organic matter, and clay fraction (Maclean, 1970; Loynet, 1977).

Water transmission properties of soils in the forest ecosystem are such that surface runoff is generally low, even in regions of intense rains with high drop size distribution. This is because water movement under saturated conditions takes place through macro-pores that dominate the pore space in the undistributed surface soil in the forest eco-system (Humbel, 1975).
The high infiltration rates observed (Lal, 1975; Wolf and Drosdoff, 1976c, d) are also related to lateral flow favoured by the honey-comb-like structure of the surface horizon. The horizontal infiltration rate is high even for heavily textured Vertisols (Queiroz et al., 1976). Moreover, well-structured clayey soils behave like sand with regard to water movement and retention (Wolf and Drosdoff, 1976a; Ahn, 1979). The capillary conductivity is also relatively high (Mensah Bonsu and Lal, 1975; Wolf and Drosdoff 1976d).

CHANGES IN SOIL AND MICRO-CLIMATE BY DEFORESTATION

Deforestation can have a significant effect on soil physical conditions and the micro-climate, though exceptions have been observed where marked changes were not obvious after removal (McDonald, 1955). Soil exposure generally results in an increase in bulk density, a decrease in porosity, and a low infiltration rate (Cunningham, 1963; Weert and Lenselink, 1972; Wood, 1977). Mechanized clearing resulted in a significant decrease in the ground level compared with manual clearing (Fig. 1). Use of heavy earth-moving equipment causes severe degradation of these properties compared with manual clearing, resulting in accelerated runoff and erosion in the tropical regions (Pereira, 1962; Thijssen, 1977a, b). Partial clearing and the use of chemicals may cause degradation of the land and the environment (Liefstingh, 1965), though there is a potential danger of polluting rivers and lakes by hazardous chemicals.

In addition to changes in soil physical characteristics, micro-climatic environments are also affected by deforestation. Increased exposure to solar radiation results in an increase in the soil and air temperature and a decrease in relative humidity (Cunningham, 1963; Lal and Cummings, 1979). Increase in the maximum soil temperature on mechanically cleared plots may be as much as 20° to 25°C (Fig. 2). Supra-optimal soil temperature regimes, commonly observed after deforestation, can cause significant yield reductions for some seasonal crops (Lal, 1975).
Fig. 1: Effect of clearing methods on decrease in the level of soil surface (Unpublished data of D.J. Cummings and R. Lal).
Fig. 2: Effect of deforestation on soil temperature.  
(Average temperature between 2-10th Dec. 1975)  
(Lal and Cummings, 1979)
EFFECTS OF CULTURAL PRACTICES ON SOIL PHYSICAL PROPERTIES

SEEDBED PREPARATION

Methods of seedbed preparation affect soil physical properties to varying degrees. Mechanical seedbed preparation involving the use of heavy machinery, though good for weed control and for temporarily loosening compacted surface soil, may have adverse effects on soil physical properties in the long run. The magnitude and severity of this deleterious effect depends on soil, crop, and other cultural practices. On the contrary, for some soils, mechanical cultivation may be necessary for proper seedbed preparation (Nicou, 1974). The planting equipment (seed drills, etc.) can also cause soil compaction (Arndt, 1977).

The effects of tillage methods on soil properties in East Africa were investigated in detail by Pereira and his colleagues. Soil mulch, as created by pulverization of the soil surface by repeated tillage, had no importance in soil-moisture conservation in the absence of weeds (Pereira, 1941). However, mechanical tillage followed by clean weeding resulted in a decrease in total porosity, drainable porosity, percolation rate; and the percentage of water-stable aggregates (Pereira and Jones, 1954). In the long run, plowing was observed to cause a deterioration in soil structure (Pereira et al., 1964; 1967). Contour ridges can be effective for stable soil and for erosion protection during gentle rainstorms if the land slope does not exceed five to seven percent (Pereira and Beckley, 1953). Mechanical seedbed preparation, followed by tie-ridging, increased the yield of cotton and grain crops, and controlled erosion (Peat and Brown, 1960). Similarly, the Basin Lister was found useful for breaking compacted and capped soil surfaces, without causing measurable compaction of the soil immediately under the blade (Hosegood, 1964). However, the soil disturbance caused by this method reduced rainfall acceptance and increased water runoff. More recently, Taylor (1974) observed that the 2 mm aggregate size was a satisfactory lower limit for a proper seedbed of maize and sorghum. Excessive pulverization of the soil by harrowing and rotovation may lead to structural degradation.
In the semi-arid regions of West Africa, mechanical seedbed preparation at the end of the rainy season has been found to improve the porosity and structure of a compacted silt loam soil (Nicou, 1974). Ploughing at the end of the rainy season has been observed to increase porosity by 10 to 20 percent, and subsequent crop yields were greatly increased. However, the improvement in soil structure by ploughing was temporary and the structure was easily degraded if precautions were not taken to preserve it. In the long run, cultivation followed by submersion due to a decrease in the infiltration rate has been observed to cause degradation of the rate of infiltration and in the index of structural stability of these sandy soils of the semi-arid region of West Africa (Maynard and Combeau, 1960).

Soil structure of the Alfisols of the humid regions of West Africa is extremely susceptible to raindrop impact when exposed by mechanical cultivation. These soils crust easily and this reduces their infiltration rate and causes accelerated runoff and erosion (Lal, 1975; Lal, 1976). Data in Fig. 3 show a progressive deterioration in the infiltration rate of an Alfisol under bare fallow. Very fine seedbed and reduced aggregate size also decrease seedling emergence and crop establishment (Falayi and Lal, 1979). Mechanically-tilled soil develops a thin but impermeable layer near the soil structure and a low percentage of macro-pores (Boyer, 1977). In addition to alterations in soil physical properties, mechanized tillage also affects the soil's organic matter and fertility status (Lal, 1976; Godefroy et al., 1977). In spite of these degrading effects of mechanized tillage on soil, there are many reports of the proposed schemes of large-scale mechanized farms in the humid regions of West Africa (Gretzmacher, 1977).

In addition to affecting soil structure and infiltration rate, seedbed preparation also influences soil temperature and moisture regimes. Supra-optimal soil temperature has been observed in cultivated lands in West Africa (Lal, 1975; Lal, 1976), in the upper Amazon regions in South America (Knight, 1958; Pougerouze, 1966; Decico and Santos, 1976) and in East Africa (Banage and Visser, 1967). In the highlands of Kenya, however, sub-optimal soil temperature regimes in bare exposed soil have proved to be the cause of low maize yield (Cooper, 1974; Cooper, 1975; Law and Cooper, 1976).
Fig. 3: Effect of soil management systems on water infiltration (Lal, 1976a).

- 1972
- x 1973
- ▲ 1974
Strongly interacting with the supra-optimal soil temperature regime is the soil moisture stress. Though the annual precipitation may be as much as 2000 mm or more (and with a positive balance when compared with annual potential evapo-transpiration), owing to the low moisture retention capacity of these soils, serious moisture deficit often occurs during the growing season (Fougerouze, 1966; Bertoni, 1968; Lal, 1975; Ghelji, 1976).

MULCHES

Continuous ground cover not only prevents the degradation of soil structure from raindrop impact, but also minimizes the fluctuations in the soil temperature regime and decreases soil-water evaporation. Pereira and Jones (1954) observed in East Africa that the soil moisture regime could be improved by applying grass mulches before the rains to improve water reception. Studies conducted on Alfisols in West Africa have indicated improvements in aggregate size, bulk density, penetrometer resistance, and saturated hydraulic conductivity of a mulched plot compared with the unmulched control (Table 1). Increase in crop yield by mulching is associated with improvements in soil physical properties, and in the general fertility level of the soil (Lal, 1975). Undecomposed crop residue mulch can also improve the water retention capacity of the soil (Fig. 4).

COVER CROPS

Planted fallows are useful in ameliorating soil physical conditions over short periods of time compared with long-term natural bush fallow. Considerable agronomic information is still needed on the choice of suitable covers and their management for subsequent arable farming on different soils and agro-ecological regions. This type of research is locality-specific and needs to be conducted in different regions.

Planted fallows, with modest or controlled grazing, are often recommended for ameliorating soil physical and chemical properties. In East Africa, Pereira and Beckley (1953) observed that roots of Rhodes grass increased the field capacity of the upper 7 to 10 cm of the soil layer: the increase in field capacity was 5.3 percent for the bare soil as against 8.3 percent under grass ley. The
Table 1. Effect of mulch material on soil physical properties under cassava

<table>
<thead>
<tr>
<th>Material</th>
<th>Bulk density (g cm(^{-3}))</th>
<th>Penetrometer resistance (kg cm(^{-2}))</th>
<th>Hydraulic conductivity (cm hr(^{-1}))</th>
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<td>Panicum maximum</td>
<td>1.17</td>
<td>0.80</td>
<td>317</td>
</tr>
<tr>
<td>Bare</td>
<td>1.47</td>
<td>1.98</td>
<td>23</td>
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<tr>
<td>Elephant grass</td>
<td>1.35</td>
<td>0.95</td>
<td>371</td>
</tr>
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<td>Black plastic</td>
<td>1.33</td>
<td>3.08</td>
<td>105</td>
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<td>Rice husk</td>
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</tr>
<tr>
<td>Andropogon</td>
<td>1.19</td>
<td>1.20</td>
<td>653</td>
</tr>
<tr>
<td>Pigeon pea stems</td>
<td>1.33</td>
<td>1.58</td>
<td>321</td>
</tr>
<tr>
<td>Oil palm leaves</td>
<td>1.37</td>
<td>1.51</td>
<td>189</td>
</tr>
<tr>
<td>Soybean</td>
<td>1.48</td>
<td>1.55</td>
<td>159</td>
</tr>
<tr>
<td>Rice straw</td>
<td>1.44</td>
<td>1.74</td>
<td>237</td>
</tr>
<tr>
<td>Typha</td>
<td>1.46</td>
<td>1.45</td>
<td>28</td>
</tr>
<tr>
<td>Cassava stems</td>
<td>1.46</td>
<td>1.98</td>
<td>27</td>
</tr>
<tr>
<td>Legume husk</td>
<td>1.50</td>
<td>1.79</td>
<td>35</td>
</tr>
<tr>
<td>Mixed twigs</td>
<td>1.32</td>
<td>1.50</td>
<td>110</td>
</tr>
<tr>
<td>Maize cobs</td>
<td>1.38</td>
<td>1.55</td>
<td>89</td>
</tr>
<tr>
<td>Eupatorium</td>
<td>1.46</td>
<td>1.60</td>
<td>93</td>
</tr>
<tr>
<td>Gravel</td>
<td>1.52</td>
<td>2.21</td>
<td>213</td>
</tr>
<tr>
<td>Transparent plastic</td>
<td>1.54</td>
<td>1.61</td>
<td>214</td>
</tr>
<tr>
<td>Sd</td>
<td>0.11</td>
<td>0.63</td>
<td>161</td>
</tr>
</tbody>
</table>

Source: Unpublished data of R. Lal and B.N. Okigbo
Fig. 4: Effect of undecomposed crop residue on the soil moisture retention characteristics (Unpublished data of R. Lal).
corresponding percolation rate was 7.1 and 13.7 cm hr$^{-1}$, respectively. In general, infiltration and percolation rates were in the order of grasses $>$ leguminous covers $>$ crops $>$ bare soil (Pereira et al., 1954; 1958).

Leguminous covers improve soil physical properties, because they have a low C:N ratio and do not immobilize soil nitrogen as much as some grasses do. However, the total nitrogen status of the soil is improved even by grass fallows and subsequent soil management is important in adequately maintaining soil physical conditions (Foster, 1971). Cover crops are also widely recommended for improving soil physical conditions in South and South-East Asia (Hadimani et al., 1975; and Bajpai et al., 1975).

Cover crops have also proved useful in ameliorating physical properties of the soils of humid regions of West Africa (Monnier, 1965). Cover crops improved soil bulk density (and total porosity) (Table 2) and infiltration rate (Fig. 5) of an Alfisol degraded by excessive cultivation and continuous farming for a period of 6 years.

**INTERCROPPING**

With the traditional methods of cultivation, bush fallow and related systems based on minimum inputs of commercial fertilizers and other farm chemicals, inter-cropping generally gives higher returns per unit area and per unit time compared with mono-cropping (Evans, 1960; Evans and Sreedharan, 1962; Grimer, 1963; Okigbo and Greenland, 1976). However, the beneficial effects of intercropping may be less for commercial mechanized farming.

There are few research reports describing the effects of intercropping on soil physical conditions and micro-climatic environments. There is no doubt, however, that cropping associations that provide continuous ground cover will minimize the extent of soil degradation caused by raindrop impact. Aina et al., (1979) reported that water runoff and soil erosion in an inter-cropping system were significantly low compared with mono-cropped cassava. There is a need, however, to quantify the effect of continuous ground cover, as provided by inter- and relay-cropping systems, on soil physical properties.
Table 2. Effects of cover crops and method of sod management on soil bulk density (mean of 15 replication)

<table>
<thead>
<tr>
<th>Cover</th>
<th>Chemical suppression</th>
<th>Mechanical suppression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brachiaria</td>
<td>1.05</td>
<td>1.48</td>
</tr>
<tr>
<td>Paspalum</td>
<td>1.49</td>
<td>1.49</td>
</tr>
<tr>
<td>Cynodon</td>
<td>1.41</td>
<td>1.43</td>
</tr>
<tr>
<td>Pueraria</td>
<td>1.44</td>
<td>1.45</td>
</tr>
<tr>
<td>Stylosanthes</td>
<td>1.45</td>
<td>1.46</td>
</tr>
<tr>
<td>Stizolobium</td>
<td>1.46</td>
<td>1.45</td>
</tr>
<tr>
<td>Psophocarpus</td>
<td>1.14</td>
<td>1.16</td>
</tr>
<tr>
<td>Centrosema</td>
<td>1.44</td>
<td>1.47</td>
</tr>
<tr>
<td>Weed fallow</td>
<td>1.39</td>
<td>1.38</td>
</tr>
<tr>
<td>LSD (.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i)</td>
<td>Chemical suppression</td>
<td>0.07</td>
</tr>
<tr>
<td>(ii)</td>
<td>Mechanical suppression</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Source: Unpublished data of R. Lal
Fig. 5: Effect of various cover crops on water infiltration capacity (Unpublished data of G.F. Wilson, R. Lal and B.N. Okigbo).
HARVESTING AND GRAZING

Carts cause soil compaction particularly if harvesting is done when the soil is wet, as is the case in harvesting the first season crops in West Africa under bimodal rainfall distribution. Research information comparing the effects of mechanized vs. manual harvesting practices for different crops on the physical properties of soils in the tropics, is not readily available or easily accessible.

Significant soil compaction from loaded carts was detected in sugarcane fields in Guyana (Howson, 1977) and in Puerto Rico (Shukla and Ravalo, 1976). In a field with soil moisture content of 27.4%, the zone of significant compaction was about 15 cm. When soil moisture at harvesting in an adjacent field was 48.3%, the zone of significant compaction was 45 cm. Similar observations on the effects of harvest traffic on soils growing sugarcane have been reported from Guyana.

Uncontrolled and excessive grazing can have a significant deleterious effect on soil physical properties. Excessive grazing not only depletes the natural soil cover and exposes the soil to high intensity tropical rains, but compacts the surface soil layer and decreases water acceptance as a result of trampling (Pereira and Hosegood, 1961; Lundgren and Lundgren, 1972).

AFFORESTATION

As with cover crops, plantation and perennial tree crops that provide continuous ground cover have beneficial effects on soil physical properties. Growing cover crops (e.g. Pueraria javanica or Centrosema pubescens) between plantation crops (e.g. rubber and oil palm) is widely practised in South-East Asia.

Afforestation of agricultural lands in India and Burma significantly increased soil organic matter, NO₃ and total N content in 20 years of afforestation (Forest Research 1946). Improvements in soil physical properties by afforestation decrease water runoff and soil erosion. In China, under a tropical monsoon climate, the establishment of forest on eroded slopes decreased annual soil erosion from about 15,000 to 3,000 m³/km² over a period of 10 years (Xiaoliang, 1977). Though there may be improvements
in soil physical conditions, some trees (pine) may decrease exchangeable bases and soil pH (Fernet, 1954). Moreover, in the initial stages of afforestation, *Pinus caribbea* may also decrease total soil N. However, after a long period (10 years or more), N reserves improve (Cornforth, 1970). Conclusive effects of afforestation on soil physical and chemical properties can only be established after a long period of thorough investigations.

**DISCUSSION AND CONCLUSION**

Shifting cultivation, though no more than subsistence farming, is a stable and viable system provided the fallow period is long enough to allow amelioration in soil physical properties and the rejuvenation of soil fertility. However, the pressure of human populations in many regions of Africa and Asia does not permit long fallows. Continuous cultivation with a minimum of commercial inputs results in soil degradation. As a result, there is a decline in the productive potential of the natural resource base, and the stability of an otherwise viable system is lost.

A soil's physical properties play an important role in maintaining its productive capacity on a continuous basis. Chemical fertilizers, though sometimes not readily available and even uneconomical, can be used to replenish the nutrients removed by crops. However, improvement in the physical properties of a degraded soil is difficult and may require a long-term fallow with limited economic returns. Methods of deforestation and subsequent soil management systems should be developed to maintain soil physical properties at a desirable level. Once degraded, these properties are difficult to improve and may require many years of special management.

The limited research results available concerning the effects of different methods of deforestation for arable farming and of tillage systems on soil properties have yielded encouraging information. Mechanical systems of deforestation are inevitable in regions of high labour demand and where large areas have to be developed over a short period of time. Subsequent management,
however, can minimize the deleterious effects of heavy machinery (Table 3). Zero-tillage systems with residue mulch minimize the adverse effects of mechanized clearing.

The role that crop residue mulches with reduced tillage systems and appropriate cover crops play in improving and maintaining soil physical properties, cannot be over-emphasized. The object is to substitute forest canopy by residue mulches and cover crops that allow arable farming with a minimum of soil disturbance. This goal has become a reality with the availability of a range of cheaper herbicides over the past two decades. Where soil erosion and degradation of the soil's physical properties are serious limiting factors in introducing continuous farming to fragile environments of the tropics, crop residue mulches with no-tillage/reduced tillage systems and with a periodic cycle of cover crops offer a viable alternative.

Their successful application to food crops depends on the results obtainable from adaptive research that must be conducted for a range of soils and agro-ecosystems in the tropics. Research information is urgently needed for suitable cropping sequences (or cropping mixtures for mixed- or relay-cropping), fertilizer requirements and methods of their application, suitable planting equipment, choice of appropriate herbicides and economical means of application, suitable cover crops and the frequency of planted fallow, appropriate methods of sod suppression, and crop residue management.

Enough research information is available to justify the conclusion that most soils currently under shifting cultivation can be used for continuous farming with sustained productivity. The keys to the successful use of these fragile soils are to disturb them as little as possible and to maintain a continuous ground cover on them.
Table 3. Effects of clearing methods and post-clearing management on maize grain yield

<table>
<thead>
<tr>
<th>Clearing methods</th>
<th>No-tillage</th>
<th>Conventional tillage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_0$</td>
<td>$F_1$</td>
</tr>
<tr>
<td>Mechanical</td>
<td>4.64</td>
<td>4.96</td>
</tr>
<tr>
<td>Slash and burn</td>
<td>4.63</td>
<td>5.75</td>
</tr>
<tr>
<td>Slash alone</td>
<td>4.21</td>
<td>4.94</td>
</tr>
<tr>
<td>Traditional*</td>
<td>3.37</td>
<td>3.68</td>
</tr>
</tbody>
</table>

LSD (.05)

(i) Between-Fertilizer levels for the same clearing and tillage methods. 0.94
(ii) Between-Clearing techniques for the same fertilizer level and tillage methods. 1.28


$F_0$ = No fertilizer

$F_1$ = 120-30-13 N, P, K, kg/ha

*Traditional clearing methods (incomplete clearing) as is done in shifting cultivation and related bush fallow systems.
DISCUSSION

Germani: In Benin, the mulching of cotton with maize straw increased nematode populations (Pratylenchus and Meloidogyne) whereas zero tillage decreased nematode populations. Do you think that the herbicides used in the zero tillage system could be held responsible?

Lal: Zero-tillage decreases the population of some parasitic nematodes. The experiments conducted at IITA indicated that some mulch materials increase the nematode population while some decrease it.

Nyangat: Experience with the neutron probe in Kenya has not been encouraging because of calibration problems, and maintenance costs are high.

When investigating infiltration and bulk density it is advisable to look at both topsoil and subsoil; compaction is associated with the second more than the first.

Lal: The importance of changes in subsoil characteristics should not be underestimated. The range of soil-loss tolerance and the adverse effect on crop growth depends on subsoil characteristics.

Pereira: My experience with the neutron probe confirms that of Dr. Lal. In the Kikuyu red loam we had a different calibration curve for each depth. I do not believe that this equipment should be issued to any group without a physicist available to spend full time on it.

Pratt: In single soils, without gravel, where most of the moisture change is in the tensiometer range, we have found the neutron probe useful.

Sanchez: In Latin America we have simple soil profiles in which neutron probes have given good results.

Lal: The neutron probe is rather expensive and its use is subjective. If the objective is to compare the depth of a wetting or drying front, it can be achieved by this method. Detailed water balances, however, depend on prior calibration for each site and every horizon.

Uriyo: Your results have shown that both clearing of land by fire and bulldozing are detrimental. Do you have any suggestion as to how land should be cleared?

Lal: If clearing is absolutely necessary, it should be done by a practice that is economical and causes a minimum reduction in soil quality. Improvements in soil properties can be achieved through some practical means. Manual clearing is definitely superior to mechanical clearing, but due to shortages and high costs of labour, the latter may be inevitable. One must, therefore, develop suitable soil management systems to minimize the adverse effects of mechanical clearing.
LITERATURE CITED


Soils in the tropics and sub-tropics with sufficient rainfall for sustained agriculture and forest production are generally weathered, acid and deficient in phosphorus. Because highly-weathered soils have a surface charge that is pH-dependent, estimates of cation exchange capacity should be based on the sum of exchangeable bases plus KCl-extractable Al. Generally soils that have a pH of five or less contain appreciable amounts of exchangeable Al. Unbuffered neutral salt solutions provide good estimates of exchangeable Al and the form of acidity that needs to be neutralized by liming. Lime rates sufficient to reduce exchangeable Al saturation to near zero will result in optimum growth of most crops. Exchangeable Ca, Mg and K are the forms readily available for plant uptake. Application of lime at rates that neutralize Al will provide adequate Ca. Adequate amounts of Mg are present when Mg saturations of the CEC (pH 7) are 5%. Exchangeable K is a good index of K supply in soils. A minimum level of 0.1 me/100g is necessary for K deficiency not to be present. Highly weathered soils have a high capacity to adsorb P if they contain relatively high amounts of Al and Fe oxides. The main inorganic forms of P in highly-weathered soils are Al-P and Fe-P, with Al-P being the form generally controlling plant-available P. Extractants that selectively extract Al-P give a good measure of plant available P. Estimates of the amount of fertilizer P required to provide critical soil test levels can be obtained from adsorption isotherms or from incubation studies where various rates of P have been added to soils and soil test levels determined. Almost all of the N in surface soils is in the organic form. Estimation of nitrogen supplies by mineralization of soil organic N that determine mineralizable N appeared to be similar for a wide range of soils. Sulphur deficiencies are apt to be common in soils of tropical and sub-tropical regions. Sulphate is held in soils by the similar mechanisms as P. Solutions of Ca phosphates are effective extractants to determine available sulphur. Micronutrient availability is associated with either the water-soluble, exchangeable or complexed forms in the soil. Measurement of these forms should provide information about the relative supply of micronutrients.

The soils of the tropics and sub-tropics can be divided into three broad groups on the basis of rainfall: humid, semi-arid and arid. In the humid tropics the soils are generally acid with a low content of bases; clays coated with Fe and Al
oxides; a low cation exchange capacity; colloids with a high capacity to absorb P, S and Mo; and low reserves of weatherable minerals. On the other hand, soils of semi-arid and arid regions are neutral-to-alkaline in reaction, contain clays with a relatively high cation exchange capacity, generally adsorb low amounts of P, S, and Mo, and often have large reserves of weatherable minerals. The soils in the areas with sufficient rainfall for sustained agriculture and forest production are generally weathered, acid and relatively infertile.

CATION EXCHANGE PROPERTIES

The exchange properties of soils are determined by the nature of the soils' colloids. Soils that have undergone intensive weathering generally contain low activity clays, such as kaolin, Al interlayed secondary chlorites and the hydrated oxides of Fe and Al (Uehara, 1973). These colloids have a pH-dependent surface charge and a low effective cation exchange capacity. The silicate clays of highly weathered soils are often coated with hydroxy-Al and hydroxy-Fe, which are proton donors of OH acceptors and result in a pH-dependent charge (Coleman and Thomas, 1967). The negative charges of organic matter in acid soils are countered by Al and hydroxy-Al ions (Coleman and Thomas, 1967). The Al ions are held very tightly by the organic matter and consequently the effective cation exchange capacity of organic matter in acid soil is low. As the pH is increased the complexed Al ions hydrolyze and the net negative charge of the organic matter increases. Liming of soils that have pH-dependent surface charges increases the net negative charge (Keing and Uehara, 1974). Because of the pH-dependent charge of highly-weathered soils, large amounts of lime may be required to change their pH, particularly when attempts are made to raise the pH to near-neutrality (Mendez and Kamprath, 1978).

Soils that have undergone less intensive weathering generally contain high activity clays, such as montmorillonite, vermiculite and illite (Keng and Uehara, 1974). These colloids have a constant surface charge that is invariant to changes in soil pH.

Traditionally cation exchange capacity has been measured with \( \text{NH}_4\text{OAc} \) buffered at pH 7 or other acetate salts such as Na
and Ca. This procedure is satisfactory for soils with a constant surface charge and soil reaction near neutrality. Buffered solutions not only displace exchangeable ions, which are also replaced by unbuffered salt solutions, but also neutralize the weak acid charges (Coleman et al., 1959). The cation exchange capacity of acid soils containing primarily pH-dependent charges is overestimated by neutral buffered solutions as compared with CEC measured at the pH of the soil (Table 1). This is not the case with neutral soils containing primarily constant-charge colloids, in which there is little difference in the CEC measured with unbuffered salts as compared with buffered salts.

Table 1: Cation exchange capacities of various soils measured with unbuffered salt solutions and with buffered salt solutions. Data from Pratt and Alvahydo (1966) and Clark and Hill (1964)

<table>
<thead>
<tr>
<th>Soil</th>
<th>pH</th>
<th>At pH of soil</th>
<th>Ca(OAc)₂ at pH 7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Yellow Latosol</td>
<td>4.3</td>
<td>2.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Red Yellow Podzol</td>
<td>4.8</td>
<td>4.2</td>
<td>7.8</td>
</tr>
<tr>
<td>Red Yellow Latosol</td>
<td>5.5</td>
<td>4.8</td>
<td>7.9</td>
</tr>
<tr>
<td>Brown Forest</td>
<td>6.6</td>
<td>22.5</td>
<td>23.8</td>
</tr>
<tr>
<td>Brown Forest</td>
<td>7.2</td>
<td>19.1</td>
<td>19.7</td>
</tr>
</tbody>
</table>

The method by which the CEC of soils is determined becomes very important in soils with primarily pH-dependent negative charges. This is particularly true when determinations are made of the base saturation of a soil in order to assess the need for lime. In view of this problem Coleman et al. (1959) suggested that a more realistic measure of the CEC of soils was obtained with a summation of the exchangeable bases and the exchangeable acidity displaced with a neutral unbuffered salt solution. When the base saturation is based on CEC (pH 8.2), all of the soils
would be classified as having a very low saturation and requiring lime (Table 2). However, when the sum of cations is used to calculate the CEC, only one of the soils would be judged very deficient in bases.

Table 2: Base saturation of Ultisols based on effective CEC as compared with CEC at pH 8.2 (Data from Coleman et al., 1959)

<table>
<thead>
<tr>
<th>Soil</th>
<th>pH</th>
<th>Exch.</th>
<th>Effective CEC</th>
<th>Base saturation</th>
<th>CEC pH 8.2 saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>me/100 g</td>
<td>me/100 g</td>
<td>%</td>
<td>me/100 g</td>
<td>%</td>
</tr>
<tr>
<td>Durham</td>
<td>5.0</td>
<td>1.9</td>
<td>3.0</td>
<td>37</td>
<td>7.8</td>
</tr>
<tr>
<td>Georgeville</td>
<td>5.3</td>
<td>1.3</td>
<td>3.5</td>
<td>63</td>
<td>10.2</td>
</tr>
<tr>
<td>Cecil</td>
<td>5.6</td>
<td>0.5</td>
<td>2.7</td>
<td>82</td>
<td>7.7</td>
</tr>
<tr>
<td>Davidson</td>
<td>5.9</td>
<td>0.1</td>
<td>4.7</td>
<td>94</td>
<td>12.1</td>
</tr>
</tbody>
</table>

CHEMICAL CHARACTERIZATION OF SOIL ACIDITY

Many of the soils in the humid tropics and sub-tropics are acid, with pH values of 5 or less (Pearson, 1975). During the 1950s considerable research established that acid soils contained exchangeable Al rather than H (Coleman and Thomas, 1967). Toxic levels of Al in acid soils, therefore, are an important factor in poor plant growth (Kamprath and Foy, 1971). Soil pH per se does not provide a good index of Al status when soils with varying chemical properties are considered, although some generalization can be made (Juo, 1977). Direct measurements of exchangeable Al are desirable for assessing soil acidity problems.

EXTRACTION OF EXCHANGEABLE Al

The exchangeable form of Al is Al\(^{+3}\). With increasing pH the Al\(^{+3}\) is hydrolyzed to Al(OH)\(^{+2}\), Al(OH)\(^{+1}\) and Al(OH)\(^{+0}\) (Coleman and Thomas, 1967). Extracting solutions that appreciably change the pH of the soil, therefore, can have a considerable
effect on the amount of Al extracted. Buffered solutions can considerably alter the soil pH, and the amount of Al extracted is not necessarily indicative of the exchangeable Al content of a soil. The pH of a neutral unbuffered salt solution, however, when added to a soil is determined by the pH of the soil. Therefore, neutral unbuffered salt solutions should be used to extract exchangeable Al (Lin and Coleman, 1960; Bhumbla and McLean, 1965). The most common extractant used for exchangeable Al is \( N \) KCl.

**EXCHANGEABLE Al CONTENTS AND SATURATION OF SOILS**

The exchangeable Al content of some acid soils from the tropics and sub-tropics are given in Table 3. The average exchangeable Al content was greater than 1 me/100 g for soils \(<\) pH 5. For all of the soils except those from Southwest Africa the average % Al saturation of the effective CEC was greater than 50. Although the average Al saturation for the southwest African soils below pH 5 was 35 to 41%, individual soils had as high as 69% Al saturation.

Aluminium concentrations in solution increase markedly when exchangeable Al accounted for more than 60% of the exchangeable cations on the active exchange sites (Nye et al., 1961; Evans and Kamprath, 1970). When the Al saturation is greater than 60% the concentration of soil solution Al generally exceeds 1 ppm, a level that is detrimental to many crop species (Kamprath, 1970). An increase in electrolyte concentration of acid soils results in an increase in the Al concentration of the soil solution (Fried and Peech, 1946; Brenes and Pearson, 1972). This is brought about by displacement of Al from exchange sites and the reduction in pH resulting from the hydrolysis of the solution Al. Thus, addition of soluble fertilizers to acid soils can intensify Al toxicity problems.

There is a general relationship between pH and Al saturation. At pH 5.5 to 6 only small amounts of exchangeable Al are present and the Al saturation of the effective CEC approaches zero (Abruna et al., 1975; Fox et al., 1962; Kamprath, 1970, Mendez and Kamprath, 1978). Below pH 5 the Al saturation of the effective CEC increases rapidly with decreasing pH.
Table 3: Exchangeable Al and Al saturation of soils in tropical and sub-tropical regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Soils</th>
<th>pH range</th>
<th>Exchangeable Al</th>
<th>Al saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>range</td>
<td>range average</td>
<td>range average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>----------</td>
<td>----------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Brazil(^1)</td>
<td>Red-Yellow Latosol</td>
<td>4.0-4.6</td>
<td>1.8-3.2</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Red Latosol</td>
<td>4.1-4.2</td>
<td>0.7-1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Colombia(^2)</td>
<td>Oxisols</td>
<td>4.2-5.1</td>
<td>0.6-5.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Malaysia(^3)</td>
<td>---</td>
<td>3.6-4.2</td>
<td>0.7-12.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Panama(^4)</td>
<td>Latosols</td>
<td>4.8-5.2</td>
<td>0.3-5.8</td>
<td></td>
</tr>
<tr>
<td>Puerto Rico(^5)</td>
<td>Ultisols</td>
<td>3.9-4.6</td>
<td>4.5-9.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Southwest Africa(^6)</td>
<td>Ultisols and Alfisols</td>
<td>5.1-5.4</td>
<td>0-2.0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.5-5.0</td>
<td>0.1-3.7</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.4-4.4</td>
<td>0.1-2.8</td>
<td>1.2</td>
</tr>
<tr>
<td>United States(^7)</td>
<td>Ultisols</td>
<td>4.5-4.7</td>
<td>0.9-4.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>

\(^1\) Data from Pratt and AlvaHydo, 1966
\(^2\) Data from Vargas, 1964
\(^3\) Data from Singh and Talibudeen, 1969
\(^4\) Data from Mendez and Kamprath, 1978
\(^5\) Data from Abruna et al., 1975
\(^6\) Data from Juo, 1977
\(^7\) Data from Kamprath, 1970

**EVALUATION OF MANGANESE TOXICITY PROBLEMS**

Manganese exists in the soils in a number of different forms, such as water-soluble, exchangeable and easily reducible (Sherman et al., 1942). The potential for Mn toxicity occurs on soils with a relatively high content of easily reducible Mn, generally greater than 100 ppm Mn (Adams and Pearson, 1967). Easily reducible Mn is extracted with hydroquinone (Sherman et al., 1942).
according to the following reaction:

\[ \text{MnO}_2 + \text{C}_6\text{H}_4(\text{OH})_2 + 2\text{H}^+ + \text{Mn}^{2+} + \text{C}_2\text{H}_4\text{O}_2 + 2\text{H}_2\text{O} \]

The concentration of water-soluble Mn increases as the soil pH decreases (Morris, 1948). Manganese toxicity symptoms occurred in lespedeza and soybeans when the water-soluble Mn (1:2 soil-to-water ratio) was greater than 1 to 2.5 ppm Mn on a soil basis (Morris, 1948; Parker et al., 1969). Liming of soils to greater than pH 5.5 generally removes any Mn toxicity problems because of the reduction of water-soluble Mn.

LIME RATES BASED ON EXCHANGEABLE Al

One reason for liming acid soils is to eliminate the toxic effects of Al. Following this line of reasoning a number of investigators have proposed that liming rates should be based on the amount of exchangeable Al present in the soil (Brauner and Catani, 1967; Kamprath, 1967, 1970; Reeve and Summer, 1970).

Lime rates chemically equivalent to 1.5 times the exchangeable Al neutralized approximately 85% of the exchangeable Al in acid soils of North Carolina and Panama (Kamprath, 1970; Mendez and Kamprath, 1978). Soil pH levels were adjusted to the range of 5.5 to 6. Toxicity of Al was eliminated in Brazilian Latosols by using a lime factor of 1.5 to 3 times the exchangeable Al (Soares et al., 1975). Exchangeable Al times 1.5 to 2 gave good estimates of the equivalent amounts of lime required for acid soils in India (Pradhan et al., 1976; Kotur et al., 1976). Amounts of lime based on exchangeable Al are considerably less than those required to adjust the pH to 6.5 and result in optimum crop growth (Pearson, 1975). Lime rates should thus be based on exchangeable Al (KCl-extractable). This will remove toxicity problems, provide adequate Ca, or Ca and Mg, and provide a favourable pH for most crops.

AVAILABLE FORMS OF CALCIUM, MAGNESIUM AND POTASSIUM

CALCIUM

Available soil Ca is usually measured by extracting with \( \text{N NH}_4\text{OAc} \). The sufficiency of a given level of soil calcium is
related to the Al saturation of the soil and the H ion concentration. Aluminium has an inhibitory effect on the uptake and translocation of Ca (Kamprath and Foy, 1971). Liming of soils to eliminate the detrimental effects of Al provides adequate levels of Ca. Where Al toxicity was not a problem Ca was adequate for root growth of cotton when the ratio of Ca to total cations was 0.12 (Howard and Adams, 1965).

Hydrogen ions have an inhibitory effect on the uptake of Ca. The inhibitory effect of H can be overcome by addition of soluble Ca materials when Al is not a problem. When the Ca concentration was increased, plant growth at pH 5 in nutrient culture was the same as that at pH 6 (Arnon and Johnson, 1942). Thus when Al and Mn toxicity are not problems in an acid soil, the amount of available Ca present is the important factor.

MAGNESIUM

Magnesium exists in soils as exchangeable Mg and as a constituent of silicate clay minerals such as montmorillonite (Salmon, 1963). Exchangeable Mg is the major source of plant available Mg which is estimated by extractions with NH₄OAc or dilute acid solutions. Acid soils of tropical and sub-tropical areas usually have relatively low reserves of Mg unless they contain morillonitic clays containing structural Mg (Rice and Kamprath, 1968).

Ultisols supplied adequate Mg for Sudan grass and Ladino clover when Mg saturation of the exchange complex was 4% (Adams and Henderson, 1962). Response to Mg was obtained on Alfisols, Ultisols, and Oxisols in western Nigeria when the Mg saturation of the CEC (pH 7) was 5% or less (Lombin and Fayemi, 1975). The exchangeable Mg content of soil was a poor predictor of the % Mg in grass (Salmon, 1964). Cation activity ratios of Mg 1/2 to (Ca + Mg) 1/2 gave a good correlation with % Mg in grass when the activities of K and H were also taken into account (Salmon, 1964). Increasing K levels and H ion concentration decreased the % Mg.

POTASSIUM

The chemical forms of soil K were categorized by Wood and
DeTurk (1940) as follows: Primary mineral $K \xrightarrow{\text{Fixed}}$ Replaceable $K \xrightarrow{\text{Water soluble}}$ K. Replaceable and water soluble K are the forms readily available for plant growth. Available K measurements involve the replacement of K from exchange sites with another cation, generally $\text{NH}_4^+$. The content of exchangeable K provides a good estimate of the relative amounts of K available for plant growth (Table 4).

Table 4: Correlation between soil K parameters and plant K

<table>
<thead>
<tr>
<th>Region</th>
<th>Range of exchangeable K</th>
<th>Crop</th>
<th>Soil K parameter</th>
<th>Correlation with plant K parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil 1/ 24 soils</td>
<td>0.02-0.62</td>
<td>cotton</td>
<td>exchangeable</td>
<td>% K 0.85</td>
</tr>
<tr>
<td>Queensland 10 soils</td>
<td>0.03-1.61</td>
<td>seteria</td>
<td>exchangeable</td>
<td>uptake 0.85</td>
</tr>
<tr>
<td>Hawaii 3/ 11 soils</td>
<td>0.08-3.90</td>
<td>sweet corn</td>
<td>exchangeable</td>
<td>uptake 0.84</td>
</tr>
<tr>
<td>North Carolina 16 soils</td>
<td>0.06-0.35</td>
<td>ladino clover</td>
<td>exchangeable</td>
<td>uptake 0.91</td>
</tr>
</tbody>
</table>

1/ Data from Freitas et al., 1966
2/ Data from Fergus et al., 1972
3/ Data from Graham and Fox, 1971
4/ Data from Wiese, 1961

Beckett (1964) proposed that the K status of soils could be evaluated by equilibrating the soil with a dilute CaCl$_2$ solution containing varying amounts of K. The amounts of K and Ca in solution are determined and the activity ratio of $K/\sqrt{\text{Ca} + \text{Mg}}$ calculated. This provides information about the quantity (Q) and intensity (I) factors in a soil and the change in I as Q changes.
A high value for Q/I indicates that the availability of K will be constant over a long period of time, while a low value indicates the supply of K is limited. Soils with micaceous clays have higher buffering capacities than soils with kaolinitic clays (Moss, 1967). Activity rations generally were not superior to exchangeable K for predicting the K status of soils (Table 4).

Boyer (1972) made an excellent review of K research in the humid tropics. His general conclusions were: (a) that the minimum level of exchangeable K for plant growth is around 0.1 meq K/100 g of soil, (b) soils are generally not lacking in K immediately after clearing the vegetation but deficiencies are apt to occur several years after clearing.

PHOSPHORUS

Soils in humid tropical and sub-tropical regions generally have low levels of available P and a high capacity to absorb P, and they form sparingly-soluble Al and Fe phosphates. On the other hand soils that have a neutral pH in their natural condition often contain adequate amounts of available P. Calcareous soils often are deficient in plant-available P because of the strong affinity of CaCO₃ for P and the formation of relatively insoluble calcium phosphates (Hsu and Jackson, 1960). Any chemical evaluation of the P status of soils must take into account the inorganic forms of soil P present, the relative availability of the P forms, and the suitability of various soil test reagents for extracting labile soil P.

FORMS OF INORGANIC SOIL P

The principal inorganic forms of soil P are phosphates of Ca, Al and Fe. The kinds of P compounds present in soil depend upon the activities of the cations, soil pH, solubility of the P compounds, mineralogical properties of the soil and soil drainage (Hsu and Jackson, 1960).

The amounts of the various forms of P in soils from different regions of the tropics and sub-tropics are given in Table 5. The data illustrate that the P content of soils is related to the degree of weathering. The highly-weathered soils, the savanna soils, Alfisols, Ultisols and Oxisols have relatively low
total P contents ranging from 127 to 139 ppm P. The least-weathered soils, Mollisols and Inceptisols, averaged 692 and 345 ppm total P, respectively. The relative organic P content of the soils tended to follow the same trend as total P. Organic P accounted for 30 to 46% of the total P, except for the savanna soils, which averaged 20% of the total. The ratio of organic C to organic P in surface soils of Nigeria was less than 200 (Udo and Ogunwale, 1977).

In soils of the rain forests with high contents of organic P, mineralization may be an important source of P. The Ca, Al and Fe phosphates are considered the active fraction of the inorganic P and would be the forms influencing P availability. The order of decreasing solubility would be Ca, Al and Fe phosphate, respectively. As the degree of soil weathering increases there is, percentage-wise, less Ca-P in the active fraction and more Fe-P. This is well illustrated with the soils from Venezuela. In areas with distinct wet and dry seasons a high proportion of the active inorganic P is in the Fe-P form (Westin and de Brito, 1969). Under impeded drainage Al-P is the main form.

Fertilizer P added to acid-to-neutral soils is rapidly converted to Al and Fe phosphates. Six months after fertilizer P was added to an Ultisol with 5% free iron oxide, the P was equally divided between Al and Fe forms (Shelton and Coleman, 1968). In calcareous soils fertilizer P reacts with exchangeable Ca and CaCO$_3$ to form Ca-P of varying solubilities (Thomas and Peaslee, 1973).

PHOSPHORUS AVAILABILITY IN SOILS

Availability of soil P can be illustrated by the following scheme:

\[
\text{Sorbed P (Quantity)} \xrightarrow{\text{Soil solution P (Intensity)}} \text{Soil solution P}
\]

The portion of the sorbed P controlling the soil solution P has been called labile P, which is plant available. In acid soils Al-P is generally the principal source of plant-available P (Halstead, 1967; McLachlan, 1965; Martens et al., 1969; Susuki et al., 1963) and Fe-P (Novais and Kamprath, 1969) in addition
to Al-P contribute to plant-available P. Phosphorus adsorbed on the surfaces of CaCO₃ is the form of P correlated with plant uptake on calcareous soils (Olsen et al., 1954).

### Table 5: Forms and amounts of phosphorus in soils from tropical and sub-tropical regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Total P, ppm</th>
<th>Organic</th>
<th>Ca-P</th>
<th>Al-P</th>
<th>Fe-P</th>
<th>Occluded and Reductant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghana</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropical Forest</td>
<td>326</td>
<td>99</td>
<td>10</td>
<td>34</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>Savanna</td>
<td>134</td>
<td>27</td>
<td>6</td>
<td>15</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>North Carolina</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultisol</td>
<td>134</td>
<td>40</td>
<td>--</td>
<td>24</td>
<td>70</td>
<td>--</td>
</tr>
<tr>
<td>Brazil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxisol</td>
<td>---</td>
<td>6</td>
<td>15</td>
<td></td>
<td>46</td>
<td>--</td>
</tr>
<tr>
<td>Venezuela</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mollisols</td>
<td>692</td>
<td>235</td>
<td>70</td>
<td>33</td>
<td>43</td>
<td>222</td>
</tr>
<tr>
<td>Inceptisols</td>
<td>345</td>
<td>119</td>
<td>11</td>
<td>102</td>
<td>68</td>
<td>45</td>
</tr>
<tr>
<td>Alfisols</td>
<td>139</td>
<td>71</td>
<td>5</td>
<td>6</td>
<td>24</td>
<td>33</td>
</tr>
<tr>
<td>Oxisols</td>
<td>127</td>
<td>48</td>
<td>2</td>
<td>6</td>
<td>11</td>
<td>60</td>
</tr>
</tbody>
</table>

1/ Data from Nye and Bartheux, 1957  
2/ Data from Shelton and Coleman, 1968  
3/ Data from Yost, 1977  
4/ Data from Westin and de Brito, 1969

**FORMS OF P EXTRACTED BY VARIOUS SOIL TEST EXTRACTANTS**

The ideal soil test extractant is the one that extracts the portion of the labile P that controls the concentration of soil P. When ³²P was added to three highly-weathered soils, an average of 44% of the NH₄F extractable P (Al-P) had equilibrated with the ³²P as compared with only 20% of the NaOH extractable P (Fe-P) (Dunbar and Baker, 1965). This indicates that the Al-P is the more soluble form. Thus, in highly-weathered soils an extractant that removes Al-P would give a good estimate of available P.
Dilute acids of strong mineral acids are commonly used as soil test extractants. The North Carolina extractant, 0.05 \( \text{N} \) \( \text{HCl} \) + 0.025 \( \text{N} \) \( \text{H}_2\text{SO}_4 \) is used in many areas. The acids will dissolve the Al-P and Ca-P. In soils containing Al and Fe-P the amount of P extracted is well correlated with the contents of Al-P (Table 6). However, where appreciable amounts of Ca-P are present, dilute acid extractants such as the North Carolina one, will also dissolve Ca-P, including relatively insoluble Ca phosphates such as apatite. Therefore, it should not be used on neutral-to-alkaline soils.

Table 6: Correlation of soil tests with the form of inorganic P

<table>
<thead>
<tr>
<th>SOIL TEST EXTRACTANT</th>
<th>Form of P correlated with soil test and correlation coefficient, ( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Michigan(^1)</td>
</tr>
<tr>
<td>Alfisols, Spodosols</td>
<td>----</td>
</tr>
<tr>
<td>and Mollisols</td>
<td></td>
</tr>
<tr>
<td>Brazil(^2)</td>
<td>Al-P</td>
</tr>
<tr>
<td>Oxisols</td>
<td>0.82</td>
</tr>
<tr>
<td>North Carolina(^3)</td>
<td>Al-P</td>
</tr>
<tr>
<td>Ultisols</td>
<td>0.96</td>
</tr>
<tr>
<td>Bangladesh(^4)</td>
<td>Ca-P</td>
</tr>
</tbody>
</table>

\(^1\) Data from Susuki \textit{et al.}, 1963
\(^2\) Data from Cajuste and Russow, 1974
\(^3\) Data from Shelton and Coleman, 1968
\(^4\) Data from Ahmed and Islam, 1975

The Bray I extractant, 0.03 \( \text{N} \) \( \text{NH}_4\text{F} \) + 0.025 \( \text{N} \) \( \text{HCl} \), was developed for acid-to-neutral soils. The fluoride ion forms a strong complex with Al and therefore the P extracted with Bray I is highly correlated with Al-P (Table 6). Calcium is also complexed by F ions and P will also be extracted from CaHPO\(_4\) (Thomas
and Peaslee, 1973). Where soils range from acid to neutral in reaction, the Bray I extractant is very satisfactory for estimating P availability.

The Olsen extractant, $0.5 \, M \, NaHCO_3$ was originally developed for use on calcareous soils. The amount of P extracted was highly correlated with the surface P of calcareous soils as measured with $^{32}P$ (Olsen et al., 1954). The Olsen extractant, however, will also extract Al-P and Fe-P (Tyner and Davide, 1962). The $NaHCO_3$ solution has a pH of 8.5 and is fairly well buffered. Extracting solutions with a high pH will remove P from Al-P and Fe-P due to the hydrolysis of Al and Fe. Thus, $NaHCO_3$ will be effective in extracting Al-P and Fe-P from acid soils.

METHODOLOGIES FOR ESTIMATING PHOSPHORUS REQUIREMENTS

Soil tests for P provide an estimate of the quantity factor but do not provide information as to how fertilizer P is required for optimum growth. Several laboratory methods have been used to determine the amount of fertilizer P required. These are: (a) sorption studies to determine the amount of P that has to be added to give a certain level of soil solution P, and (b) incubation studies to determine the amount of fertilizer P that has to be added to give the critical soil test level.

Solution culture studies have shown that optimum plant growth can be obtained with P concentrations in the range of 0.1 to 0.2 ppm P. Based on this a number of investigators (Beckwith, 1964; Ozanne and Shaw, 1967; Fox and Kamprath, 1970) have proposed that fertilizer P requirements could be based on the amount of fertilizer P that would have to be added to give a solution P concentration in the range of 0.1 to 0.2 ppm. In this procedure, soils are equilibrated with $0.01 \, M \, CaCl_2$ solution containing varying concentrations of P and the amount of P remaining in solution after a certain time of equilibration is then determined. Because diffusion of P is less in sandy soils than in clayey soils, higher concentrations of solution P are necessary in the former than in the latter for optimum growth (Olsen and Watanabe, 1963). Adsorption isotherms for P provide information about the quantity-intensity relationship and the buffering capacity of the soil with respect to P supply.
The amount of fertilizer P required to give soil solution concentrations of 0.1 and 0.2 ppm P for soils with different chemical properties are given in Table 7. The highly-weathered soils required four to five times the amount of sorbed P to give the same concentration of solution P as the weakly-weathered soil. The data also show the high fixation capacity of volcanic ash soils containing allophane.

Table 7: Amounts of sorbed P required to give soil solution concentrations of 0.1 and 0.2 ppm P in soils with varying chemical properties (data from Rivera-House, 1971)

<table>
<thead>
<tr>
<th>Soil</th>
<th>Dominant Clay mineral</th>
<th>Clay %</th>
<th>Sorbed P (µg/g soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Inceptisol</td>
<td>Montmorillonite</td>
<td>27</td>
<td>65</td>
</tr>
<tr>
<td>Ultisol</td>
<td>Kaolinite</td>
<td>38</td>
<td>285</td>
</tr>
<tr>
<td>Oxisol</td>
<td>Kaolinite</td>
<td>36</td>
<td>310</td>
</tr>
<tr>
<td>Andept</td>
<td>Allophane</td>
<td>11</td>
<td>500</td>
</tr>
</tbody>
</table>

Another approach for estimating fertilizer P requirements is to added various rates of P to a soil, incubate the soil and then determine the soil test levels of P resulting from the additions of fertilizer P. From these data one can determine the fertilizer P required to give the critical soil test P level obtained from previous greenhouse or field experiments with similar soils.

An example of this approach is given in Table 8. Previous field and greenhouse studies had indicated that the critical soil test levels for optimum growth were 20 ppm P on sandy soils having low P adsorption capacity, and 8 to 10 ppm on clayey soils having high P adsorption capacity. Incubation studies indicated that to reach these critical soil test levels, additions of 27 µg P/g of soil and 86 µg P/g of soil in the form of superphosphate were required for the sand and silty clay loam soils, respectively.
Table 8: Soil test P levels resulting from the addition of various rates of P fertilizer. Critical soil test levels underlined (Data from Woodruff, 1963)

<table>
<thead>
<tr>
<th>Soil</th>
<th>P added</th>
<th>Soil Test P$^{1/}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µg/g soil</td>
<td>µg/g</td>
</tr>
<tr>
<td>Norfolk sand</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>Georgewille silty cl. l.</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>86</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>174</td>
<td>22</td>
</tr>
</tbody>
</table>

$^{1/}$ P extracted with 0.05 N HCl + 0.025 N H$_2$SO$_4$ four weeks after fertilizer was added and soil incubated at field capacity.

ESTIMATION OF NITROGEN SUPPLY

Most of the N in surface soils is in the organic form. Availability of this N for plant growth is dependent upon the mineralization of the organic nitrogen. The conversion of organic N to inorganic N is influenced by various factors, such as C/N ratio, pH, aeration, temperature, moisture and nature of the organic N (Harmsen and Kolenbrander, 1965). The capacity of soils to supply N to growing crops has been evaluated by incubating soil at optimum conditions and measuring the net amount of inorganic N produced. Results from incubation studies have been correlated with crop response to N fertilizers to determine how much of the crop requirement for N can be supplied by the soil. These empirical results generally only apply to soils with similar properties and climatic conditions (Harmsen and Kolenbrander, 1965).
Recently there again has been interest in estimating the amount of N that a soil can supply. The approach has been to determine the amount of potentially mineralizable N in the soil. The cumulative net mineralized N resulting from intermittent incubation over a period of 30 weeks was linearly related to the square root of time expressed as weeks (Stanford and Smith, 1972). The kinetics of N mineralized at 35°C was found to follow first order kinetics described by the equation:

$$\log (N_0 - N_t) = \log N_0 - (k/2.303t)$$

in which $N_0 =$ mineralization potential (ppm N),

$N_t =$ ppm N mineralized at various times,

$t =$ time in weeks, and

$k =$ mineralization rate constant.

The average rate constant for 39 varied soils was 0.054 or 5.4% per week. The time to mineralize one-half of the total mineralizable N was 12.8 weeks. These researchers found that the regressions of $N_t$ on $t^{1/2}$ were linear and that the slopes of these regressions were related to $N_0$ according to the equation $N_0 \approx 6.5 \frac{\Delta N_t}{\Delta t^{1/2}}$. The results of this study indicated that the forms of organic N contributing to $N_0$ were similar in the 39 soils which included Mollisols, Alfisols and Ultisols. The disadvantage of the method is that relatively long incubation times are required.

Stanford et al (1974) found that $N_0$ could be estimated from amounts of $N_t$ mineralized during a two-week incubation if the soil was previously incubated for one to two weeks and the mineralizable N leached out before incubating again. The value for $N_0$ was obtained by solving for $N_0$ in the first order equation using the expression $N_0 = N_t / 1 - 10^{-kt/2.303}$. For a two-week incubation period and using the value 0.054 for $k$, the value of $N_0 = 9.77 N_t$.

The approach of Stanford and co-workers offers a means for investigating the N supplying power of soils. However, it must be kept in mind that temperature and moisture variations can have a large effect on the amount of N mineralized and these factors must be considered when extrapolating to field conditions.
DIAGNOSIS OF SULPHUR AVAILABILITY

There is a close relationship between the total N of surface soils and total sulphur and thus it has been concluded that most of the sulphur is in the organic form. The average ratio of N to S in surface soils in humid and semi-arid regions ranged from 10:1 to 10:1.45 (Freney and Stevenson, 1966). Over a long time period the relative rates of mineralization of organic N and S appear to be similar and the amounts becoming available are in the same ratio as they occur in organic matter. In the highly weathered soils that have not been fertilized the amounts of total S are generally quite low. Bolle-Jones (1964) concluded that the ferrallitic soils in Africa, with alternating wet and dry cycles receiving in excess of 600 mm annual rainfall, will likely be sulphur deficient. The highly-weathered soils of Brazil had relatively low sulphur supplying capacities (McClung et al., 1959). Under intensive management sulphur deficiencies are apt to be quite common in tropical and sub-tropical regions.

Where soils have been adequately fertilized with sulphur-containing fertilizers, accumulation of sulphates have been found in the B horizons (Bromfield, 1972; McClung et al., 1959). The sorbed sulphates are plant-available if roots grow into the subsoils. Sulphates are absorbed by the hydrated oxides of Fe and Al and sorption is decreased as pH increases and the level of available phosphate increases (Kamprath et al., 1956). Liming of surface soils and additions of P fertilizers will result in limited amounts of sulphate being adsorbed in the surface.

Because sulphate is adsorbed by the same soil materials that adsorb phosphate, solutions of Ca or K phosphate have been used as extractants of adsorbed sulphate. Critical levels of adsorbed sulphate are in the range of 8 to 10 ppm of \( SO_4^- \)S (Ensminger and Freney, 1966; Reisenauer, 1975). Both surface soils and subsoils need to be analyzed for diagnosis of the sulphate status of soils.

DIAGNOSIS OF MICRONUTRIENT AVAILABILITY

Information on micronutrient levels in tropical soils is somewhat limited. Drosdoff (1972) indicated that deficiencies of B, Zn and Mo are more common than Cu, Fe and Mn in the soils.
of the humid tropics. With intensified cropping micronutrient deficiencies are more likely to occur. Chemical evaluation of micronutrient availability can help identify those soils where deficiencies are more apt to occur.

Viet (1967) has suggested that the micronutrients in soils exist in five pools. These are: (a) water-soluble, (b) exchangeable, (c) adsorbed, chelated and complexed, (d) secondary clay minerals and insoluble metal oxides, and (e) primary minerals. The first three pools are postulated to be in equilibrium and control the supply of micronutrients for plant uptake. Any chemical evaluation of micronutrient availability should measure one or more of these pools.

The soil pools important in the supply of micronutrients for plant growth are listed in Table 9. The selection of a chemical test to measure availability of a given micronutrient must take into account the pool or pools that regulate the supply of that micronutrient. Water extractions obviously will measure the water-soluble pool. Exchangeable Zn and Mn are usually extracted with NH₄OAc or CaCl₂. The complexed micronutrient cations are extracted with solutions containing EDTA and DTPA which form strong complexes with the cations. Sometimes the complexed cations are extracted with dilute HCl. The adsorbed molybdate is generally extracted with ammonium oxalate. A detailed discussion on soil tests for micronutrients is given by Cox and Kamprath (1973).

Table 9: Soil pools important in estimating the supply of micronutrient available for plant uptake

<table>
<thead>
<tr>
<th>Micronutrient</th>
<th>Pools important in Estimating Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>exchangeable, complexed</td>
</tr>
<tr>
<td>Mn</td>
<td>water soluble, exchangeable complexed</td>
</tr>
<tr>
<td>Fe</td>
<td>complexed</td>
</tr>
<tr>
<td>Cu</td>
<td>complexed</td>
</tr>
<tr>
<td>B</td>
<td>water soluble</td>
</tr>
<tr>
<td>Mo</td>
<td>adsorbed</td>
</tr>
</tbody>
</table>
CONCLUSIONS

Soils in the tropics and sub-tropics with adequate rainfall to support sustained agriculture and silviculture are generally weathered, acid and phosphorus-deficient. Because the cation exchange capacities of highly-weathered soils are pH-dependent, measurements of CEC should be based on the sum of exchangeable bases plus KCl-extractable acidity. Generally soils of pH 5 or less contain appreciable amounts of exchangeable Al. Lime rates should be based on the amount of acidity extracted with a neutral unbuffered salt solution such as NaCl.

Exchangeable Ca, Mg, and K are the forms readily available for plant growth. Lime rates that neutralize exchangeable Al will supply adequate Ca and if dolomitic is used sufficient Ca and Mg will be supplied. Magnesium is in adequate supply when Mg saturation of CEC (pH 7) is 5%. Exchangeable K is a good indication of the amount of K available to an annual crop.

Phosphorus is generally deficient in highly-weathered soils and their capacity to adsorb P is high if the soils contain large amounts of Al and Fe oxides. The main inorganic forms of P in highly-weathered soils are Al-P and Fe-P with Al-P being the form generally controlling plant available P. Extractants that selectively extract Al-P give a good measure of plant available P. Estimates of the amount of fertilizer P required to provide critical soil test levels can be obtained from adsorption isotherms or from incubation studies where various rates of P have been added to soils and soil test levels determined.

Almost all of the N in surface soil is in the organic form. Estimation of N supplied by mineralization of soil organic N can be obtained from incubation studies. The forms of organic N that determine mineralizable N appear to be similar for a wide range of studies. No quick routine test, applicable to a wide range of soils, exists to measure N availability.

Sulphur deficiencies are apt to be common in soils of tropical and sub-tropical regions. Sulphate is held in soils by similar mechanisms as P. A Ca phosphate solution is an effective extractant to measure available sulphate.
Available soil micronutrients are in the water-soluble, exchangeable or complexed forms in the soil. Measurement of these forms should provide information about the relative supply of micronutrients.

**DISCUSSION**

Dommergues: Do these relationships apply to the semi-arid areas of the tropics, with Psamment soils of low CEC, pH 5.0-5.5 and a low reserve of minerals?

Kamprath: The principles discussed for liming should also apply to acid soils in the semi-arid regions.


Kamprath: K is often released quite rapidly from volcanic soils, particularly where the negative charges are pH-dependent. Another possibility is that Mg is close to the critical level and K applications may cause an imbalance and thus induce Mg deficiency.

Sánchez: Dr. Kamprath's critical levels are based on annual crops. A substantial modification is likely to exist when applying these concepts to pastures and trees. The concepts are universal, but the critical levels of P, for pastures for example, are 1/3 to 1/5 of the critical levels for annual crops in Colombia. The P sorption isotherms are even more useless in the case of pastures, as the levels get so close to the origin that extrapolation is not possible. It is best to use soil tests for P.

Kamprath: In this situation preparation of a soil test curve with various rates of P additions would provide a basis for establishing P fertilizer rates.

Pereira: A word of warning to agroforesters about tree responses which are different from annual crops. In East Malling apples did require more K than their soil test values suggested.

Pratt: A similar situation was observed in California orchards.

Kamprath: Long-term studies are required with tree crops to determine the nutrient requirements as related to soil tests. New, improved, high-yielding varieties may have much higher nutrient requirements. For this reason, soil test correlation studies must be done when new varieties are introduced.

Singh: Most investigators feel that an equilibrium concentration of 0.2 ppm P in solution is adequate for most crops. Do you agree with this generalization?
Kamprath: This varies with soil texture and crops species. A concentration of 0.05 ppm P was optimum for corn in some clayey soils while 0.2 was required in loamy sands. The different critical levels are due to the effect of texture on P diffusion and P buffering capacity.

Pratt: What chemical methods do you recommend to characterize soils used in field experiments in agroforestry? Please summarize.

Kamprath: Cation exchange capacity should be based on the sum of exchangeable bases (Ca+Mg+K+Na+1N KCl-exchangeable Al). A solution of 1N NH4Ac is a good extractant for exchangeable bases. Phosphorus availability can be measured on acid to neutral soils with the Bray I extract, and on calcareous soils with the Olsen method. Available S can be extracted with Ca or K phosphates.

Huxley: Establishing "critical" or "optimum" levels for different soil nutrient needs has to bring in considerations of age as well as the seasonal growth patterns of perennial species. The magnitude of changes in nutrient requirements brought about by these factors can often be considerable.

Kamprath: Optimum levels of nutrients based on the yield of the harvestable product will take into account the varying plant requirements with time, whether these are annuals or perennials.

Nyandat: We have not been able to obtain yield responses with K on most Kenya soils with the Mehlich method and the critical level of 0.2 meq/100 g soil.

Kamprath: For many crops the greatest response to K fertilizers occurs at levels less than 0.1 meq K/100 g soil. Moderate response is found between 0.1 and 0.15 meq.

Nyandat: Kenyan soils classified as Andepts are always deficient in copper, specially for wheat, although EDTA extractions show appreciable levels of available Cu. Is there a similar experience elsewhere?

Kamprath: Copper deficiency is often associated with high organic matter soils which tend to bind Cu rather strongly. The availability of Cu also decreases as soil pH increases.

LITERATURE CITED


MONITORING SOILS IN AGROFORESTRY: SOIL BIOLOGY AND BIOCHEMISTRY

Rosemary Sylvester-Bradley* 

ABSTRACT

The necessity of studying only certain aspects of soil biology and biochemistry, and of restricting the choice of techniques for their study are discussed. Aspects of soil biology and biochemistry are selected on the basis of their known importance to plant production in the tropics and the availability of suitable methods to study them. Methods for the study of nitrogen fixation associated with legume and grass roots, other nitrogen-fixing systems, endomycorrhizae, ectomycorrhizae, phosphate solubilizing bacteria, root distribution, root exudation, denitrification, nitrification, soil respiration, decomposition, microbial biomass, and the soil fauna are described briefly and discussed. The importance of designing long field experiments with the study of soil biological properties in mind, is emphasized, and some possible experiments and sampling programmes suggested. Examples are drawn from Amazonia. Pathogenic organisms are not included.

The study of soil biology and biochemistry involves the evaluation of quantity, quality and activity of all the organisms that live in the soil. It includes viruses and other microorganisms, enzyme activity, plant roots, soil micro- and mesofauna that may live permanently or temporarily in the soil, up to large burrowing animals such as armadillos, anteaters and the like. It includes interactions between these subgroups whether they be pathogenic, harmless or beneficial, between them and the physical and chemical properties of the soil, and between them and other parts of the ecosystem. Clearly it is necessary to select the study of only certain aspects of the subject when monitoring changes in soil properties.

There is also a wide range of techniques available for the study of soil biology and biochemistry utilizing a wide range of equipment from simple to ultra-sophisticated and expensive. disturbance of the soil for sampling purposes interferes with the

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activities of soil organisms, and storing the samples for any length of time before studying them makes extrapolation of the results to the natural system very unreliable. It is therefore necessary that the laboratory be near the sampling site, which means that the type of analysis that can be done is dependent on the facilities available near at hand. In the tropics the acquisition and maintenance of scientific equipment is difficult. The methods used should therefore depend as far as possible on equipment chosen for its easy availability and simplicity.

The microscopic nature of many soil organisms and the lack of light in their habitat introduces another restriction into the choice of methods for their study. Many of their characteristics cannot be observed directly, so it is necessary to use indirect techniques, which disturb the very activities they are designed to measure, often in an unquantifiable manner. In order to understand the activities of soil organisms it is thus often better to apply more than one technique to measure one process, so that the results can be compared and related to the possible errors involved in each method. It is also often helpful to compare results obtained by the same method from different field situations. On the other hand, a single plant-related parameter may often be more helpful to the agriculturalist than several complex soil parameters. For example, foliar nitrogen analyses of legumes are simpler and of more direct application than measurements of nitrogenase activity in their roots. The choice of techniques and intensity of effort obviously has to be carefully related to the purpose of the experiment.

The traditional method for the study of soil bacteria and fungi is the plate count. This involves the use of artificial media into which dilutions of samples are inoculated. After incubation the number of colonies that have developed are counted. They may subsequently be isolated, purified and identified. Unfortunately there are serious disadvantages to this method, as it depends on the assumption that those organisms that are metabolically active in the soil will grow in the media and under the incubation conditions chosen. It is very unlikely that this would be the case, except possibly in very extreme environments.
where the conditions can be fairly well imitated in the laboratory. On the other hand the method can usefully be employed to study certain groups of organisms that are easily recognized in culture media by means of specific characteristics such as colony form, microscopic appearance or biochemical reactions.

One refinement of the plate count technique is the most probable number method, where dilutions of the sample are inoculated into replicate tubes containing a selective medium that enriches for a certain group of organisms. The number of positive tubes at each dilution is counted, which gives the number of organisms in the original sample on consultation of a statistical table (e.g. Harris and Somers, 1968). Criteria for considering a tube positive may be growth in a selective medium of a biochemical reaction, such as gas production from lactose in the presence of bile salts for Enterobacteriaceae, acetylene reduction in nitrogen-free medium for nitrogen fixers, growth on ammonium in the absence of another energy source for autotrophic nitrifiers, etc.

Both plate counts and the most probable number method depend on individual colonies and positive tubes from the highest dilutions growing from a single organism. As microorganisms in the soil are often clumped and grow within slimy substances, it may be difficult to separate them into single units. The inclusion of a dispersing agent such as Na hexametaphosphate and vigorous shaking may be used to partially overcome this problem (Babiuk and Paul, 1970).

Although numbers of microorganisms are not necessarily related to their activity in the samples, changes in numbers in relation to time or environmental conditions, and in relation to the total number of microorganisms do indicate that they have an active role in the environment. It is thus important that counts of specific groups of microorganisms should be accompanied by total counts, even if these are known not to represent the actual total number of microorganisms in the soil. If the methods, media and incubation conditions are the same for each sampling point in time or place, the results are at least comparable between these points, and often useful conclusions can be drawn from such comparisons.
Direct observations of microorganisms in the soil often show organisms that are never obtained in pure culture. The study of soil fungi by direct observation is particularly important because fungi growing in artificial media usually originate from spores, whereas the hyphae are the most metabolically active part in the soil.

Specific groups of microorganisms can be directly observed in the soil by means of immunofluorescence (Schmidt, 1974). This technique has been applied extensively to the study of the ecology of rhizobia (Schmidt, 1978). Agglutination and immune-diffusion techniques can also be used for bacteria whose antigenic properties are related to their ecology in the soil (Vincent, 1970).

As many microorganisms exist in the soil in an inert state (Clark, 1968), it is not only necessary to investigate their types and numbers but also their activities. Most modern methods for studying soil microbiology involve activity measurements rather than numbers and types. The only problem with these activity measurements is that they are often not very specific and as one is dealing with a complex undefined substrate (the soil) they are open to interference by unknown factors and hence gross under- or over-estimation of the real values. However, in combination with estimates of numbers of specific groups of microorganisms or with activity measurements obtained by different methods, they are often extremely informative.

Methods for studying the soil fauna are somewhat more straightforward because the animals can be removed from the soil and usually identified from their morphological characteristics. The major difficulty is in choice of method for extracting the animals from the soil, as each method is selective for a different group. Problems may also arise from their greater mobility than that of microorganisms, in that their distribution may change rapidly with changes in soil conditions such as temperature and humidity, and from daytime to nighttime. Some soil animals can be studied by a system of baiting. For example termite activity was estimated by burying wood blocks in the soil at various intervals (Lee and Wood, 1971).
One aspect of the biology of the soil not normally considered to be within the realm of the soil biologist is the plant root. The plant root is, however, a major link between life below and above the soil surface. It transfers solar energy to soil microorganisms, which in turn make water and nutrients available to the plant. Plant roots play a particularly important and little understood role in the tropics, where heavy rainfall can leach nutrients from the soil rapidly unless roots are particularly efficient at retaining them, and where on the other hand roots may be a very important determinant of plant survival during periods of drought. The study of root development and distribution and root exudation is thus a very important aspect of soil biology in the tropics, and should not be omitted from attempts to monitor changes in soil conditions under agroforestry situations.

The choice of aspects of soil biology that should be studied for monitoring changes in soil biological properties is limited by our lack of knowledge about the systems involved, particularly in the tropics. As here we are mainly interested in plant production, aspects known to be plant related will be stressed.

Some soil biological properties can be manipulated to improve plant production, for example inoculation of more efficient and competitive strains of *Rhizobium* that occur naturally in the soil to ensure high rates of nitrogen fixation by legumes, inoculation of pine and eucalyptus seedlings with ectomycorrhizae, use of nitrification inhibitors to prevent loss of nitrogen from the soil, control of pathogens with toxic chemical compounds or by introducing predators into the system. It is therefore important that these aspects should be studied so that maximum control over them can be achieved. There are however many other soil biological properties known to be beneficial to plant growth but as yet not manipulable in the field. These properties are strongly affected by environmental conditions, as are often their own genetic characteristics and those of the plants with which they are associated. As it is probably unfeasible to study all of them at any one site and the characteristics of each site vary, the final choice of aspects to be studied should be left to those with most experience in the area. Often local inhabitants are very informative about important biological processes in their environment.
Here methods for the study of root distribution, root exudation, endomycorrhizae, ectomycorrhizae, phosphate-solubilizing bacteria, nitrogen fixation associated with legume and grass roots, other nitrogen-fixing systems, denitrification, nitrification, soil respiration, decomposition, microbial biomass and the soil fauna are described briefly and discussed. Methods for studying microorganisms responsible for cycling of nutrients other than nitrogen and phosphorus are excluded, as these are the two elements that most commonly limit plant growth. There may be situations however in which other systems should be studied. Again, this choice should be left to the discretion of those most closely involved in the particular study. Pathogens have also been omitted; as space and time do not allow them to be covered properly. Clearly, however, their study is important to plant production, and samples should always be examined by a pathologist.

**ROOT DISTRIBUTION**

Root distribution can be measured by dry weight of roots in a given volume of soil, samples being collected at different depths and distances from the plant, usually with an auger (e.g. Weng, 1976; Vandermeer, 1977). However, a false impression may be obtained by this method as it is often the finer and lighter roots that are more important in nutrient absorption and water uptake. Also in heavy soils root washing may be inadequate to clean the roots entirely. Root lengths give a less biased impression of root distribution and density from this point of view. A method for measuring root length was described by Newmann (1966). This method involves spreading roots collected from a given volume of soil over a rectangle (Figure 1) on which straight lines of a given length are distributed randomly at random angles. The number of times the roots intersect with the lines is counted, from which root length in the sample can be calculated using a formula \( R = \pi \frac{NA}{2H} \) where \( R \) = total root length

\[
\begin{align*}
2H & \quad N = n^2 \text{ of intersections} \\
A & \quad \text{area of rectangle} \\
H & \quad \text{total length of straight lines}
\end{align*}
\]

Melhuish and Lang (1968) described a method of embedding soil cores in resin and calculating root surface area from the number
Fig. 1: Rectangle containing random lines for calculation of root length.

(Courtesy of Dr. T.V. St. John). Reduced 1,33X. Total length of lines within rectangle = 96.0 cm. Area of rectangle = 275 cm$^2$. 

$R = N \times 4,500$
and diameter of roots intersecting with the surface of the core. They suggest that root surface area is more closely related to the "water-absorbing-power" of the root than root length, volume or mass. Nye and Tinker (1977) state that the method is too tedious for routine use and suggest that Newman's method is still probably the most appropriate.

An interesting technique for the study of the effect of microorganisms on root branching was demonstrated with cocoa trees (Ted St. John, pers. comm.) where mycorrhiza-free roots were obtained by surface sterilization of roots still attached to the tree, and maintained so in a box buried in the leaf litter. This technique could also be used for studies on root exudates.

ROOT EXUDATION

Hale et al. (1978) evaluated methods for the study of root exudation. They suggest that methods using model systems in which the individual parts of the system are each studied separately, and in situ systems where the whole plant-microorganism-soil complex is studied, both have advantages and disadvantages, and that a combined approach may thus be most favourable. They also suggest that isotopes have been under-used in studies on root exudates, normally $^{14}$C as CO$_2$ or $^{14}$C glucose applied to the leaves. This same suggestion was made by Rovira (1965).

Exudates of plants grown in sterile culture can be identified by bioassays using microorganisms with specific nutrient requirements.

Methods involving isotopes and sterile plants are probably too complex however for monitoring changes in soil properties. Perhaps the most applicable method is the study of numbers and types of microorganisms occurring in the rhizosphere of different plants and comparison with those in root-free soil.

Wallace and Lochhead (1949) and Rouatt and Katznelson (1961) used media containing different substrates likely to occur in the rhizosphere to compare the populations in rhizosphere and root-free soil of various crop plants. Probably the use of aerobic, semi-aerobic and anaerobic incubation conditions should
be included as an oxygen gradient across the plant root means that all three groups of microorganisms occur there. This method is subject to the pitfalls of microbiological plating methods already discussed and the precise definition of the rhizosphere is somewhat complex (Figure 2; Balandreau and Knowles, 1978), so interpretation of the data may be difficult. However, root exudates change with age and health of the plant (Hale et al., 1978) and changes in rhizosphere populations would be the first indication of effects of different plant cultures on soil biology.

ENDOMYCORRHIZAE

Vesicular-arbuscular (VA) mycorrhizae constitute a symbiotic association between phycomycetous fungi and the roots of plants. These fungi infect a wider range of plants than all other types of mycorrhizae combined. Endomycorrhizae also have a wide geographical distribution and have been shown to be important in the absorption of nutrients by plants, particularly phosphorus (Hauman, 1978). Growth of the fungus alone has not yet been achieved in pure culture which has hampered research on the topic.

Surveys of the level of infection of roots can be carried out using the clearing and staining technique described by Phillips and Hayman (1970). A large number of samples can be rapidly screened by separating a certain proportion of roots from the sample cut into approximately equal lengths, and expressing the number of root pieces infected as a percentage of the total (Hauman and Mosse, 1978).

Gerdemann and Nicolson (1965) described a method for separating endomycorrhizal spores from the soil. This can be used as an estimate of the potential of the soil for endomycorrhizal infection.

It is important that the level of endomycorrhizal infection in agroforestry situations should be maintained, and monitoring should be carried out for this purpose.

ECTOMYCORRHIZAE

Unlike endomycorrhizae, ectomycorrhizae are usually distinctive structures, differing sharply from the non-mycorrhizal
Fig. 2: Diagrammatic representation of the root tip region showing the relationship between various components (from Balandreau and Knowles, 1978)
root (Zak, 1973). They can be identified and cultured more easily than endomycorrhizae as they form morphologically distinctive sporocarps. Rhizomorphs or mycelium can be traced from the mycorrhiza to the sporocarp. Examination with a hand lens can be used to confirm that the characteristics of the fungus in mycorrhiza and sporocarp are the same. Zak (1973) describes several methods for the identification of ectomycorrhizae and suggests that none should be regarded as exclusive, and that two or more should be applied when feasible.

Ectomycorrhizae are less common in tropical than in temperate forests (Meyer, 1973). Inoculation is therefore necessary of trees requiring mycorrhizae planted in these areas, (Mikola, 1973). Marx and Krupa (1978) suggest that Pisolithus tinctorius may be especially suited to tropical soils because of its tolerance to high temperatures. Pine trees are known to require mycorrhizae, but information on other trees with potential in agroforestry situations is scarce. Preliminary surveys should therefore be carried out, and followed by inoculation experiments and evaluation of mycorrhizal establishment in the systems under investigation.

PHOSPHATE-SOLUBILIZING BACTERIA

Inoculation of seedlings with bacteria capable of solubilizing phosphate has been largely unsuccessful (Barber, 1978). Positive effects obtained may have been due to growth substances produced by the bacteria rather than their phosphate-solubilizing abilities. Greaves and Webley (1965) showed that 90% of the population of bacteria associated with roots of pasture grasses possessed phosphatase. In this case inoculation with phosphate-solubilizing bacteria would be unlikely to be successful. However, it is possible that the situation is different in phosphorus-deficient soils such as occur in Amazonia. In this case evaluation of the occurrence of phosphate-solubilizing bacteria might be worthwhile.

NITROGEN FIXATION ASSOCIATED WITH LEGUME AND GRASS ROOTS

Several methods are available for the study of nitrogen fixation. The first reports (Burns and Hardy, 1975) were based
on Kjeldahl analyses of nitrogen in plant material. This method is not sensitive enough to detect small changes in nitrogen fixing activity, although from an agricultural point of view it is probably still the most relevant. Other commonly used methods are exposure of samples to $^{15}\text{N}_2$ and subsequent analysis of fixed $^{15}\text{N}$, the acetylene reduction assay and counts of nitrogen-fixing organisms. The $^{15}\text{N}_2$ method is tedious and expensive and cannot therefore be used for field surveys. It is still however the most reliable, relatively sensitive method, and should always be used to verify data obtained by other methods on specific and well-defined systems. The method has been described by Burris (1972, 1974).

Fried and Broeshart (1975), Fried and Middleboe (1977) and Fried and Mellado (1978) described a method for measuring nitrogen fixed by field crops, using application of small quantities of $^{15}$N-labelled fertilizer. The proportion of $^{15}$N-labelled nitrogen in the plant is calculated after the growing season. If the soil is initially deficient in nitrogen it can be assumed that non-labelled nitrogen in the plant originates from $^{14}\text{N}_2$ in the atmosphere. If however there is a possibility that there is sufficient nitrogen in the soil for plant growth, preliminary experiments must be carried out using labelled nitrogen fertilizer to determine relative absorption from the two sources. Tests should also be carried out to ensure that the levels of $^{15}$N-labelled fertilizer applied do not inhibit nitrogen fixation.

The acetylene reduction assay was introduced by Hardy et al. (1968) and has resulted in a "publication explosion" on nitrogen fixation in the last decade.

The method depends on the fact that acetylene is an alternative and usually preferred substrate for the enzyme nitrogenase. The theoretical ratio of acetylene reduced to $\text{N}_2$ fixed is 3:1, based on the electron requirements of the two reactions, assuming that in both cases the substrate saturates all the active sites on the enzyme:

\[
\begin{align*}
3\text{C}_2\text{H}_2 + 6\text{H}^+ + 6\text{E}^- & \rightarrow 3\text{C}_2\text{H}_4 \\
\text{N}_2 + 6\text{H}^+ + 6\text{E}^- & \rightarrow 2\text{NH}_3
\end{align*}
\]
The recommended procedure (Burris, 1972, 1974; Postgate, 1972) involves the enclosure of the sample in a gas-tight container with a septum; the regulation of oxygen concentration to the required level; injection of 10 - 15% acetylene which can be generated from CaC₂ (Balandreau and Dommergues, 1972); inclusion of control with no sample for detection of ethylene contaminant in the acetylene; and another with sample but no acetylene to detect non-acetylene-mediated ethylene production by the sample. After a suitable incubation period the gas phase is analyzed for the presence of ethylene on a gas chromatograph with flame ionization detector, using Porapak R or N as a column. As in all enzyme activity measurements, the measurements should be made during the initial linear phase of activity.

In cases of very large samples, plastic bags can be used as containers, but in this case an internal standard such as propane must be injected so that the volume and any leakage can be calculated. In this case a 10% Na₃PO₄ on Spherosil XOB 075 100-200 µ column is used (Balandreau and Dommergues, 1973).

For experiments carried out in the field at a distance from the gas chromatograph, the gas samples can be injected into evacuated glass tubes with septa containing dry KOH to absorb CO₂ and moisture (Schell and Alexander, 1970; Stutz and Bliss, 1973). The tubes do not usually leak and can be kept for months before the analysis is carried out. The only disadvantage is the dilution of the sample involved and thus reduced sensitivity of the method.

For assay of activity in legume roots, the plants are normally decapitated and the whole root system placed in the container, care being taken not to lose nodules during removal of the soil. Washing the roots and detaching the nodules may inhibit activity (Hardy et al., 1973).

In the case of grasses, removing roots from the soil appears to result in a lag before the onset of acetylene reduction activity (Döbereiner et al., 1972). The use of soil cores rather than extracted roots for the analysis is therefore advisable. Wright et al. (1978) developed a method that overcomes the problem of delayed diffusion of the acetylene into soil cores. The core
was placed in a plastic bag which was sealed with a portable plastic bag sealer with some air space at each end of the core. A tape was fixed externally round the middle of the core. Acetylene was injected through a septum. Diffusion was facilitated by alternately squeezing each end of the bag. This was repeated each time a gas sample was collected. (Figure 3).

La Rue and Kurz (1973) described a colorimetric method for determination of ethylene that could be used in the absence of a gas chromatograph. The analyses took twice the time of gas chromatographic analyses and were less sensitive, being adequate for legumes but perhaps not for free-living bacteria and blue-green algae.

At first the acetylene reduction assay was accepted as a cheap and much more efficient substitute for $^{15}$N analyses. However, there are many problems with the method which means that it is not a quantitative measure of nitrogenase activity. (See Table 1). These problems cannot be discussed in detail here. Some of them can be solved by adapting the methods used and introducing additional controls. Others cannot be solved by the acetylene reduction assay and in this case $^{15}$N$_2$ should be used. The choice of appropriate methodology depends on the characteristics of the particular sample under study, and must be judged by each individual researcher.

Counts of nitrogen fixing bacteria are a useful complement to acetylene reduction assays. All colonies growing on nitrogen-free medium are not necessarily nitrogen fixers (Hill and Postgate, 1969) so the combined characteristics of growth in nitrogen-free medium and acetylene reduction activity are usually used. The most probable number technique is particularly well adapted for this. (e.g., Campbell and Evans, 1969). The nitrogen-free medium can be made selective for different genera of bacteria, for example semi-solid malate medium for 

\textit{Azospirillum} (Von Bulow and Döbereiner, 1975), $\text{SO}_4$ medium and reducing conditions for 

\textit{Desulfovibrio}, methanol containing medium for methane oxidizers etc. For bacteria whose colony form is easily recognized, e.g., 

\textit{Azotobacter}, plate counts can be used. Döbereiner (in press) has reviewed methods for studying "free-living" aerobic nitrogen fixing bacteria.
Fig. 3: Method for rapid diffusion of gas in acetylene reduction core assays (after Wright et al., 1978)
Table 1: Some problems of the acetylene reduction technique for the detection of nitrogenase activity, and some possible solutions

PROBLEM

1) Hydrogenase activity inhibited by acetylene. (Smith et al., 1976; Evans et al., 1978).

2) Activity of nitrogen-fixing methane-oxidizers inhibited by acetylene when growing on methane. (De Bont and Mulder, 1976)


4) Acetylene 65 X more soluble in water than N₂. (Bergersen, 1970).

5) Ethylene remains dissolved in aquatic samples (Flett et al., 1976).

6) Inhibition of acetylene reduction by N₂. (Hardy et al., 1966).

7) Inhibition by acetylene of growth (Brouzes and Knowles, 1971) of N₂ fixing organisms, of methanogenesis (Oremland and Taylor, 1975), and of denitrification (Yoshinari and Knowles, 1976).


No known solution except calculation of ¹⁵N₂ : C₂H₂ ratio.

Use ¹⁵N₂ for samples known to contain methane oxidizers, use methanol as substrate or use of N₂O instead of acetylene.

Include controls of samples without acetylene but with ethylene to detect ethylene uptake. In case of ethylene uptake use ¹⁵N₂.

No problem if nitrogenase in system under study known to be saturated with N₂.

Calculate total ethylene from concentration in gas phase, and relative volume of gas and aquatic phases.

Flush samples with inert gas : O₂ : CO₂ mixture before injecting acetylene. If no difference from samples incubated with N₂ can continue to use N₂.

No known solution except calculation of ¹⁵N₂ : C₂H₂ ratio.

Make measurements during initial linear phase of reaction.
OTHER NITROGEN-FIXING SYSTEMS

Nitrogen fixing may occur in systems other than roots in farming systems in the tropics. Photosynthetic nitrogen-fixing blue-green algae may occur in mats on the soil surface and in water of rice paddies. Photosynthetic nitrogen-fixing bacteria would be expected to occur in similar habitats (Odu, 1977). Nitrogen-fixation by non-photosynthetic organisms not associated with plants is likely to be limited by energy. Rates would therefore be higher in habitats with a large energy supply or high C/N ration such as decaying wood and the guts of wood-eating animals (Knowles, 1978). Methane-oxidizing bacteria can also fix nitrogen and occur in large numbers at the interfaces of anaerobic and aerobic environments, such as the surface of waterlogged soil (Whittenbury, per. comm.).

To estimate nitrogen-fixation in these systems the same methods as in the previous section can be used. Particular care should be taken to consider the individual characteristics of each system and to match assay conditions, particularly light and oxygen tension with those in the natural environment. It seems unlikely that any of them would be an important source of nitrogen for plant growth except in rice paddies. Decay of wood is nitrogen-limited however, and the rate of nitrogen fixation in the wood or associated animals could be important in controlling the rate of decomposition. (Sylvester-Bradley et. al., 1978). Measurements of this activity might therefore be worthwhile in areas in which there are large amounts of decaying wood.

DENITRIFICATION

Denitrification is the dissimilatory reduction of $\text{NO}_3^-$ to $\text{NO}_2^-$, $\text{N}_2\text{O}$ and $\text{N}_2$. It functions as an alternative to oxidative metabolism, using $\text{NO}_3^-$ as the electron acceptor under conditions in which $\text{O}_2$ is limiting. It occurs in various anaerobic bacteria, (Broadbent and Clark, 1965) but some may be aerobes. It is important in agriculture as it acts as a nitrogen sink from the soil to the atmosphere.

Until recently the methods available for the study of denitrification were measurement of $\text{NO}_3^-$ uptake, $\text{N}_2\text{O}$ or $\text{N}_2$ evolution,
tracing of $^{15}$N-labelled NO$_3^-$, counts of denitrifying bacteria using the most probable number or plate count methods (Focht and Joseph, 1973; Patriquin and Knowles, 1974; Gamble et al., 1977; Volz, 1977), and calculation of nitrogen loss from the difference between total inputs and outputs of nitrogen to and from the system. The problem with NO$_3^-$ uptake experiments is that NO$_3^-$ amendment of the soil results in stimulation of denitrification activity, and N$_2$ measurement by gas chromatography is insensitive. Counts alone are not an adequate assessment of activity. Calculations from the nitrogen balance depend on the accuracy of the other methods used.

The recent discovery that acetylene inhibits dissimilatory nitrate reduction after N$_2$O production (Yoshinari and Knowles, 1976; Baldeston et al., 1976) has introduced a new tool for the study of denitrification, as small concentrations of N$_2$O can be measured on a gas chromatograph with a thermal conductivity detector, or (more sensitive) an electron capture detector. Yoshinari et al. (1977) and Scott Smith et al. (1978) evaluated the technique for the measurement of soil denitrification. Analyses for acetylene reduction can be carried out on the same samples, gas samples being injected into a Y-shaped column leading to the two detectors (Beard and Guenzi, 1976).

**NITRIFICATION**

Nitrification is the oxidation of nitrogen-containing compounds to nitrate. It functions as an electron-donating system for the obligately autotrophic bacteria *Nitrosomonas* and *Nitrobacter* where the substrate is ammonia and is also carried out by some heterotrophic bacteria and fungi (e.g. Odu and Adeoye, 1970). The topic is discussed in detail by Alexander (1965). It makes nitrate available for leaching and denitrification and hence plays a role in nitrogen loss from the soil to the atmosphere. Chemical compounds that inhibit nitrification are sometimes applied to the soil to diminish this loss (e.g. Huber et al., 1977).

Nitrification can be studied by measuring the nitrate flux
in the soil (e.g., Greenland, 1958; Cunningham, 1962; Ishaque and Cornfield, 1972). Bremner (1965) has described methods for studying nitrate in soils. The extent to which increases in soil nitrate are related to nitrification is difficult to assess because nitrate is rapidly taken up by plants and other microorganisms. However, most probable number counts (e.g., Alexander and Clark, 1965; White et al., 1977) can be related to nitrate and nitrite concentrations. Parkinson et al. (1971) describe a perfusion method developed by Lees and Quastel (1946) for the study of nitrification in soils. The method can be adapted for the study of other soil activities as well as nitrification. It has the disadvantage that the activity is measured at a soil moisture content near to water-logging. Rennie and Schmidt (1977) studied *Nitrobacter* by means of immunofluorescence. This method is probably over-specific for monitoring changes in soil properties however.

### SOIL RESPIRATION AND SUBSTRATE DECOMPOSITION

Witkamp (1973) compared different methods for measuring microbial activity and counts of bacteria and fungi. He found that most parameters were related to CO$_2$ evolution and substrate weight loss (see Figure 4). He recommended that these two measurements should always be made to allow for comparison between the results of different workers.

CO$_2$ evolution can be measured by a variety of methods (Parkinson et al., 1977), the simplest of which involves inserting a cylinder sealed with a gas-tight cover into the soil. A dish containing KOH is placed on a tripod inside the cylinder and the amount of CO$_2$ evolved measured by back titration. Diurnal variations in respiration rate must be taken into account. This method is limited by the fact that it includes root respiration, which may vary from one site to another, and depends on the diffusion of the CO$_2$ out of the soil. If the roots are removed from the soil the samples show higher rates than undisturbed soil plus roots, presumably because of facilitated gas diffusion (Santos, 1977). This problem is avoided when using bags containing litter instead of cores of soil (Witkamp, 1966a).
Fig. 4: Highly significant positive linear relationships between microfloral parameters and substrate transformations based on experimental and literature data. In particular, evolution of CO$_2$ (stippled) and weight loss (hatched) are related to many of the
Methods aimed to overcome gas diffusion problems involve the use of a battery-operated pump which draws the gas from the soil and through the CO₂- absorbing solution, or alternatively flushing with air which is subsequently passed through an infrared gas analyzer (Parkinson et al., 1971).

Substrate decomposition can be measured by enclosing weighed amounts of the chosen substrate in nylon or fibre-glass bags of varying mesh size to allow the entry of various size groups of soil organisms. The bags are buried at various depths in the soil and removed at time intervals for weighing (Parkinson et al., 1971). Substrates may be cellulose (cotton wool), leaf litter, wood or other material. Loss in area of leaf discs may be measured instead of weight loss. As leaves of different trees show different decomposition rates, leaves from the predominant trees in the area should be chosen.

There are other methods available for measuring microbial activity in soil as dehydrogenase activity measurements (Parkinson et al., 1971; Ohle, 1972) and microcalorimetry (Mortensen et al., 1973). However, these methods are probably less applicable for our purpose than the two methods described above.

MICROBIAL BIOMASS

The two most appropriate methods for measuring biomass are probably by direct counting (Jones and Mollison technique: Parkinson et al., 1971) and ATP measurements (Holm-Hansen, 1972; Ausmus, 1973).

In the Jones and Mollison technique a weighed sample of soil is ground with water in a mortar and combined with molten agar. This suspension is allowed to solidify on a haemocytometer slide, which gives an agar film of defined thickness (0.1mm). This is floated off onto an ordinary microscope slide where it may be stained with aniline blue. The mycelial length and number of bacterial cells can be measured by projection or from photographs of the microscope field. Mycelial length can be calculated by a method similar to that already described for root length determination. (Witkamp, 1966a,b; Thomas et al., 1965). The results
per gram of soil can be calculated from the known dilution of the soil and the magnification of the microscope field. This method does not distinguish between dead and live cells but in combination with ATP measurements is a good indication of the total soil microbial population.

Until recently the ATP method was only applied to water samples because of the difficulties associated with extracting ATP from soils and sediments (Holm-Hansen, 1972). The method is based on the dependence of the enzyme luciferase on ATP for light emission from its reduced substrate, luciferin. Luciferin and luciferase are produced from fire-fly lanterns. Extrapolation of ATP measurements to biomass depends on a factor that may vary from one group of microorganisms to another (Ausmus, 1973). Ausmus (1973) compared different methods for extraction of ATP from soils, showing that butanol and H$_2$SO$_4$ were the two best extractants, and described the H$_2$SO$_4$ extraction method, which was the most convenient.

SOIL FAUNA

The soil fauna play a very important role in the mechanical decomposition of litter, which increases the area available for microbial attack. It also contributes to soil structure and aeration. The micro- and mesofauna of tropical soils include protozoa, nematodes, springtails, mites, termites, ants, molluscs, potworms and earthworms, apart from many other less abundant arthropods and other animals. The larger members of the macrofauna are not included by commonly used soil sampling techniques and separate observations should be made to assess their activity. Animals that inhabit decaying wood, and nest-builders (e.g., termites) must also be taken into account.

Methods for the study of the soil fauna are described by Phillipson (1971), so here they will only be summarized.

Protozoa can be counted by methods similar to those used for bacteriological counts, with an edible bacterium included in the medium. Clearing of the medium indicates the presence of protozoa.
All other soil animals are studied by means of a variety of extraction methods that are in themselves straightforward, but small modifications of which may alter significantly the efficiency of the extraction.

Nematodes can be extracted from the soil by a variety of elutriating and decanting techniques.

Arthropods are usually extracted by modifications of the Berlese-Tullgren funnel. This consists of a funnel into which the sample is placed and a light bulb above it that forces the animals downward into a collecting solution by means of the establishment of a temperature and humidity gradient. It is important that the collecting solution should not repel the animals.

Potworms can be extracted into cooled sand placed on the top of the soil sample which is heated in a water bath. They are very common in Amazonian soils but have virtually not been studied at all (H. Schubart, pers. comm.).

There are various methods available for the extraction of earthworms from soil (potassium permanganate, formaldehyde, electric current, baiting, etc.). However, these are only applicable when earthworm densities are relatively high. At low densities manual sorting is the most commonly used method. Earthworms occur at high densities in humid soils in Amazonia (I. Ayres, pers. comm.) but in agricultural soils they are very rare. Management techniques that conserve soil humidity would therefore be expected to increase earthworm populations.

SUGGESTIONS

The effect of techniques used in tropical agriculture such as mulching, low tillage and green manuring on soil biology has been little studied and is likely to vary from region to region. Long-term field experiments aimed to determine the effects of certain agricultural systems on soil properties necessarily include many treatments with different crops, clearing methods, rotations, soil conservation techniques, etc. It is thus not possible to include extra treatments for the evaluation of effects.
of particular factors on soil biological properties. Many of these effects could be evaluated in short-term experiments as the short generation-time of most soil organisms means a rapid response to changing conditions. The results of such preliminary experiments might be very useful in the selection of treatments to be used in long-term experiments, and of parameters that should be monitored.

Such short-term experiments might include the establishment of a series of different ground covers managed by different methods, and the study of as many soil biological properties as possible. Preliminary experiments could also include the study of the distribution of the major groups of soil organisms, for example depth profiles, occurrence in decaying logs lying on the soil surface, termite mounds etc.

With these preliminary results, the amount of work necessary to monitor changes in soil properties in long-term experiments would be considerably diminished.

ACKNOWLEDGEMENTS

I would like to thank my colleagues at INPA for their helpful discussion and ideas.

DISCUSSION

Dommergues: I agree with Dr. Bradley on the importance of studying roots. It is the major input of energy in the soil. How can you measure root turnover?

Bradley: Perhaps with $^{15}$N.

Dommergues: An inverted periscope can be used to measure the root system's growth without disturbance. Do you have evidence of increase in P uptake by inoculating with P solutions?

Bradley: No. It may work in low P soils, but the inoculation potential is probably greater with mycorrhiza.

Dommergues: How about $N_2O$ evolution?

Bradley: It seems to work.
Pratt: It works in California. There are forthcoming papers by John Ryden, et al. in the Soil Science Society of America Journal on N₂O measurements in the field. They have found N₂O measurements to be useful.

Keya: Can microorganisms give us an idea on soil nutrient status?

Bradley: In Brazil and elsewhere they are using Azotobacter spp. to measure molybdenum status.

Kamprath: You cannot use a spade to take soil samples for acetylene reduction. A 30 cm depth probe is required.

Dommergues: This is the way it is done in Minnesota, where they calibrate the acetylene-core method with Kjeldhal N.

Redhead: Spore counts of ecto-mycorrhizae are misleading. You should measure infection.

Pratt: Some of the methods are cumbersome and often just qualitative. What are the simplest methods you can recommend?

Bradley: The procedures described in the paper can be managed by two graduate students per site.

Pratt: Is it not better to measure microbiological effects? In California they admitted that it is better to measure effects in the case of denitrification.

Bradley: No. It is better to measure the biological activity. Now there is a good method for estimating denitrification.

Dommergues: New methods for mycorrhiza infection are becoming easier. The core methods for acetylene reduction and mycorrhiza work quite well.

Bradley: If you supplement this with bacterial counts, the interpretation of the results improves.

Huxley: Interactions are important. Do we know enough about the soil system to interpret estimates of nitrogenase activity from soil cores well enough? Especially in complex agroforestry situations?

Bradley: Apparently so. But there is little evidence for the tropics.

Huxley: In very arid regions surface crusting is a critical factor affecting seed germination, seedling survival and regeneration. Measurements of surface crusting should be refined.

Pereira: Indeed, there is more need generally to monitor soil physical properties in the field. Too few soil physicists measure physical properties in the field to solve land-use problems. For example, simple and portable field rainfall simulators have been invented and tested by a dozen researchers, yet every new study published is to produce a new design. We need to have them used so as to compare field results on a meaningful scale.

Sánchez: There is a common tendency in many tropical institutions to obtain very sophisticated equipment for soil physics research. Dr. R. Lal lectured at a recent EMBRAPA meeting in Belem where he described very simple techniques that can be used for monitoring all essential soil physical properties in agroforestry at very low cost.
LITERATURE CITED


MONITORING SOILS IN AGROFORESTRY: PHYSICAL PROPERTIES

Andrew P. Uriyo*

ABSTRACT

Soils under forestry when brought to agriculture generally provide favourable conditions for plant growth as a result of the long build-up of soil fertility and favourable soil physical conditions. But the cleared forest land sustains production for only a few years; thereafter its productivity deteriorates rather quickly. Research so far undertaken shows that soil physical conditions play a significant role in maintaining the soil's ability to grow forest trees and agricultural crops. Some of the methods currently used for measuring soil physical properties that might be used in an agroforestry system are outlined and discussed. Their limitations, where known, are also indicated. Particular emphasis is put on methods of measuring soil moisture, which is related to porosity, infiltration, percolation and, to a certain extent, erosion. Available information on the measurement of soil physical properties under agro-forestry systems of land-use are scanty. Therefore, no generalizations or recommendations are made on the suitability or otherwise of using a particular method in a given ecological zone. In the humid tropics, agroforestry systems offer much promise for supporting human settlement in the future, and methods of measuring soil physical properties needed for evaluating these types of land-use need to be tested for their suitability.

People in the humid tropics still depend on the system of shifting cultivation for the production of their food. Nye and Greenland (1960) reviewed this system of agriculture and pointed out that although scientists from the temperate regions condemn it as wasteful and primitive, they have failed to understand all its processes and after 25 years of experimentation have not yet found a superior method. The main aim of shifting cultivation is to exploit the fertility of the soil of newly-cleared land by cropping it for 2-3 years and then falling it for 7-12 years. After two years of cropping many tropical soils are incapable of producing another crop (Cunningham, 1963).

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It is becoming increasingly apparent that most of the good agricultural and forestry land in the tropics is already utilized. However, new varieties of plants that mature rapidly and with a lower water requirement are now being produced for growing in areas hitherto regarded as being of low potential. In such areas rainfall is rather erratic and it often falls during intense storms. The physical condition of the soil can thus be the major factor in deciding whether a certain type of land-use is a success or failure. Soil physical characteristics, surprisingly, have not been studied much in the past. Many of the land areas used for agroforestry are marginal and an adequate supply and balance of plant nutrients is needed if these areas are to remain productive.

Information available on the measurements of soil physical characteristics is based mostly on soils used for monoculture. Mixed cropping and agroforestry systems of land use will make varying demands in terms of soil physical characteristics and methods to monitor such characteristics will, of necessity, have to vary from one system to another. The methods for monitoring soil physical characteristics that are discussed in the following pages may not be necessarily applicable to every situation and system of land use; but they form a base from which to begin. As more information and data are collected from agroforestry systems of land use, modifications will have to be made.

SOIL TEMPERATURE

In many agroforestry systems in tropical Africa, shifting cultivation is often practised, which involves clearing land formerly occupied by forest and shrubs and then putting it under intercropping or monoculture farming system. In shifting cultivation fire is often used to clear the land. This brings about marked soil temperature changes. Air temperature during the burning of a tropical forest may reach 450 to 650°C at 2 cms above the soil surface (Sanchez, 1973). Air temperature decreases at the rate of 100°C per cm below the soil surface for the first 5 cm (Zinke, Sabhasri and Kundstadler, 1970*). Mason (1948), in

*Zinke, P.J.; Sabhasri, S. and Kundstadler, P. 1970. Soil fertility aspects of Lua forest fallow system of shifting cultivation. Univ. of California, School of Forestry and Conservation, Berkeley (unpub. mimeo).
a very careful study of bush-burning in Senegal, found that the greatest rise in temperature recorded by a thermocouple buried 2 cm beneath the soil surface was only 14.4°C under a bush fire. On the surface of the soil, however, a fire burning fiercely in a 120-cm-high bush, in a light wind, raised the temperature momentarily to 850°C. Burning also reduces the number of microorganisms on the upper layer of the soil, as shown by Meiklejohn (1955) on Kenya upland soil which was exposed to bush-burning.

Information on soil temperature is of interest to a variety of earth sciences and it is of particular concern to soil scientists. Accurate estimates of soil temperature are particularly important in soil taxonomy. The selection of appropriate classes of soil moisture and soil temperature regimes requires this information (Soil Conservation Service, 1975).

In experimental studies, a series of treatments is usually involved that can be expected to affect soil temperature. Soil temperature is measured typically at no more than one or two depths, sometimes periodically but more generally once or twice daily, using soil thermometers or thermocouples (Taylor and Jackson, 1965). Measurements or estimates of soil thermal properties are almost never made. Plant or crop behaviour is documented in terms of yield, development and related parameters that represent the accumulated effect of plant processes over long periods of time. The local practical value of such experiments can be considerable, but it is difficult to generalize findings to include other soil types and climatic conditions than those of the specific experiment.

SOIL MOISTURE

Soil moisture is generally expressed on a percentage basis, either as weight of water per 100 g oven-dry soil, or sometimes as the volumetric fraction of water. Gravimetric determination of moisture content, by oven-drying at 105°C, is the most accurate and commonly-used laboratory method. However, it is lengthy and requires thermostatically-controlled ovens and accurate balances. Other methods, faster but less accurate, are sometimes used. These include: (i) radiation drying using infrared or heat lamps often in conjunction with an incorporated balance, (ii) repeated...
burning of the soil saturated with alcohol which takes only a short time and can yield results almost as good as oven-drying, and (iii) mixing a known weight of the fresh soil with calcium carbide in a sealed container and measuring the pressure of the acetylene produced.

For *in situ* soil moisture determinations over some length of time the following methods can be employed:

**USE OF TENSIOMETERS**

A tensiometer consists of a porous cup filled with water and attached to a vacuum or mercury manometer. A hole is bored or dug into the soil to a desired depth, a handful of loose soil is placed into the hole, and the cup pushed firmly into the soil. Additional soil is packed around the cup and around the tube as necessary to ensure firm contact with the soil. A temporary connection is soon established between the water inside the cup and that in the soil. As water moves out of the cup due to suction or tension existing in the soil water, the vacuum created in the cup is registered on the gauge. Fluctuations in soil moisture are registered by the tensiometer as long as the tension does not exceed about 0.8 atmospheres. At greater tension, air enters the closed system through the pores of the cup and the instrument looses its accuracy. Under such a situation, the soil moisture tension must be lowered by irrigation or rain and the system filled with water before it will operate properly again.

**ELECTRICAL RESISTANCE BLOCKS**

Resistance gypsum blocks have been used in soil moisture studies in East Africa for quite sometime (Pereira, 1951). The electrical conductivity of porous materials varies with water content and it is, therefore, possible to use a porous device that can get into equilibrium with water in the soil for moisture content estimation. Various types of materials have been used, e.g. gypsum, nylon, fibreglass, or a mixture of these.

The salt concentration in the soil solution has much less influence on the electrical resistance of gypsum blocks than some of the other types of clocks because the solution filling the pores of the gypsum block is in all cases saturated with Ca**++** and SO**4**-. Stainless steel electrodes have been found to be
the best materials for the electrodes imbeded in the blocks as they are highly resistant against wear.

The estimation of the soil water by electrical resistance blocks is an indirect one and it has to be calibrated against, for instance, the gravimetric method, the pressure plate and the pressure membrane apparatus. Electrical resistance blocks are less sensitive than tensiometers in the moisture range of 0-0.5 bar negative potential. On the other hand, they can be used in the whole range from about 0.5 bar down to 15 bar negative potential.

THE NEUTRON PROBE

The neutron probe method for soil moisture determination, introduced about three decades ago (Blecher et al., 1950), has been used by research and industrial organizations throughout the world. The method is rapid and accurate, and measures moisture content in situ. The operation is based on the principle that hydrogen atoms are the only major cause of reduction in the kinetic energy of fast neutrons to thermal level. It is assumed that hydrogen atoms are present in the form of water and that the activity of the thermal neutrons is proportional to the moisture content of the medium. A theoretical treatment of the subject is given by McHenry (1963) and Olgaard (1965).

It is recognized that several other soil elements can absorb some quantities of thermal neutrons and thus introduce an error in the relationship of thermal neutron activity to moisture content. Chlorine, boron, and iron may be present because of the nature of soil parent material or fertilizer application practices. Opinions differ as to the use of a single calibration curve for all soils differing in mineralogy, texture, density, salinity, composition, fertilizer practices and land-use patterns. (Benz et al., 1965; Waters and Moss, 1966; Holmes, 1966; Marais and Smit, 1960).

FIELD CAPACITY

The "field capacity" can be evaluated for a surface soil in the field by determining the moisture content of a soil sample taken 24 to 48 hours after a heavy rainfall when the soil surface has been covered to prevent any loss of moisture through
evaporation. The amount of water a soil can hold at field capacity can be determined approximately for most soils by subjecting a saturated undisturbed soil to a suction of 1/3 bar, the normal moisture capacity being found when water extract ceases (Salter and Williams, 1965).

PERMANENT WILTING POINT

The approximate value of the permanent wilting point may be obtained by sampling soil under wilting plants in the field and determining the moisture content. The permanent wilting point of a soil may be measured more accurately by using pot-grown sunflower plants in soil that is allowed to become progressively dry. The permanent wilting point is that moisture content of the soil when the sunflower fails to recover from wilting when placed in a water-saturated atmosphere.

The sunflower method is a lengthy process of at least several weeks duration. A much more rapid technique is to subject a saturated soil to a pressure of 15 bars. The soil water is driven through a porous ceramic plate or permeable membrane. Equilibrium is attained in a few days and the soil water retained has a close correlation with the permanent wilting point percentage (Lehane and Staple, 1970; Salter and Williams, 1965).

AVAILABLE SOIL MOISTURE

Taken by itself, the moisture content is of limited value since not all moisture in the soil is available to plants. The moisture above the field capacity or below the permanent wilting point is not utilized by plants. There are, however, many important limitations to this principle. Available water is not uniformly available in soils, roots do not extract uniformly, and the replenishment of water in the depleted areas may be slow enough to cause wilting even in the presence of ample water (Sanchez, 1976). While working in Zambia with Oxisols, Inceptisols, Vertisols and Entisols, Maclean and Yaeger (1972) showed that soil moisture tensions between 0.1 and 0.2 bar approximate actual field capacity better than the classic 0.3 bar. When available water was calculated as the difference between 0.3 and 15 bars, the result was an under-estimation of the available water range by 35% compared with actual field measurements in these soils.
AVAILABLE WATER CAPACITY (A.W.C.)

The available water (A.W.) is the difference between the upper and lower limits of available water, and can be expressed as a percentage, as in Equation 1, or more usefully as available water capacity when converted into centimetres of a given depth D of a soil as in Equation 2:

\[
\text{A.W.\%} = \text{Percentage moisture content at } (F.C. - P.W.P.) \quad [1]
\]

\[
\text{A.W.C.} = \frac{\text{A.W.\%} \times \text{bulk density} \times D}{100} \quad [2]
\]

Bulk density may be determined according to the method described by Blake (1965).

The available water capacity of a soil is one of the most useful of its physical characteristics. It can be regarded as an index of the ability of a soil to store water and thus allow plants to maintain normal growth during dry periods. Most arable soils can store between 4 and 7 cm of water per 30 cm depth; sandy soils hold less and a few soils considerably more. The available water depends both on the soil's available water capacity and the plant's rooting depth. A high available water capacity will not be of much use if the soil is shallow and thus restricts the rooting depth. On the other hand very deep friable soils can supply large amounts of water to plants that are deep-rooted and thus can extract the stored water. *Cenchrus ciliaris* grown in Kenya had roots extending to 6.1 metres depth 18 months after planting and had developed a 61 cm moisture deficit at 20 months (Dagg, 1966): Under such conditions deep-rooting grasses and trees continue to grow for a considerable time after the rains have ceased.

The situation may be more complicated under mixed farming and forestry conditions where the root depth of the crop combination or forest plants may differ. Root studies by Pereira and Hosegood (1962) indicated that the bulk of the roots of clove trees is concentrated in the first 100 cm of soil. The initial study was confined to seasonal availability of water in the 100 cm of soil under clove trees with a ground cover of tall weeds, compared with clove trees with a heavy cover of kudzu. The cloves with kudzu as a cover crop appeared to create a more prolonged moisture deficit but the deficit developed by both
covers were severe. Elimination of the clover roots showed that neither weeds nor kudzu were themselves drying the soil to the 100 cm depth and that there was, in fact, little difference between the two covers; however, kudzu used slightly more water.

In a second study, the soil under kudzu cover was in the lower tension range of free available water for 100 days more, and kudzu appeared to use less water than weeds only; but when combined with clove trees the consumptive use of water was the same as that of clove with weeds. While the kudzu roots used more water at depth, they did not in fact use as much water from the top soil.

**WATER MOVEMENT**

The benefits of a satisfactory soil depth and available water capacity can only be fully realized if water flow into and through the soil is unimpaired. Soil water movement can be divided into two aspects: (a) hydraulic conductivity, the rate of water transmission through the soil, and (b) infiltration, the rate at which water passes into the soil at the soil-atmosphere interface.

**HYDRAULIC CONDUCTIVITY**

Field measurements of the rate of water flow through a soil profile above a water table, or through sections of a profile are lengthy, can require specialized and costly apparatus and large quantities of water (Boersma, 1965). In general such methods consist of measuring the water flow rate from an auger hole into the soil after constant flow has been established. Laboratory measurements of hydraulic conductivity require less water, take less time to reach equilibrium and utilize simple equipment.

The hydraulic gradient is the difference in head at the inlet and outlet faces of the core divided by the length of the core. Although the flux may be measured with any desired precision, the applicability of such measurements and the need for precision is limited by problems of assuring that field structure is maintained or attained in reconstitution (Baver *et al.*, 1972). Shrinking and swelling during handling and microbial activity often lead to appreciable changes from field conditions.
Furthermore, vertical and horizontal conductivity often differ. Since field flow rarely is restricted exactly to either the vertical or the horizontal, field hydraulic conductivity is not easy to obtain from laboratory measurements on reconstituted samples. Both laboratory and in situ methods (Klute, 1965), require considerable replication to offset the effect of these heterogeneously distribution features.

In the laboratory method, free water is allowed to stand above the soil core surface until a constant flow-rate through the soil is obtained. The hydraulic conductivity is then found by maintaining the standing water at a fixed head and noting the quantity of water, \( Q \), collected at the base of the core in time, \( t \). The hydraulic conductivity may be calculated by means of equation (3): 

\[
H.C. = \frac{Q}{At} \left( \frac{L}{H_1 - H_2} \right)
\]

\( A \) = cross sectional area, 
\( L \) = length of the soil core, and 
\( H_1 - H_2 \) = difference in height between the water surface of the fixed head, \( H_1 \), and base of the soil core \( H_2 \).

Alternatively, the water head in a standpipe of cross sectional area \( a \), can be allowed to fall from \( H_1 \) to \( H_2 \) in time \( t \) and the H.C. calculated using equation (4): 

\[
H.C. = \frac{aL}{At} \ln \left( \frac{H_1}{H_2} \right)
\]

The falling head technique is particularly useful where the H.C. is low.

The flow rate through a soil profile is equal to the conductivity of the least permeable layer in that profile. Hard pans, compacted layers, and zones of clay particle deposition have low conductivities which reduce the ability of the entire profile to transmit water. Man-made compacted layers, caused by ploughing at the same depth for some years, and by the passage of heavy farm implements in moist conditions, can greatly reduce the conductivity and give rise to water-logging or run-off. In addition, compaction can cause reduction in aeration, and in extreme cases limit root penetration and seedling establishment.
Soils that have been under forest are protected from intensive radiant drying. When these areas are cleared for arable and sometimes perennial crop farming, dessication under high intensities of solar radiation alternating with intense rainfall becomes a common feature. Drying out the rain-damaged surface layer under intense radiation might affect its hydraulic conductivity when wetted. Rose (1962) showed that infiltration into soil samples that had experienced radiant drying was only half that for samples that were not subjected to the radiation, and the decrease was very highly significant.

INfiltration Rate (IR)

The infiltration rate may be determined in the field by natural rainfall, artificial rainfall, or flooding. The first two techniques are used on sloping land, the infiltration rate being calculated from the difference between the runoff and the water applied. On level land using the flooding method, an enclosing barrier is erected and the infiltration rate found from the quantity of water needed to maintain a constant head on the soil surface. The same principle may be applied on a smaller scale using double concentric rings both flooded with water, the inner ring having a constant head.

Absolute measurements of infiltration rate using natural rainfall are difficult to achieve as the rainfall intensity rarely remains constant for any length of time. However, useful data may be obtained from the runoff during a rainstorm with the use of an automatic raingauge.

Artificial rainfall has the advantage of a controlled and constant intensity; the raindrops can be produced by sprinklers, drip screens and drip towers. Parr and Bertrand (1960) have reviewed many methods of determining infiltration rate. Most of the field methods suffer from having apparatus that is large, cumbersome and costly. Bertrand (1965) designed a sprinkler using a single full-cone nozzle spraying downwards from a height of about 3 metres. The drop size, distribution and kinetic energy of the artificial rain compared favourably with that of natural rainfall.
When tracts of land are cleared of forests and annual crops established, infiltration of rain water can be seriously impeded because of the removal of the forest litter and grass cover which act as mulch. The percentage acceptance and infiltration rate may be computed as follows:

\[
\text{Acceptance \%} = \left(1 - \frac{\text{Vol. of run-off}}{\text{Vol. of rainfall applied}}\right) \times 100
\]

\[
\text{I.R.} = \text{Rainfall intensity} \times \text{acceptance percentage}
\]

The infiltration rate can be of critical importance to bare sloping soils, for it determines how much water gets into the rooting zone for a given rainfall intensity, and what quantity is lost as run-off leading to erosion. The moisture content of a top-soil at the start of a rainfall appreciably affects the infiltration rate. Baver (1937) and Tisdall (1951) have found that the lower the initial soil moisture content the greater the infiltration rate. In general, run-off will occur if the rainfall intensity exceeds the infiltration rate at any time during a rainstorm.

Under permanent vegetative cover the infiltration rate is normally greater, or equal to the hydraulic conductivity of the soil; and on the occasions that the rainfall intensity exceeds this, the roots, stems and fallen leaves of the vegetative cover provide both a retarding effect on the lateral movement of surface water and anchorage against water transport of soil particles.

Rainfall on any bare soil causes, to some extent, some degradation of the soil aggregates due to kinetic energy of raindrops and translocation of primary and smaller secondary particles by the splash effect. Freshly cultivated land can have an initial infiltration rate exceeding that of the same soil under permanent vegetative cover. However, with each successive rainfall the infiltration rate is reduced due to the increasing blockage of the macropores by the translocated particles. The run-off point occurs at a lower time and/or intensity interval with each successive storm. The whole chain of events leading to erosion is largely governed by the degree of resistance of the soil aggregates to raindrop impact. All soils are susceptible in varying degrees during the period between ploughing and complete ground cover by the crop.
Experimental data are available from Uganda on the high intensities of tropical rainstorms. The significance of rainfall intensity in determining run-off and the amount of soil lost by erosion was recognized and measured (Hutchinson et al., 1958) using special instruments over a period of six years. The data (Table 1) demonstrate the important characteristic relationships between intensity, duration and amount of rainfall in tropical storms.

In the work reported from Namulonge, Uganda, ten times more run-off occurred from bare plots than from grass-covered plots, and a grass-mulch cover was twice as effective as a stone mulch in terms of run-off control. Infiltration of water into the soil was most rapid under grass cover, being three times as rapid as on a bare plot thus showing that a grass cover not only retains water at the surface but also allows it to penetrate more rapidly into the soil than all the other treatments considered. A grass mulch was however almost as effective in encouraging infiltration and percolation.

SOIL STRUCTURE

Soil structure can be defined as the arrangement of soil particles, both of the primary particles, sand, silt and clay and of aggregates composed of the primary particles. There are no absolutely direct measurements of structure as the particle arrangements within a soil are infinitely variable. An indirect but valid approach to the measurement of structure is the examination of the pore spaces between the arrangements of soil particles. Pereira (1955, 1956), working in East Africa, compared several dry-sieving and wet-sieving techniques to measure aggregate stability with porosity determinations, infiltration rates and a rainfall acceptance test in an attempt to separate good and bad soil structure as visually observed in the field. The influence of root or insect channels was the primary cause for the failure in percolation rates.
Table 1: Run-off in mm (a) and overall percolation rates in mm/hour (c) for small plots under various treatments at Namulonge, Uganda (modified after Hutchinson, Manning and Farbrother, 1955)

<table>
<thead>
<tr>
<th>Year</th>
<th>Rain mm (1)</th>
<th>Rain storms 6 mm</th>
<th>Bare a</th>
<th>Soil c</th>
<th>Stone a</th>
<th>Mulch c</th>
<th>Grass a</th>
<th>Mulch c</th>
<th>Grass a</th>
<th>Cynodon c</th>
</tr>
</thead>
<tbody>
<tr>
<td>1951</td>
<td>1840</td>
<td>1148</td>
<td>666</td>
<td>23</td>
<td>158</td>
<td>53</td>
<td>94</td>
<td>64</td>
<td>165 1</td>
<td>53 1</td>
</tr>
<tr>
<td>1952</td>
<td>1180</td>
<td>633</td>
<td>264</td>
<td>33</td>
<td>51</td>
<td>58</td>
<td>41</td>
<td>66</td>
<td>20</td>
<td>76</td>
</tr>
<tr>
<td>1953</td>
<td>1220</td>
<td>805</td>
<td>493</td>
<td>18</td>
<td>201</td>
<td>43</td>
<td>61</td>
<td>79</td>
<td>69</td>
<td>74</td>
</tr>
<tr>
<td>Average</td>
<td>1410</td>
<td>862</td>
<td>474</td>
<td>25</td>
<td>137</td>
<td>51</td>
<td>65</td>
<td>70</td>
<td>45 2</td>
<td>52 2</td>
</tr>
</tbody>
</table>

1   Before full turf cover established
2   Average of two years

(1) Annual rainfall totals after E.A. Met. Dept., 1966
PORE SPACE DISTRIBUTION

Pore sizes can be arbitrarily divided into two major categories:

(a) Macro-, or non-capillary, pores which are sufficiently large to allow water to drain by gravity alone. Macro-pores are largely responsible for soil aeration, the hydraulic conductivity and infiltration rates.

(b) Micro-, or capillary, pores which retain water against gravity and are responsible for plant moisture supply.

Both pore size categories have an essential role in plant growth.

In order to find the percentage of soil volume occupied by macro- and micro-pores, it is first necessary to determine the total pore space (T.P.S.) using the formula:

\[
\text{T.P.S.} \% = (1 - \frac{\text{bulk density}}{\text{particle density}}) \times 100
\]

Except for the most accurate work, a value of 2.65 is generally accepted for the particle density of the majority of soils (Baver et al., 1972).

The percentage of macro-pores may be found using the same procedure as for the laboratory determination of field capacity, and applying the following equation:

\[
\text{Macro-pore space} \% = \text{T.P.S.} \% - (\text{M.C.} \% \text{ at 1/3 bar} \times \text{bulk density})
\]

M.C. = moisture content

From this may be calculated the approximate percentage of pores drained by gravity. A more accurate figure may be obtained by using the M.C.\% of soil at field capacity under natural drainage.

The difference between the macro- and total pore space percentages will yield the total capillary pore space percentage. The percentage of useful capillary pore spaces is equal to \(\text{(M.C.\% at F.C. - M.C.\% at P.W.P.)} \times \text{bulk density}\). It can be seen that pore size distribution found in this way can give a measure of the soil structure, with particular emphasis on the soil potential to supply water and air to plants.
Plants vary in their need for aeration: paddy for example obtains its initial oxygen requirement from that dissolved in water. However, it is generally thought that for satisfactory plant growth soil should have at least 10% of its volume occupied by macro-pores (Stephenson and Schuster, 1937; Baver et al., 1972; and Russell, 1973). With too high a percentage of macro-pores, as in sandy soils, there are insufficient water-retaining capillary pores, making such soils susceptible to drought. Conversely, heavy clay soils often lack enough macro-pores and suffer as a result from poor drainage and inadequate aeration.

Measurement of the soil structure under an agroforestry system of land use can be a tricky problem, for soil structure quickly changes when the land is cleared of forest and cropped to either perennial or annual crops. Such soils will normally support a good crop for the first few years before it is allowed to revert to bush. The use of fire to keep standing hay mowed down, over-grazing and the use of machinery of varying horsepower for cultivation, complicates the picture further. Cunningham (1963) observed a decrease in total porosity from 52 to 43 percent and a similar decrease in water-stable aggregates within three years of clearing in a latosol in Ghana without cropping.

Soil composition, pore-size distribution and temperature govern the retention of water in the soil. Amounts of inorganic and organic constituents determine differences in soil composition.

Pore size distribution of a soil in most instances can be predicted from particle size distribution or soil texture. However, for some Hawaiian soils, the laboratory determination of particle size did not always correspond to the field texture. For example, particle size analyses by Kawano and Holmes (1958) showed some Oxisols and Ultisols to be clays, but their water-release characteristics were similar to material of coarse texture at low suction (Sharma and Uehara, 1968).

Methods of Kawano and Holmes (1958), Uehara et al. (1962), and Cagauan and Uehara (1965) have been used to study the soil macro-structure or the inter-aggregate arrangement of soil voids. The existence of inter-aggregate voids in Hawaiian soils was first reported by Cagauan and Uehara (1965). Later, Sharma and Uehara (1968) demonstrated how influential both inter- and
interaggregate voids were on the water characteristics of two Hawaiian Oxisols. The rapid release of water at low suctions and the high water content at higher suctions were attributed to the presence of inter-aggregate and intra-aggregate voids, respectively.

STRUCTURAL STABILITY

Under systems of agroforestry land-use the stability of the structure of the soil changes rapidly. Almost all the methods for measuring structural stability that have been widely used have depended on measuring the stability of the crumb-size rather than the pore-size distribution (Russell, 1971). The most widely used methods for determining the stability of the crumb-size distribution have been variations of the wet-sieving technique.

DRY SIEVING

Dry soil aggregates are placed on top of a nest of sieves progressively smaller in size, and subjected to both horizontal and vertical movement by a mechanical rotary sieve-shaker. After a set time, the contents of each sieve are weighed and the extent of aggregate disintegration determined.

Dry sieving has been found to give an index of the susceptibility to wind erosion (Chepil, 1951) and may be a useful index to measure, especially in areas that were once under forestry cover and subsequently cleared for arable crop production.

WET SIEVING

On wetting, aggregates undergo various stresses that can cause disintegration, but this depends on such factors as the moisture content of the soil clods before wetting, the rate of wetting, the size of the clod used, and the mechanical forces to which the wet clods and crumbs are subjected during the process of determining the size of the crumbs or fragments into which the clod breaks up.

MIDDLETON'S DISPERSION RATIO

Both the dry and wet-sieving techniques use aggregates of a known size fraction. Middleton's method (Middleton, 1930)
uses whole soil which is submerged under water in a cylinder for 24 hours; the cylinder is then inverted 20 times. The soil/water suspension is allowed to settle and an aliquot from 10 cm depth is sampled by pipette after the appropriate settling time for silt and clay-sized particles. From this procedure the percentage of silt and clay brought into suspension by wetting and inversion may be found.

An index 'R' of the ease with which soil aggregates are disintegrated when flooded and subjected to mild mechanical action may be obtained by the ratio:

\[ R = \frac{\text{\% age silt + clay after wetting and inversion}}{\text{total \% age silt + clay in soil (by particle size analysis)}} \]

AGGREGATE STABILIZATION USING PERSPEX SOLUTION

Williams (1963) devised an extremely sensitive method to obtain an index of structural stability by measuring the volume of water extracted by gentle suction, firstly from saturated 4-6 mm diameter aggregates subjected to mild agitation, and then from similar aggregates stabilized by a 1% W/V solution of perspex in chloroform. The chloroform is removed from the aggregates by water bath distillation.

Williams (1963) reported that the stability index, \( a/b \times 100 \), where \( a \) and \( b \) are the volumes of water removed from natural and stabilized aggregates, respectively, is sensitive enough to detect the beginnings of structural degradation after soil under grass is ploughed for arable crops. It was found that a three-year-old grass ley had a stability index of 82; 26 days after ploughing this had decreased to 77; and after a further 28 days it had fallen to 49.

With methods such as these it becomes feasible to follow structural changes resulting from farming systems, and in some cases to anticipate potentially adverse conditions long before any effect is noticeable, either in soil condition or crop yields.

In many countries of the humid tropics, with the trend towards larger farm units and heavier implements, there is possibility of serious soil damage occurring as a result of cultivation having to be done when soil is not in good tilth. In many
areas the length of the rainy season is short and planting is
essential as soon as possible after the start of the rains. Much of the cultivation and seedbed preparation is undertaken under dry conditions, when the soil is hard, and aggregates are pulverized into dust by the implements. In areas where black cotton soils occur, some land is inevitably tilled late under wet conditions where puddling and smearing occur and compacted layers may be produced. Under these conditions the rainfall penetration rate is reduced, increasing the possibility of run-off and loss of valuable water and top soil, especially if the land has a gradient and the crops grown do not provide adequate cover. Table 2 shows that on work done in India, run-off and soil loss were significantly affected by slope. Natural cover significantly reduced run-off and soil loss. Among the crops grown, maize gave highest run-off and soil loss, which was marginally next to cultivated fallow.

TEXTURE

Traditionally the field assessment of texture is a subjective test made by a finger manipulation of the soil, and it attempts to assess the field behaviour under tillage and natural processes.

The advantage of the manual textural assessment is that it is a test procedure that is comparable with field tillage operations, since both respond to the same physical properties such as hardness, friability, plasticity, firmness, softness and abrasive content. Its disadvantage is that it is subjective and, therefore, liable to variation of personal standards. Although not entirely borne out by experience, it is often claimed that this variation can be reduced to small proportions by the training of assessors using standard soils, but nevertheless the criticism is inherent in the method.

The advantage of using particle-size composition (Day, 1965) is that it is objective and, therefore, not liable to differences of personal opinion, although the methods of obtaining the particle size distribution and interpreting the results in terms of texture must be carefully standardized in order to obtain this advantage.
Table 2: Run-off and soil loss data (Modified after Bhola, Khybri and Dayal, 1975)

<table>
<thead>
<tr>
<th>Treatments</th>
<th>1967 Soil loss (tons/ha)</th>
<th>1968 Runoff off of monsoon rainfall (mm)</th>
<th>1969 Soil loss (tons/ha)</th>
<th>1969 Runoff off of monsoon rainfall (mm)</th>
<th>Mean Soil loss (tons/ha)</th>
<th>Mean Runoff off of monsoon rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural cover</td>
<td>0.4</td>
<td>142.0</td>
<td>16.9</td>
<td>0.3</td>
<td>29.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Cultivated fallow</td>
<td>8.8</td>
<td>224.4</td>
<td>25.5</td>
<td>3.8</td>
<td>111.2</td>
<td>16.0</td>
</tr>
<tr>
<td>Cowpea</td>
<td>5.7</td>
<td>209.4</td>
<td>23.7</td>
<td>2.1</td>
<td>94.4</td>
<td>13.2</td>
</tr>
<tr>
<td>Greengram</td>
<td>2.2</td>
<td>200.8</td>
<td>22.6</td>
<td>2.1</td>
<td>129.0</td>
<td>18.1</td>
</tr>
<tr>
<td>Guar</td>
<td>3.0</td>
<td>215.2</td>
<td>24.4</td>
<td>2.0</td>
<td>85.1</td>
<td>11.9</td>
</tr>
<tr>
<td>Maize</td>
<td>6.9</td>
<td>231.9</td>
<td>26.4</td>
<td>2.7</td>
<td>108.2</td>
<td>15.2</td>
</tr>
</tbody>
</table>

A. 0.5% slope

| Natural cover       | 0.4                     | 102.2                                    | 12.1                     | 0.6                                      | 20.1                     | 2.8                                      | 46.7                                    | 6.1                                      |
| Cultivated fallow  | 9.9                     | 245.4                                    | 27.6                     | 4.6                                      | 164.2                    | 23.0                                     | 158.2                                   | 21.1                                     |
| Cowpea              | 6.7                     | 205.4                                    | 22.8                     | 2.8                                      | 108.8                    | 15.3                                     | 122.8                                   | 16.2                                     |
| Greengram           | 4.6                     | 185.5                                    | 20.9                     | 2.5                                      | 144.9                    | 20.2                                     | 127.0                                   | 17.1                                     |
| Guar                | 5.3                     | 178.3                                    | 20.0                     | 2.2                                      | 88.5                     | 12.4                                     | 106.3                                   | 14.2                                     |
| Maize               | 5.4                     | 237.3                                    | 27.1                     | 3.3                                      | 160.2                    | 22.5                                     | 153.5                                   | 20.6                                     |

B. 1% slope

Total monsoon rainfall (mm) when run-off was collected

<table>
<thead>
<tr>
<th>1967</th>
<th>1968</th>
<th>1969</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>837.9</td>
<td>510.4</td>
<td>713.4</td>
<td>687.2</td>
</tr>
</tbody>
</table>
Tillet and Sauner (1959) have shown that the percentage of available water in Rhodesian forest soils was better correlated with clay and silt content than with either clay or silt content alone.

In estimating particle size analysis of forest soils, care has to be exercised. Forest soils like Andepts usually have very low bulk density values because of their organic matter content and porosity. The absence or near-absence of layer silicate clay mineral in many of these soils makes particle-size analysis practically meaningless (Sanchez, 1976). Furthermore, these soils are very difficult to disperse because of this intimate association between allophane and organic matter.

SOIL COLOUR

The colour of light can be accurately described by measuring its three principal properties, hue, value and chroma.

The Munsell notation of colour is a systematic numerical and letter designation of each of the three variable properties of soil colour.

The Munsell notation for a given soil sample can be quickly determined by comparison of the sample with a standard set of colour chips (Munsell soil colour charts, 1954). The chips are mounted in a notebook with all the colours of a given hue on one page. The pages are arranged in the order of increasing or decreasing wavelength of the dominant colour in order to facilitate the matching of the standards. Accurate estimation of soil colour is important in soil taxonomy (Soil Conservation Service, 1975) and also in choosing soil suitability for certain crops, for example tea, which in East Africa usually require soils of light colour and often reddish in hue (Smith, 1962).

CONCLUSION

The human population in the humid tropics is increasing while renewable resources such as pastures and forests are decreasing. The ability of the available land to continue to provide sufficient quantities of food, fibre, pasture, fuel and wood to sustain the population is becoming increasingly questionable. To ensure that the land will continue to support human
life at a reasonable standard we must arrest any further deterioration of the physical characteristics of the soil and evolve systems of land-use that take account of the physical properties of soil and prolong its productivity.

The land-use pattern must, therefore, include areas for forestry trees and tree crops such as coffee, and where livestock can be raised, areas for pastures must be set aside. This system will reduce soil erosion by maintaining a permanent vegetation cover. This type of land-use may not produce enough food for the population, but with the limited land available people will have to try to produce most of their own requirements such as grains, animal proteins, fuel and building materials from the limited available land. Integration of limited food-crop production with forestry, the taungya system or agrisilviculture (King, 1968) i.e. interplanting tree crops with food crops at the initial stages of forest regeneration, merits more attention than it has yet received (Greenland, 1975).

Studies by Lal (1975) indicate that, at least on slopes up to 15%, food crop production can be practised without serious erosion risk provided that zero or minimum tillage is used, together with crop and weed residues maintained as a mulch. These provide protection to the surface of the soil against raindrop impact, and the well-developed surface aggregation due to the activities of the soil animals ensures rapid infiltration of water into the soil. Mulch is also advantageous in that it also helps to conserve plant nutrients and to reduce wide temperature fluctuations, which in bare soils can be sufficiently high to inhibit germination and restrict early growth of some crops.

Mixed and relay cropping techniques can keep plant cover over the soil for most of the year, which can also reduce the soil erosion hazard. Yields in excess of those from sole cropping can be obtained (Mongi et al., 1976) and such methods may be particularly advantageous when combined with zero tillage methods (Greenland, 1975). Considerable advantages are to be expected when breeding programmes produce plants adapted to production in the mixed crop patterns (Trenbath, 1974). In addition to soil erosion control and the higher yields obtained, the diversity of crops improves the nutritional value of the produce.
Grass leys will provide fodder for livestock, improve and maintain the structure of the soil. Good soil structure will improve soil aeration and increase infiltration of rain water which can then be utilized by plants.

Grass and plant cover reduce wide soil temperature fluctuations which would adversely affect soil microorganisms and the general development of plants.

LITERATURE CITED


Several soil-test methods or indices of availability of a single plant nutrient element have been developed but none is universally suitable. A suitable method or index is one that can distinguish correctly among deficient and sufficient soils with respect to the element in question. Therefore, the selection of a suitable method/index of each nutrient element and the calibration of the soil-test data obtained by the suitable method against yield/response to applied nutrient(s) for a specific soil-crop (be it a crop or tree) system is a prerequisite in utilizing soil-test data for fertilizer (manure or chemical) recommendation purposes. Calibration not only attaches meaning to an empirical soil-test value but also enables one to identify the critical soil-test values and appropriate soil fertility classes. Various approaches for the selection of an index, calibration and interpretation of soil-test data, and formulation of fertilizer recommendations are discussed. This kind of information is needed if external application of any plant nutrient is required, especially at the nursery or early establishment stages, under agroforestry conditions. Optimum nutrient element levels in some soils and crops are also discussed.

In an agroforestry system, a low availability of plant nutrients in the soil adversely affects the growth of forest trees (especially in the early stages) that are planted in the land cleared from bush and natural forest, and of food and/or pasture crops (including tree crops) that are grown in the interspace until the forest trees have closed their canopy. Low nutrient status also limits the growth of seedlings of forest trees in the nursery. It is necessary, therefore, that optimum but economical levels of essential nutrient elements be maintained for reasonable growth and development of all the crops (including trees) in an agroforestry system. The availability of certain

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nutrients such as N, P and S may be increased by soil inoculation with bacteria and fungi capable of dissolving elements from insoluble organic and inorganic complex compounds. To some extent, this method has promise in the forest nursery, where encouraging results have been obtained (Agnihotri, 1970; Ralston and McBride, 1976; Rosendahl, 1942).

Application of artificial fertilizer is a quick and possibly the easiest way of replenishing the nutrients removed by plants or trees and lost from the soil by other pathways. Wassink (1977) advocated that fertilizers should not be introduced into the agroforestry system until farmers have sufficient money to invest on them. But the author is of the opinion that fertilizers should be introduced into the agroforestry system. The financial constraint may be taken care of through subsidies from national or international organizations and withdrawn gradually once farmers improve their economic conditions and they have been trained in the advantages and technology of fertilizer use. Financial incentives would persuade farmers to adopt agroforestry and would induce them to plant forest trees at the same time as they plant food crops, even on land cleared for shifting cultivation. In fact, Greenland (1975) recommended the use of fertilizers in shifting cultivation. Locally available manures and other such materials may be added to soil, but they are often of poor quality. An adequate supply of deficient nutrients through fertilizers would help in the rapid establishment of forest trees and a good harvest from food or pasture crops. Of course, fertilizer application may not be needed in most mature forest stands because the trees establish a closed nutrient cycle with the soil (Hardy, 1936; Sanchez, 1976).

A careful appraisal of the nutrient status of soil is necessary for a rational use of fertilizers for crops grown under agroforestry conditions, so as to apply the right amount to the neediest soil. In this respect, soil testing would be of tremendous help. Three steps are involved in a soil fertility evaluation programme meant to utilize soil-test values for making fertilizer recommendations:
(1) Correlation between soil-test values and yield or response data for the purpose of selecting a suitable soil-test method or index of availability of the various essential plant nutrient elements for a specific soil-crop system;

(2) Calibration of the soil-test values obtained by a suitable method against crop yield or response; and

(3) Interpretation of fertilizer response data and recommendation.

A suitable soil-test method is one that can distinguish correctly among deficient and sufficient soils with respect to the nutrient element in question. Numerous efforts made in the past to find a suitable method have resulted in the development of several biological and chemical tests for assessing the availability of a single nutrient element in soils, but none is universally suitable. The existing methods should, therefore, be assessed for their suitability before adopting any of them for a specific situation. In many developing countries (e.g., Tanzania: Nandra, 1974; Singh et al., 1977) only little effort, if any, has been made to screen the suitability of existing soil-test methods. Several organizations involved in soil testing have chosen a method either at random or on mere personal consideration or on scanty scientific data.

A soil-test value per se is an empirical number having no meaning unless calibrated against crop yield or response data. The purpose of calibration is to identify critical soil-test values or soil-test categories (fertility classes). A separate fertilizer recommendation is made for soils in each fertility class.

**NUTRIENT AVAILABILITY INDICES**

**NITROGEN**

Biological techniques for assessing potentially available N in soils are incubation (aerobic or anaerobic), the *Pseudomonas aeruginosa* test (Boswell et al., 1962), the algal test (Cullimore, 1966; Tchan, 1959) and measuring CO₂ production (Cornfield, 1961).
Among these, the incubation method has been used extensively. In this method, a suitable amount of soil is incubated aerobically or anaerobically for a certain length of time under optimum conditions for N mineralization. The sample is then analyzed for NH$_4^-$-N and/or NO$_3^-$-N. The aerobic incubation method is considered (Bremner, 1965a; Harmsen and van Schreven, 1955) most satisfactory for estimating soil N availability to plants. The argument is that the organisms responsible for N mineralization are the same in soil incubated in the laboratory as that in the field. But the conditions in the two situations are not the same. Although good correlation between mineralized-N and crop yield is reported (Baynes and Walmsley, 1973; Cornforth and Walmsley, 1971), the incubation method is unsuitable for routine soil testing because it is too time-consuming.

Chemical methods for estimating the potential N-supplying capacity of soils normally determine the ammonia released from soil organic matter by treatment with certain extracting agents. Organic carbon is also considered as an index of N availability in soils. Chemical methods for assessing the initial inorganic N in soils determine NH$_4^+$-N and/or NO$_3^-$-N. The direct distillation method of Keeney and Bremner (1966) is rapid and requires smaller amounts of only a few chemicals. If accessible, specific ion electrodes for NH$_4^+$ and NO$_3^-$ may be used. Dahnke and Vasey (1973) advocated that only those tests that measure potentially available N should be considered as true indices of N availability, and that the initial inorganic N should be removed before making an availability index test. But, in fact, both NH$_4^+$-N and NO$_3^-$-N tests per se have been used for making fertilizer recommendations for several crops (Smith, 1977). It should be emphasized that the NO$_3^-$-N test of only a plough-depth sample in certain instances may have little value as a basis for recommendations because of the free movement of NO$_3^-$ ions in soil with moisture. While using the NO$_3^-$-N test, many factors such as time of sampling relative to climate, depth of sampling relative to rooting pattern and distribution in the profile, should be taken into consideration. In fact, profile sampling is becoming popular for the NO$_3^-$-N test in several developed countries including the U.S.A. (Smith, 1977). A few chemical N availability
indices are given in Table 1. Some other extracting agents for evaluating N availability in soils are dilute $H_2SO_4$ (Purvis and Leo, 1961; Richard et al., 1960), HCl (Peterson et al., 1960), NaOH (Cornfield, 1960), $Na_4P_2O_7$ (Stanford, 1968), NaHCO$_3$ or $Na_2CO_3$ (Jenkinson, 1968; MacLean, 1964), boiling 0.01M CaCl$_2$ (Stanford, 1960; Stanford and Demar, 1969), boiling H$_2O$ (Keeney and Bremner, 1966; Stanford, 1968) and 2M KCl (Herron et al., 1968).

PHOSPHORUS

Most of soil P remains in complex combinations with organic and inorganic constituents. From the standpoint of plant nutrition, calcium, aluminium and iron phosphates are important inorganic P forms. Transformation from one form to another is primarily controlled by soil pH. Due to differences in P forms and in soil properties in relation to P solubility, it is difficult to develop a single extracting reagent to assess P availability in all the soils. Some of the extraction methods developed in the past are included in Table 1. A modified Truog method in which 0.02N instead of 0.002N $H_2SO_4$ is used was found suitable for highly-weathered tropical soils in Hawaii (author's personal experience) but not in Tanzania (Singh et al., 1977). Other extractants are 0.1N ammonium lactate-0.4N acetic acid (Egner et al., 1960), 0.1N NaOH (Saunders, 1956), 0.3N HCl (Baver and Bruner, 1939) and 0.02N Na$_2$EDTA (Hanna et al., 1962). The Olsen method has been modified by adding EDTA to the original extracting solution, which has increased the effectiveness of the method and has made it possible to determine K, Ca, Mg, Zn, Mn, Fe, Cu and NH$_4$-N in the same extract as for P (Sanchez, 1976).

POTASSIUM

With respect to the extent of availability to plants, soil K may be grouped in three categories which exist in a dynamic equilibrium as shown below:

- Readily available K (Exchangeable + Soil solution K)
- Slowly available K (Non-exchangeable or fixed K)
- Relatively unavailable K (K in rocks and minerals)
Table 1: Some chemical indices of availability of N, P and K in soils

<table>
<thead>
<tr>
<th>Index</th>
<th>Extractant</th>
<th>Reference for method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NITROGEN</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kjeldahl total -N</td>
<td>Concentrated $\text{H}_2\text{SO}_4$</td>
<td>Bremner, 1965b.</td>
</tr>
<tr>
<td>Organic C</td>
<td>$1N \text{K}_2\text{Cr}_2\text{O}_7$</td>
<td>Walkley and Black, 1934.</td>
</tr>
<tr>
<td>KMnO₄, oxidisable -N</td>
<td>$0.32% \text{KMnO}_4$</td>
<td>Subbiah and Asija, 1956.</td>
</tr>
<tr>
<td>Ca(OH)₂ hydrolysable -N</td>
<td>Ca(OH)₂</td>
<td>Prasad, 1965.</td>
</tr>
<tr>
<td>Initial NH₄-N</td>
<td>$1N \text{KCl}$</td>
<td>Bremner, 1965c.</td>
</tr>
<tr>
<td>Initial NO₃-N</td>
<td>$1N \text{KCl}$</td>
<td>Keeney and</td>
</tr>
<tr>
<td>Initial inorganic -N</td>
<td>$1N \text{KCl}$</td>
<td>Bremner, 1966</td>
</tr>
<tr>
<td><strong>PHOSPHORUS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bray -1P</td>
<td>$0.03N \text{NH}_4\text{F} + 0.025N \text{HCl}$</td>
<td>Bray and Kurtz, 1945.</td>
</tr>
<tr>
<td>Bray -2P</td>
<td>$0.03N \text{NH}_4\text{F} + 0.1N \text{HCl}$</td>
<td></td>
</tr>
<tr>
<td>Olsen -P</td>
<td>$0.5M \text{NaHCO}_3$ (pH 8.5)</td>
<td>Olsen et al., 1954.</td>
</tr>
<tr>
<td>Truog -P</td>
<td>$0.002N \text{H}_2\text{SO}_4 + (\text{NH}_4)_2\text{SO}_4$ (pH 3.0)</td>
<td>Truog, 1930.</td>
</tr>
<tr>
<td>Mehlich -P (North Carolina)</td>
<td>$0.025N \text{H}_2\text{SO}_4 + 0.05N \text{HCl}$</td>
<td>Nelson et al., 1953</td>
</tr>
<tr>
<td><strong>POTASSIUM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₄OAc -K</td>
<td>$1N \text{NH}_4\text{OAc}$ (pH 7.0)</td>
<td>Pratt, 1965.</td>
</tr>
<tr>
<td>Cold $\text{H}_2\text{SO}_4$ -K</td>
<td>Concentrated $\text{H}_2\text{SO}_4$</td>
<td>Pratt, 1965.</td>
</tr>
<tr>
<td>Boiling HNO₃-K</td>
<td>$1N \text{HNO}_3$</td>
<td>Pratt, 1965; Wood and DeTurk, 1941.</td>
</tr>
</tbody>
</table>

Exchangeable K and soil solution K constitute "available" K which can be successfully extracted by NH₄OAc. For estimating slowly and relatively unavailable K, strong acids are used. Some common K availability indices are given in Table 1. Potassium in the extract obtained by the extractants for P has also been used as an index of its availability in soils (Pathak et al., 1975; Sanchez, 1976).
CALCIUM AND MAGNESIUM

Neutral normal NH₄OAc is an excellent extractant of exchangeable (available) Ca and Mg. In fact, the leachate/filtrate obtained during ammonium saturation of a soil for the cation exchange capacity determination (Chapman, 1965) is quite suitable for the estimation of exchangeable Ca, Mg, K and Na.

Generally, Ca and Mg are adequately supplied indirectly through fertilizers and soil amendments. Sometimes a deficiency of Ca or Mg is induced by a sufficiency of other cations. Unfavourable ratios of Ca, Mg and K induce their deficiencies in plants even when they are adequately available in soil. For instance, plant growth is reduced when the quantity of exchangeable Mg greatly exceeds that of Ca. The tendency to Mg deficiency increases with increasing amounts of exchangeable K in soil.

SULPHUR

Like N, most of the soil S remains in organic combinations that become available to plants only after microbial transformation to SO₄-S. Organic S could be considered as an index of the S-supplying capacity of soils. The incubation method can measure the potentially available S in soils, but it is too time-consuming.

Some chemical extractants claimed to provide a reliable index of S availability are 0.15% CaCl₂ (Barrow, 1961; Kowalenko and Lowe, 1975; Williams and Steinbergs, 1959), NH₄OAc (Bardsley and Lancaster, 1960; McClung et al., 1959; Rehm and Caldwell, 1968), Ca (H₂PO₄)₂ (Fox et al., 1964) and NaHCO₃ (Kilmer and Nearpass, 1960). Information on the relative suitability of various S extractants for tropical soils is lacking. Recently, Singh et al. (1979) observed that although 0.5M NH₄OAc and 0.01M CaCl₂ extracted about the same amount of SO₄-S from some Tanzanian soils, the latter tended to extract more than the former from organic matter-rich soils.

MICRONUTRIENTS

Some extractants for assessing the availability of essential micronutrients in soils are given in Table 2. The extract obtained by a modified Olsen method can also be analyzed for various micronutrients as mentioned earlier.
Table 2: Some chemical soil-test methods for assessing the availability of micronutrients in soils

<table>
<thead>
<tr>
<th>Micronutrient</th>
<th>Extractant</th>
<th>Reference for method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>$1N NH_4OAc$ (pH 4.8)</td>
<td>Olson and Carlson, 1950</td>
</tr>
<tr>
<td></td>
<td>$0.001M EDDHA + 0.1M NaNO_3$</td>
<td>Johnson and Young, 1968*</td>
</tr>
<tr>
<td></td>
<td>DTPA**</td>
<td>Lindsay and Norvell, 1969*</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.2% Hydroquinone + $1N NH_4OAc$</td>
<td>Sherman et al., 1942</td>
</tr>
<tr>
<td></td>
<td>$3N NH_4H_2PO_4 + 0.1N H_3PO_4$</td>
<td>Adam, 1965</td>
</tr>
<tr>
<td>Zinc</td>
<td>NH_4OAc + dithizone</td>
<td>Shaw and Dean, 1952</td>
</tr>
<tr>
<td></td>
<td>$0.1N HCl$</td>
<td>Nelson et al., 1959</td>
</tr>
<tr>
<td></td>
<td>EDTA + ($NH_4)_2CO_3$</td>
<td>Trierweiler and Lindsay, 1969</td>
</tr>
<tr>
<td></td>
<td>DTPA**</td>
<td>Lindsay and Norvell, 1969*</td>
</tr>
<tr>
<td>Copper</td>
<td>NH_4OAc (pH 4.8)</td>
<td>Fiskell and Westgate, 1955</td>
</tr>
<tr>
<td></td>
<td>$0.1N HCl$</td>
<td>Cheng and Bray, 1953</td>
</tr>
<tr>
<td></td>
<td>Citrate-EDTA</td>
<td>Cheng and Bray, 1953</td>
</tr>
<tr>
<td></td>
<td>DTPA**</td>
<td>Lindsay and Norvell, 1969*</td>
</tr>
<tr>
<td>Boron</td>
<td>Hot H_2O</td>
<td>Berger and Truog, 1939</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>($NN_4)_2C_2O_4$ (pH 3.3)</td>
<td>Grigg, 1953</td>
</tr>
<tr>
<td></td>
<td>(Tamm's solution)</td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>H_2O</td>
<td>Reisenauer et al., 1973</td>
</tr>
</tbody>
</table>

* Quoted by Cox and Kamprath (1972).
** 0.005M DTPA + 0.01M CaCl_2 + 0.1M triethanolamine (pH 7.3).
EDDHA = Ethylenediamine dio-hydroxyphenylacetic acid.
DTPA = Diethylenetriaminepentaacetic acid.
EDTA = Ethylenediaminetetraacetic acid.
SCREENING SOIL-TEST METHODS FOR THEIR SUITABILITY

For selecting a soil-test method that would provide the best index of availability of a nutrient element to plants we require: (1) soil-test values by the prospective methods, and (2) yield or response data from greenhouse or field tests.

Soil samples are collected from various locations in the area for which a suitable method is sought. Normally 15-20 samples are collected such that they not only represent the area but also differ widely in fertility with respect to the element in question.

Proper techniques of sampling and preparing samples for analysis must be followed. Each sample is then analyzed by all the prospective methods. The crop of interest is grown on each soil either in greenhouse or in the field from where the soil was samples. All essential nutrients except the one in question are provided adequately. In greenhouse studies, subsamples of a soil should be treated alike before testing in greenhouse and laboratory. Grain yield is finally recorded. In case response to applied nutrient is desired, two treatments - one with and the other without the element in question will be required.

Correlation analysis has been used widely to screen the suitability of soil-test methods. For each method, a correlation coefficient (r value) is calculated, with soil-test values as independent, and corresponding yield or response data as dependent variables. The soil-test method leading to the highest significant r value is considered most suitable for the soil-crop system under investigation.

Cate and Nelson (1971) developed a discontinuous linear regression model (analysis of variance model) for partitioning the soil-test correlation data into two classes. This model can also be used for screening the suitability of soil-test methods. The model requires data on relative yield which is computed as follows:

\[
\text{Relative yield} = \frac{\text{Yield due to treatment including all except the nutrient in question}}{\text{Yield due to treatment including all essential nutrients}} \times 100
\]
Figure 1: Scatter diagram showing relationship between soil-test value (Kjeldahl total-N) and yield response of maize to 100 kg N/ha, and arbitrary grouping of soil-test categories. (Source: Singh and Uriyo).
For each method, soil-test values and corresponding relative yields are used to compute a series of coefficient of determination ($R^2$) values, through successive splitting of the relative yield data into two populations, using tentative critical levels of soil-test values to determine a particular level that will maximize the overall $R^2$. The maximum $R^2$, which may be abbreviated as $R^2_m$, is a measure of predictability of the soil-test method. The average soil-test value corresponding to $R^2_m$ is known as the critical soil-test value, the significance of which will be explained later on. Computational details are given by Cate and Nelson (1971) and Waugh et al. (1973). The soil-test method leading to the highest $R^2_m$ is considered most suitable.

The discontinuous linear regression model of Cate and Nelson (1971) was used by Singh et al. (1977) for screening the suitability of some indices of N and P availability to maize in the soils of Morogoro (Tanzania); the results are given in Table 3. The Kjeldahl total-N and Bray-1P were found most suitable.

**CALIBRATION OF SOIL-TEST VALUES AGAINST YIELD OR RESPONSE DATA**

Soil-test values obtained by a suitable method become useful only when calibrated against yield or response data. For calibration, a scatter diagram of yield or response data vs soil-test values is prepared as shown in Figure 1. A continuous mathematical function, such as a regression equation, is fitted through the scattered points. The continuum of the points is then broken arbitrarily into several soil-test categories such as "low", "medium" and "high".

Cate and Nelson (1965) developed a graphical method (discontinuous model) for correlation and calibration of soil-test values with plant response data, which involves the following steps:

1. Draw a scatter diagram of relative yields (y-axis) vs soil-test values (x-axis). The data collected for screening the suitability of soil-test methods can be used.
Table 3: Relative suitability of some indices of N and P availability to maize in the soils of Morogoro (Tanzania) and the corresponding critical soil-test values obtained by the discontinuous linear regression model of Cate-Nelson (Source: Singh et al., 1977)

<table>
<thead>
<tr>
<th>Index†</th>
<th>Range of soil-test value‡</th>
<th>Critical soil-test value‡</th>
<th>( R^2 ) m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NITROGEN</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kjeldahl total -N</td>
<td>0.08 – 0.19</td>
<td>0.60***</td>
<td>0.12</td>
</tr>
<tr>
<td>Organic C</td>
<td>1.12 – 2.49</td>
<td>0.32*</td>
<td>1.72</td>
</tr>
<tr>
<td>KMnO₄ oxidisable -N</td>
<td>130 – 279</td>
<td>0.29*</td>
<td>225</td>
</tr>
<tr>
<td>Ca(HO)₂ hydrolysable -N</td>
<td>23 – 91</td>
<td>0.34*</td>
<td>60</td>
</tr>
<tr>
<td>Initial NH₄-N</td>
<td>8 – 47</td>
<td>0.10</td>
<td>15</td>
</tr>
<tr>
<td>Initial NO₃-N</td>
<td>7 – 54</td>
<td>0.23*</td>
<td>24</td>
</tr>
<tr>
<td>Initial inorganic -N</td>
<td>22 – 79</td>
<td>0.35**</td>
<td>30</td>
</tr>
<tr>
<td><strong>PHOSPHORUS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bray - 1P</td>
<td>15 – 35</td>
<td>0.37**</td>
<td>25</td>
</tr>
<tr>
<td>Olsen - P</td>
<td>33 – 160</td>
<td>0.34**</td>
<td>110</td>
</tr>
<tr>
<td>Truog - P</td>
<td>24 – 258</td>
<td>0.36**</td>
<td>50</td>
</tr>
<tr>
<td>Modified Truog - P</td>
<td>33 – 266</td>
<td>0.28*</td>
<td>100</td>
</tr>
</tbody>
</table>

† References for methods appear in Table 1.
‡ ppm except total N and organic C which are in ‘/..’
*, **, *** significant at 5, 1, 0.1% probability, respectively.

2. Prepare a clear plastic overlay with a pair of perpendicular lines drawn on it with black India ink, so that the plastic sheet is divided into four quadrants having roughly the same relative sizes as shown in Figure 2.

3. Position the overlay on the scatter diagram so that the maximum number of points fall in the positive and a few or none at all in the negative quadrants.
4. With the plastic overlay in position, make the following observations:

(i) A perfect correlation between the two parameters would put all the data points in the positive quadrants, thus giving a situation that results in a discontinuous model.

(ii) The horizontal line of the overlay separates those relative yields (low values) that indicate a large response to applied nutrient from those that indicate small or no response.

(iii) The vertical line identifies a critical soil-test value that splits the population into two distinct soil-test categories. A large response to the applied nutrient in question is expected on soils-testing below, while a little or none at all on those testing above the critical level.

Figure 2: Format of the plastic overlay used in the graphical method of Cate-Nelson. (Source: Cate and Nelson, 1965).
As mentioned earlier, Cate and Nelson (1971) developed a
discontinuous linear regression model for partitioning the soil-
test correlation data into two classes. The mean soil-test value
corresponding to the $R^2_m$ is the critical level, which is the
same as that obtained by the graphical method (Cate and Nelson,
1965). In fact, the values of $R^2$ can be plotted on the same
diagram as for the graphical method as shown in Figure 3. The
critical soil-test values for some indices of N and P availabil-
ity in the soils of Morogoro (Tanzania) are given in Table 3.
Waugh et al. (1973) advocated that the correlation scatter diagram or relative yield vs soil-test values may not be treated as a continuous function because the relationship is not linear. Even when some kind of curvilinear model is fitted through the scattered points, it is not clear what such a correlation means.

Sanchez (1976) brought up several fundamental and practical advantages of the Cate-Nelson models over the conventional correlation techniques. By separating the data points into two populations, the Cate-Nelson models follow the Leibig's law of minimum, because beyond the critical soil-test value the nutrient in question remains no longer a limiting factor. In contrast, the continuous regression models, which follow the law of diminishing returns, force the groupings into soil-test categories to be arbitrary as they show no inflection points. The Cate-Nelson model separates soils into responsive and non-responsive categories. The graphical method identifies the soils in which the selected extractant does not work well. These points lie in the negative quadrants and they may require further investigation. Unlike the continuous models which require a complicated computing device, the Cate-Nelson's graphical method needs only a piece of transparent paper. Even the discontinuous linear regression model can be handled conveniently using a desk calculator.

It is worth mentioning that the critical soil-test value is specific for a soil-crop category. Each laboratory, therefore, should establish critical values for major soil groups and crops within its jurisdiction.

Even while using the Cate-Nelson's approach, more than two soil-test categories can be made. In this case, the "medium" category lies near the critical value.

**INTERPRETATION OF FERTILIZER RESPONSE DATA AND FORMULATION OF RECOMMENDATIONS**

Grouping soils into fertility categories by using either continuous or discontinuous models does not tell the amount of a fertilizer to be applied. For formulating fertilizer recommendations, yield or response data need to be obtained from field tests. Since field trials are expensive and time-consuming,
the sites should be selected carefully. A limited number of experiments should be conducted so as to manage them nicely.

The purpose of interpretation of fertilizer response data is to determine the amount of the nutrient in question to be applied to obtain a desired yield or response of a crop on soils belonging to a specific soil-test category (Waugh et al., 1973). A separate recommendation is required for soils of each fertility category identified during the calibration because the magnitudes of response to fertilizer application differ on soils of different soil-test categories, as depicted in Figure 4. Likewise, various crops, perhaps widely differing varieties of a crop, differ in magnitude of response to the same quantity of a nutrient applied to soils of similar fertility.

The classical continuous curvilinear models commonly employed to describe the effects of fertilizer application on yield or response are the quadratic, square root, logarithmic and Mitscherlich. First of all it is necessary to choose a model that suits the soil-crop system in question. Statistical techniques are available for this purpose, by which an $R^2$ value is computed for each model. The model leading to the largest $R^2$ is considered most suitable and is then used for computing the "optimum" or "economic" fertilizer rate graphically or mathematically. In the graphical method, the optimum fertilizer rate is at a point in the revenue vs cost curve where the marginal revenue equals the marginal cost. In other words, the point where the price of last yield increment equals the cost of last fertilizer increment (Sanchez, 1976).

The marginal revenue and cost approach, discussed above, may work well in situations where "risk" is virtually nil. However, the approach has little value in most developing countries in the tropics, where risk is high due to variability in rainfall, plant pests and diseases and possible losses due to vermin and other unforeseen causes. Prices of both inputs and outputs fluctuate widely. Most of the agricultural operations are usually carried out by hand. Under these conditions, a farmer must be assured of a definite return per unit investment in order to induce him to adopt a new agrotechnology, or an agroforestry system for that matter. The experiences of Professor R.J. Foote (personal communication, University of Dar es Salaam, Morogoro, Tanzania) showed that a benefit/cost ratio of 5:1 was necessary
Figure 4: Variation in the magnitudes of response of maize to fertilizer N and P applied to soils of different soil-test categories based on Kjeldahl total-N and Bray-1P, respectively in Morogoro, Tanzania. Source: Singh and Uriyo.
for rice in Vietnam after the war. Fogg (quoted by Ruthenberg, 1968) while studying socio-economic factors affecting the development of smallholder agriculture in Nigeria, felt that a ratio of at least 2:1 is required to induce a farmer to accept changed agrotechnology. Ruthenberg (1968) stressed a need for a ratio of 2:1 or 3:1 in terms of direct fertilizer costs to induce fertilizer use in Tanzania. For successful adoption of an agro-forestry system, a somewhat assured benefit/cost ratio would be required. The mathematical method using the most suitable curvilinear model can be employed to compute the optimum or economic fertilizer rate at a desired benefit/cost ratio. Eventually, the rate so computed will vary with fluctuations in the costs of fertilizers and produce as well as with the benefit/cost ratio desired. Waugh et al. (1973) have discussed some difficulties and limitations of the continuous curvilinear models that deserve attention before using them.

Waugh et al. (1973) developed a discontinuous linear response-and-plateau model for interpretation of fertilizer response data and formulation of fertilizer recommendation. The model is essentially a logical extension of the Cate and Nelson (1965) graphical method and is based on the Leibig's law of minimum. Several investigators (e.g. Bartholomew, 1972; Boyd, 1970) have observed that the fertilizer response curve obeys the Leibig's law of minimum and can be characterised by a sharp linear increase followed by a flat horizontal portion called plateau. This led Waugh et al. (1973) to develop their linear response-and-plateau model which involves fitting of two lines graphically on a fertilizer response diagram. The first sloping straight line is drawn through the points on the ascending portion of the graph, which represents a steep response to an applied nutrient until it ceases to be a limiting factor. This is followed by a horizontal line or flat plateau representing maximum yield, i.e. further fertilizer additions do not increase the yield to any appreciable extent.

The linear response-and-plateau model is illustrated in Figure 5.
Figure 5: Diagram illustrating the use of the linear response-and-plateau model for estimating fertilizer N and P requirements of maize in Morogoro, Tanzania. Each point is an average of several field experiments on low-N and low-P soil-test categories. (Source: Singh and Uriyo).
The fitted curve consists of two main points:

(i) Threshold yield - yield at zero level of the nutrient in question but not of all nutrients, and

(ii) Plateau yield - yield at the point where the nutrient in question ceases to be a limiting factor; it is not the maximum yield because other factors may still limit the yield.

These two parameters are used to compute the relative yield as follows:

\[
\text{Relative yield} = \frac{\text{Threshold yield}}{\text{Plateau yield}} \times 100
\]

The amount of a nutrient to be applied is the point at which a perpendicular from the point of intersection of the two lines intersects the x-axis, e.g. 70 kg N/ha and 45 kg P/ha in Figure 5.

Several advantages in favour of the linear response-and-plateau model have been indicated by Sanchez (1976) and Waugh et al. (1973). Being the minimum rate required to reach the plateau yield, the estimated fertilizer rate may represent a biological optimum. Perhaps the rate so estimated may also be realistic and economical because it is still on the side where response is increasing. The model does not require computer facilities or complex calculations because in most cases a visual fit is sufficient. The model ignores yield decreases with excessively high rates of fertilizer application as this part of the curve, when it exists, is of no significance in formulating recommendations.

OPTIMUM NUTRIENT ELEMENT LEVELS IN SOILS

The critical soil-test values and optimum levels for the soil-test categories with respect to certain crops that may be grown under agroforestry conditions are given in Tables 4 and 5. Similar information concerning forest trees is lacking. Wilde et al. (1964) advocated that minimum levels of soil fertility factors for planting jack pine (\(P. \) banksiana, Lamb.) are: total N- 0.042%, available P- 6.6 ppm, available K- 25 ppm,
exchangeable Ca -0.5 me/100 g and exchangeable Mg -0.15 me/100 g soil. Leaf (1968) reported deficiency levels for K and Mg in the surface soil as 0.04 and 0.1 me/100 g soil, respectively for red pine (P. resinosa Ait.). Based on the dry weight measurements, Safford (1975) reported that optimum Mn concentration in solution culture for P. radiata (D. Don) was near 0.5 ppm.

It should be mentioned that soil-test categories such as "low", "medium" and "high" are relative terms. Their implication with respect to fertilizer needs would vary according to specific crops and soils. The capacity of a soil to supply nutrients to plants is affected by its physico-chemical and biological properties. Since the magnitude of these properties in all the soils is not the same, they differ in their capacity to supply nutrients to plants. Similarly, forest trees (including seedlings) and food crops vary in their nutritional requirements. Thus, critical soil-test values or soil-test categories have to be established for each set of soil-crop systems. The methodologies on correlation, calibration, interpretation of fertilizer response data and formulation of recommendations discussed in this paper would be of tremendous use in this respect. The information contained in Tables 4 and 5 could serve as guidelines but the data cannot be applied for situations other than those for which they have been developed.

**RECOMMENDATIONS**

In light of the foregoing discussions, I wish to offer the following recommendations:

1. In an agroforestry system, essential nutrients in soil should be maintained at an optimum but economical level for reasonable growth and production of forest seedlings in the nursery, planted forest trees in the cleared land during their early stages and food or pasture crops grown in the interspace. Artificial fertilizers could prove useful in quickly replenishing the nutrients removed by crops or trees and lost by other pathways from the soil. Locally available manures and other such materials could be used but only as a supplement to fertilizers.
**Table 4: Critical soil-test values above which a crop may, and below which a crop may not, respond to an applied nutrient.**

<table>
<thead>
<tr>
<th>Index</th>
<th>Crop</th>
<th>Critical soil-test</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NITROGEN</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kjeldahl total-N (%)</td>
<td>Maize</td>
<td>0.12</td>
<td>Singh et al., 1977</td>
</tr>
<tr>
<td>Inorganic-N (ppm)</td>
<td>Maize</td>
<td>30</td>
<td>Singh et al., 1977</td>
</tr>
<tr>
<td><strong>PHOSPHORUS (ppm P)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bray-1P</td>
<td>Maize</td>
<td>25</td>
<td>Singh et al., 1977</td>
</tr>
<tr>
<td></td>
<td>Rice</td>
<td>20</td>
<td>Wong, 1971</td>
</tr>
<tr>
<td>Bray-2P</td>
<td>Sugarcane, acid soils</td>
<td>65</td>
<td>Wong, 1971</td>
</tr>
<tr>
<td></td>
<td>calcareous soils</td>
<td>120</td>
<td>Wong, 1971</td>
</tr>
<tr>
<td>Truog-P</td>
<td>General (acid - slightly acid soils)</td>
<td>20-30</td>
<td>Reynolds, 1973</td>
</tr>
<tr>
<td><strong>POTASSIUM (me K/100 g soil)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₄OAc-K</td>
<td>Sugarcane, rice</td>
<td>0.18-0.21</td>
<td>Wong, 1971</td>
</tr>
<tr>
<td></td>
<td>Pineapple</td>
<td>0.36</td>
<td>Wong, 1971</td>
</tr>
<tr>
<td></td>
<td>Alfalfa</td>
<td>0.23</td>
<td>Seay et al., 1950</td>
</tr>
<tr>
<td></td>
<td>Maize</td>
<td>0.19</td>
<td>Barber, 1950</td>
</tr>
<tr>
<td></td>
<td>Tobacco</td>
<td>0.24</td>
<td>Winters, 1946</td>
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<tr>
<td><strong>CALCIUM AND MAGNESIUM (me/100 g soil)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₄OAc-Ca</td>
<td>Alfalfa</td>
<td>7</td>
<td>Chapman, 1973</td>
</tr>
<tr>
<td>NH₄OAc-Mg</td>
<td>General</td>
<td>0.24</td>
<td>Bray, 1948</td>
</tr>
<tr>
<td></td>
<td>acid soils</td>
<td>0.12</td>
<td>Peach, 1948</td>
</tr>
<tr>
<td></td>
<td>Tomatoes, sweet potatoes</td>
<td>0.24</td>
<td>Hester et al., 1947</td>
</tr>
<tr>
<td><strong>SULPHUR (ppm S)</strong></td>
<td></td>
<td></td>
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<tr>
<td>1N NH₄OAc</td>
<td>Millet</td>
<td>6 - 7</td>
<td>McClellan et al., 1959</td>
</tr>
<tr>
<td>500 ppm P-Ca(H₂PO₄)²⁻</td>
<td>Maize</td>
<td>8</td>
<td>Fox et al., 1964</td>
</tr>
<tr>
<td></td>
<td>Alfalfa</td>
<td>10</td>
<td>Fox et al., 1964</td>
</tr>
<tr>
<td>500 ppm P-Ca(H₂PO₄)²⁻ + 2N HOAc</td>
<td>Alfalfa</td>
<td>10</td>
<td>Hesse et al., 1973</td>
</tr>
<tr>
<td>NaH₂PO₄+2N HOAc</td>
<td>Pasture</td>
<td>10</td>
<td>Hesse et al., 1973</td>
</tr>
<tr>
<td>500 ppm P-KH₂PO₄</td>
<td>Pasture</td>
<td>8</td>
<td>Cooper, 1968</td>
</tr>
<tr>
<td>0.15% CaCl₂</td>
<td>Pasture</td>
<td>6</td>
<td>Cooper, 1968</td>
</tr>
<tr>
<td>0.5M NaHCO₃</td>
<td>Cotton</td>
<td>10</td>
<td>Kilmer and Nearpass, 1960</td>
</tr>
<tr>
<td><strong>IRON (ppm Fe)</strong></td>
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<td></td>
</tr>
<tr>
<td>DTPA</td>
<td>General</td>
<td>2.5-4.5</td>
<td>Cox and Kamprath, 1972</td>
</tr>
<tr>
<td><strong>MANGANESE (ppm Mn)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₄OAc</td>
<td>General</td>
<td>15-20</td>
<td>Cox and Kamprath, 1972</td>
</tr>
<tr>
<td>3N NH₄H₂PO₄ + 0.1N H₃PO₄</td>
<td>General</td>
<td>25-65</td>
<td>Cox and Kamprath, 1972</td>
</tr>
<tr>
<td>0.2% Hydroquinone + 1N NH₄OAc</td>
<td>General</td>
<td>2</td>
<td>Cox and Kamprath, 1972</td>
</tr>
<tr>
<td><strong>ZINC (ppm Zn)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDTA (pH uncontrolled)</td>
<td>Oats</td>
<td>50</td>
<td>Hames and Berger, 1960</td>
</tr>
<tr>
<td><strong>COPPER (ppm Cu)</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>EDTA</td>
<td>General</td>
<td>0.5</td>
<td>Brown et al., 1971</td>
</tr>
<tr>
<td>(NH₄)₂CO₃</td>
<td>Maize</td>
<td>1.4</td>
<td>Trierweiler and Lindsey, 1965</td>
</tr>
<tr>
<td></td>
<td>General</td>
<td>0.2</td>
<td>Cox and Kamprath, 1972</td>
</tr>
<tr>
<td><strong>Boron (ppm B)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot H₂O</td>
<td>General</td>
<td>0.1-0.7</td>
<td>Cox and Kamprath, 1972</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.5</td>
<td>Bray, 1948; Bucher, 1957</td>
<td></td>
</tr>
<tr>
<td>Legumes</td>
<td>0.15</td>
<td>Rogers, 1947</td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>0.15% CaCl₂</td>
<td>0.15</td>
<td>Cooper, 1968</td>
</tr>
<tr>
<td></td>
<td>Pasture</td>
<td>0.15</td>
<td>Cooper, 1968</td>
</tr>
<tr>
<td></td>
<td>Pasture</td>
<td>0.15</td>
<td>Cooper, 1968</td>
</tr>
<tr>
<td></td>
<td>Pasture</td>
<td>0.15</td>
<td>Cooper, 1968</td>
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</table>
Table 5: Soil-test categories for some crops

<table>
<thead>
<tr>
<th>Index</th>
<th>Crop</th>
<th>Very low</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Very high</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>NITROGEN</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Kjeldahl total-N (%)</td>
<td>General</td>
<td>&lt;0.1</td>
<td>0.1-0.3</td>
<td>0.3-0.6</td>
<td>0.6-1.0</td>
<td>&gt;1.0</td>
<td>Blakemore et al., 1972</td>
</tr>
<tr>
<td>Organic C (%)</td>
<td>General</td>
<td>&lt;2</td>
<td>2-4</td>
<td>4-10</td>
<td>10-20</td>
<td>&gt;20</td>
<td>Blakemore et al., 1972</td>
</tr>
<tr>
<td>PHOSPHORUS (ppm P)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bray - IP</td>
<td>General</td>
<td>&lt;7</td>
<td>7-20</td>
<td>&gt;20</td>
<td>Bingham, 1973</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olsen - P</td>
<td>General</td>
<td>&lt;5</td>
<td>5-10</td>
<td>&gt;10</td>
<td>Bingham, 1973</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truog - P</td>
<td>General</td>
<td>&lt;3</td>
<td>3-7</td>
<td>&gt;7</td>
<td>Barker, 1977</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mehlich - P</td>
<td>General</td>
<td>&lt;10</td>
<td>10-20</td>
<td>20-30</td>
<td>&gt;30</td>
<td>&gt;50</td>
<td>Reynolds, 1973</td>
</tr>
<tr>
<td>POTTASISUM (me K/100 g soil)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₄Ac-K</td>
<td>General</td>
<td>&lt;0.1</td>
<td>0.1-0.5</td>
<td>0.5-0.8</td>
<td>&gt;1.2</td>
<td>&gt;1.5</td>
<td>Taylor and Pohlen, 1970</td>
</tr>
<tr>
<td>Potassium</td>
<td>General</td>
<td>&lt;0.1</td>
<td>&lt;0.12</td>
<td>&lt;0.18</td>
<td>Taylor and Pohlen, 1970</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field crops</td>
<td>General</td>
<td>&lt;2</td>
<td>2-5</td>
<td>5-10</td>
<td>20-30</td>
<td>&gt;30</td>
<td>Taylor and Pohlen, 1970</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>General</td>
<td>&lt;3</td>
<td>4-8</td>
<td>&gt;9</td>
<td>Fox et al., 1964</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTPA - Fe</td>
<td>Sensitive crops</td>
<td>&lt;2.5</td>
<td>2.5-4.5</td>
<td>&gt;4.5</td>
<td>Viets and Lindsay, 1973</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Mn</td>
<td>Crops</td>
<td>&lt;1.0</td>
<td>-</td>
<td>&gt;1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Zn</td>
<td>&lt;0.5</td>
<td>0.5-1.0</td>
<td>&gt;1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Cu</td>
<td>&lt;0.2</td>
<td>-</td>
<td>&gt;0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot H₂O - B</td>
<td>General</td>
<td>&lt;1</td>
<td>1-5</td>
<td>&gt;5</td>
<td>Reisenauer et al., 1973</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>&lt;0.5</td>
<td>-</td>
<td>&gt;0.6</td>
<td>Anderson and Boswell, 1968</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa, oats</td>
<td></td>
<td>0.3</td>
<td>&gt;3</td>
<td>Mortvedt and Osborn, 1965</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(NH₄)₂C₂O₄ - Mo</td>
<td>Clover - grass pasture</td>
<td>&lt;0.1</td>
<td>0.1-0.2</td>
<td>0.2</td>
<td>Griggs, 1957</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A niger test for Mo</td>
<td>Pine in nursery</td>
<td></td>
<td>0.1</td>
<td>Tanaka et al., 1967</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2. Most farmers may not have money to invest on fertilizers. The financial constraint may be taken care of through subsidies from national or international organizations. In fact, an assurance of a definite benefit/cost ratio in the initial stages would induce the farmers to adopt agroforestry systems of any kind. The financial incentive, however, should be coupled with extension education on the advantages and technology of fertilizer use. Such an incentive should be withdrawn gradually with the improvement in the economic conditions and understanding of fertilizer use by the farmers.

3. An extensive soil-testing programme should be developed for each soil-crop system so as to apply the right amount of fertilizers to the neediest soil. This would require that:

(i) a suitable soil-test method or availability index of each essential nutrient be selected through appropriate correlation techniques,

(ii) soil-test values obtained by a suitable method be calibrated against yield or response data from greenhouse or field tests in an attempt to attach meaning to the empirical soil-test value and to identify appropriate soil-test categories or critical soil-test values, and

(iii) fertilizer response data from the field tests be interpreted carefully to make appropriate fertilizer recommendations for a specific crop to be grown on a specific soil-test category.

4. Several continuous and discontinuous graphical or mathematical models have been developed in the past for correlation and calibration of the soil-test data, interpretation of fertilizer response data, and recommendation. The prospective models should be evaluated for their suitability and the most fitting one should be adopted for a specific purpose.
5. Recommendations made here should first be tested on a few sites in an agroforestry system. The experiences should then be extended to a large area. Imported packages of practices should not be relied upon.

ACKNOWLEDGEMENTS

The author appreciates useful discussions regarding this paper with Mr. J.A. Maghembe of the Division of Forestry, University of Dar es Salaam. He is thankful to Professor A.P. Uriyo, Head, Department of Soil Science, University of Dar es Salaam, for his constructive criticisms and suggestions during the preparation of this manuscript.

DISCUSSION

Pratt: If one is to generalize, it is better to say that fertilizers should be used, rather than that fertilizers should not be used at all.

H.O. Mongi: Dr. Singh's main point was methodology, but what is his definition of fertilizers?

Singh: I excluded manures from my definition for the purpose of this paper. The main point is to illustrate the current concepts of soil nutrient availability.

Pereira: Rothamsted is following the linear response and plateau models but the optimum is below the inflection point. Also, should the differences in varieties not be considered?

Sanchez: As long as you are on the slope of the response curve the exact point depends on the local input:output cost ratios. Definitely, varietal differences in fertilizer responses are major. For example, we cannot use the N response of tall rice varieties for the new short-statured rice varieties.

Kamprath: The crop species that require the most fertilizers should determine the fertilizer rates in agroforestry systems.

Tejwani: The techniques described in the paper are seemingly more applicable to intensive agriculture than to agroforestry. In the developing countries, fertilizers are not only often unavailable but, when they are available, they are generally restricted for application to selected field and plantation crops. Thus, there is not enough fertilizer to spare for tree fertilization. Trees and grasses seem to require less fertilizer. They also give good responses to better land management. A careful choice of cultural practices can reduce the initial field fertility requirements. For example, the use of older seedlings of Eucalyptus spp. has resulted in satisfactory establishment and growth; and tie ridges have also given good growth response. We should endeavour to find the trees and crops that can be grown together with advantage, particularly from the point of view of soil conservation and fertility requirements.
Singh: My presentation assumes that inputs will be available. Some of the methodologies, such as the Cate-Nelson approach, are clearly geared towards maximizing the use of limited inputs.

Nyandat: For small-scale growers of maize in Kenya there was too much emphasis on fertilizers. There is a need to establish the minimal requirement. Fertilizer needs must be complemented by good cultural practices.

LITERATURE CITED


Singh, B.R. and Uriyo, A.P. Unpublished data. Faculty of Agriculture, Forestry and Veterinary Science, University of Dar es Salaam, Morogoro, Tanzania.


APPLICATION OF ISOTOPE TECHNIQUES IN RESEARCH INTO THE CHEMISTRY AND AVAILABILITY OF PLANT NUTRIENTS

M. Fried and K.B. Mistry*

ABSTRACT

Inorganic nutrition of crops essentially concerns the uptake of nutrient ions from the soil-plant system in which ions are continuously removed from the system at one end (the soil) and accumulated at the other end (the plant). Isotope tracers have contributed significantly to advancement of our knowledge of the behaviour of macro- and micro-nutrients in all major facets of the soil-plant continuum. The paper presents illustrative examples of isotope-tracer-aided research into soil chemical reactions of plant nutrients, including: ion-exchange; adsorption and self-diffusion processes; the turnover of plant residues and formation and decomposition of soil organic matter as related to availability of inorganic nutrients; transformations of nitrogen in soil including nitrification from organic matter, denitrification, and losses due to leaching and volatilization; characterization of nutrient supply mechanisms to plant roots; and determination of root activity patterns of crops with special reference to economically important tree crops. Recent concepts underlying the use of isotope techniques for integrated quantitative measurement of soil nutrient availability, which are also relevant to the direct assessment of fertilizer management practices, and for the estimation of biological fixation of atmospheric nitrogen by leguminous crops are discussed, giving examples of their application in the field.

From the standpoint of practical agriculture, the inorganic nutrition of plants essentially concerns the uptake of nutrient ions from the soil-plant system. The soil-plant system, with regard to inorganic nutrition, is an open one in which ions are continuously removed at one end (the soil) and accumulated at the other (the plant) as shown in Equation 1 (Fried, 1965, 1967):

\[ M (\text{Soil}) \rightleftharpoons M (\text{Solution}) \rightleftharpoons M (\text{Plant Root}) \rightleftharpoons M (\text{Plant Top}) \]

Equation 1 describes the uptake of nutrient ions by the plant as a sequence of reactions that can be described in the quantitative terms of physical chemistry. The first term in

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this sequence is M (soil), which refers primarily to adsorbed ions insofar as the next term in sequence M (solution) is concerned. However, over a long period of time minerals containing nutrient ions can be a further source of supply, as can organic matter if it is decreasing in amount over the years. In the absence of plant roots the concentration of a nutrient ion depends upon the nature of the reaction between the ion in solution and the ion in the solid phase, and the quantitative descriptions available for this relationship need elucidation. However, the nutrient ion, after it is in solution, must traverse a physical distance in order to reach the ion-accumulating mechanism in the plant. This movement must take place either by diffusion or by bulk movement with the water phase.

Uptake of nutrient ions is a continuously dynamic process, and all the reactions suggested and implied in Equation 1 are going on all the time. The individual reactions making up this continuum of ultimate accumulation of an ion initially present in the solid phase of the soil can be studied individually, but their significance to the overall accumulation process cannot be evaluated without consideration of the rest of the continuum. The components of the first two parts of Equation 1 are, in the main, included in the connotation of the widely used term "nutrient availability" to describe the ability of plants to use the nutrient resources of the soil.

Isotopes are atoms of the same element with differing mass number or "weight". Isotopes that are unstable and disintegrate spontaneously are termed "radioactive isotopes", and emit alpha or beta particles as well as gamma radiation. A number of radioisotopes are known to exist in nature, and radioisotopes of nearly every element — including macro- and micronutrient elements — are produced artificially, e.g. in atomic reactors and by particle accelerators. Sensitive detection equipment such as Geiger-Muller counters, proportional counters, and liquid and solid scintillation counting systems, permits accurate determination of very low quantities, for example, $10^{-12}$ to $10^{-15}$ g of the radioisotope of phosphorus $^{32}$P, which is far below the sensitivity attained by any other physical or chemical analytical method. Since isotopes have chemical and physical properties identical with atoms of the same element (only slight mass
differences), and can be obtained in high specific activity (defined as the activity of a particular radioisotope per unit mass of its element or compound) or "tracer" concentration, they can be used to follow the behaviour and pathway of entities such as inorganic ions, compounds and organic molecules in a chemical, physical or biological system: this is the basis of the isotopic tracer technique. In practice, the choice of a radioisotope for a given investigation is governed by the ease of incorporation and attachment of the radioactive label and its stability of attachment to the entity under study, the energy characteristics of the emitted radiation, its ease of detection and its half-life. In the case of inorganic nutrient elements, convenient radioisotopes are available of most macro- and micronutrients (Table 1): phosphorus ($^{32}$P, $^{33}$P); calcium ($^{45}$Ca); sulphur ($^{35}$S); magnesium ($^{28}$Mg); iron ($^{55}$Fe); zinc ($^{65}$Zn); copper ($^{64}$Cu); manganese ($^{54}$Mn); molybdenum ($^{99}$Mo); and chlorine ($^{36}$Cl).

Table 1: Plant nutrients and usefulness of isotopes for their study

<table>
<thead>
<tr>
<th>MACRONUTRIENTS (used in larger quantities)</th>
<th>MICRONUTRIENTS (used in lesser quantities)</th>
<th>ELEMENTS ASSOCIATED WITH NUTRITION STUDIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
<td>Isotope</td>
<td>Usefulness</td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>N</td>
<td>$^{13}$N</td>
<td>*</td>
</tr>
<tr>
<td>P</td>
<td>$^{32}$P, $^{33}$P</td>
<td>***</td>
</tr>
<tr>
<td>K</td>
<td>$^{40}$K, $^{42}$K</td>
<td>**, *</td>
</tr>
<tr>
<td>Mg</td>
<td>$^{28}$Mg</td>
<td>*</td>
</tr>
<tr>
<td>Ca</td>
<td>$^{45}$Ca</td>
<td>***</td>
</tr>
<tr>
<td>S</td>
<td>$^{35}$S</td>
<td>***</td>
</tr>
<tr>
<td>H</td>
<td>$^{2}$H, $^{3}$H</td>
<td>***</td>
</tr>
<tr>
<td>O</td>
<td>$^{18}$O</td>
<td>**</td>
</tr>
<tr>
<td>C</td>
<td>$^{14}$C</td>
<td>***</td>
</tr>
</tbody>
</table>

*** Very useful
** Useful
* Less useful

Suitable radioisotopes are not available in the case of nitrogen and potassium ($^{40}$K is of very limited availability and excessive cost at present), and as discussed in the subsequent paragraphs, stable isotopes of these nutrient elements can be utilized as tracers. The stable isotope offers the advantages...
of zero radiation hazard and infinite life. However, while in practice one radioactive atom is detectable, $10^{12}$ or more atoms of a stable isotope constitute the smallest detectable amount, and it therefore does not match the supreme sensitivity of radioisotopic tracer definition.

In the case of nitrogen, the longest-lived radioisotope, $^{13}$N, has a half-life of only 10 minutes, and the use of a stable isotope is consequently a necessity for tracer technique applications in agricultural research. Natural nitrogen consists of two stable isotopes, $^{14}$N and $^{15}$N, and the abundance ($A$) of $^{15}$N is approximately four $^{15}$N-atoms in every 1000 nitrogen atoms, or more precisely, $A_{^{15}N}$ = 0.365 atom percent (atom %). $^{15}$N-enriched nitrogen with $^{15}$N atom % in excess of 0.365 permits its use as a tracer for nitrogen in a manner analogous to the use of the specific activity concept in the case of a radioisotope. $^{15}$N-enriched nitrogen and its compounds have become commercially available at costs that place this isotope within the grasp of most researchers today, and with the development of mass- and emission-spectrometric techniques, $^{15}$N is widely used as a tracer in soil-plant research. Very recent development of technology for production of $^{15}$N-depleted nitrogen, i.e. depletion of native $^{15}$N in atmospheric N$_2$, has made available another relatively inexpensive isotope source of nitrogen (Schreiber, 1971; Star et al., 1974).

Isotopic tracers have been extensively used in the past two to three decades in the entire spectrum of research into the soil-plant continuum and have contributed very significantly to furthering our knowledge in these areas. This paper will attempt to review the recent isotope-techniques-aided research into the chemistry and availability of nutrients in soils through illustrative examples drawn from relevant studies on macro- as well as micronutrients within the framework of the soil-plant system described in Equation 1.

**ISOTOPE TECHNIQUES IN STUDIES OF SOIL CHEMICAL REACTIONS OF PLANT NUTRIENTS**

Of the various soil chemical reactions involving plant nutrient ions, the ion exchange reactions of clays and other colloids are among the most important.
The mineral matrix, pedogenetically derived from the parent material, forms the main framework supporting chemical reactions in the soil. Its main components are the micas, kaolins and halloysites; the oxides of Fe, Al and Si mainly; the carbonates of Ca and Mg and, occasionally, zeolites and more exotic minerals. Of these, the layer-silicates with expanding inter-layer spaces are the primary seat of cation exchange reactions. Their different chemical compositions and minute variations in crystal lattice dimensions, the negative charge per unit cell and its site in the crystal, the size of crystallites and exposed specific surfaces—all these result in electrical charge density and lattice dimensions of the surfaces that are important components of specific cation adsorption in soils (Talibudeen, 1972).

Isotopes of Na, K, Al, Cs, Ca, Sr, and S have been used in cation exchange studies with micas, kaolins, zeolites, feldspars, carbonates and oxides. Several examples can be cited of recent isotope-aided studies on cation exchange in soil matrices leading to directly useful information.

Experiments with labelled Ca-saturated soils (Diest and Talibudeen, 1967) show that the decrease in their negative charge (or cation exchange capacity) with increasing exchangeable K, is caused mainly by labelled Ca ions being entrapped rather than by K⁺ fixation, implying complete reversibility of "ion entrapment" and "release." This type of new information cannot be obtained without employing isotopic tracers. It has been possible to detect small amounts of minerals, not identifiable in the soil matrix by more conventional methods, that control the release of cations to plants, e.g. clinoptilite for K⁺ (Schulz et al., 1965) and analcime for Na⁺ (Diest and Talibudeen, 1967) using isotopes of Na and K.

Isotope tracers have also contributed to our present understanding of the ion exchange processes in the formation of salt-affected soils and the definition of their characteristics (Schulz et al., 1965; Babcock and Schulz, 1965; Szabolcs and Darab, 1965). Studies of the kinetics of sodium isotope adsorption in bentonite Na-salt systems have indicated a multi-component process; the first two components are very rapid cation exchange
processes with a very slow third component (Szabolcs and Darab, 1965). In systems containing neutral Na salts (NaCl or Na$_2$SO$_4$) the quantity of $^{24}$Na adsorbed by bentonite decreased to an ever-greater extent as a function of concentration. In the bentonite-Na$_2$CO$_3$ solution system, however, the quantity of $^{24}$Na isotope adsorbed by the bentonite increased at the beginning with the concentration of the Na ions, and it reached maximum values at a Na ion concentration of 50 me/l; the electrokinetic potential values determined on the basis of electrophoretical velocity also reached the maximum with increasing Na$_2$CO$_3$ concentration. The striking increase in ion adsorption is largely due to changes in the degree of dispersion and the surface charge of the system. Results of these studies help to provide a rational explanation of the empirical observation that from the standpoint of alkalinization of soils, the use of ground water or irrigation waters containing Na salts capable of alkaline hydrolysis (Na$_2$CO$_3$, NaHCO$_3$, Na$_2$SiO$_3$) is much more hazardous than the use of solutions that contain neutral Na salts, such as NaCl or Na$_2$SO$_4$ (Szabolcs and Darab, 1965).

Self-diffusion studies of cations in the soil matrix, which can only be undertaken with the help of isotopes, have been performed for major nutrient ions such as K and Ca. Self-diffusion of K into an illite using $^{40}$K provided an important parameter for computing very long-term K release by a soil containing predominantly illitic mineral (Talibudeen, 1972; De Haan, 1965). The calculated "exchangeable" K provided a suitable limiting value for K uptake by crops from the soil (Talibudeen, 1972). This type of data would permit the prediction of K reserves and their availability rate more precisely and usefully than would determining total K, and extractable K or K extracted with tetraphenyl boron, or H$^+$ resins.

Recent "double isotope label" experiments, coupled with K release experiments with Ca-saturated resin and ryegrass, indicate directly that fine clay-size (0.1µm) micaceous particles ingrained in the coarse and fine silt fractions of the soil are involved equally with the soil clay fraction (Talibudeen and Weir, 1972). Another important attribute of the "double-label"
self-diffusion experiments was the ability to distinguish between volumes within crystallites in the soil fractions that were dominated by K⁺ or Ca⁺, and were indistinguishable by physical methods.

Quantitative data on nutrient cation competition for exchange sites on various mineral components of the soil obtained through isotope-aided ion exchange studies together with knowledge of the gross composition of field soils, can provide useful information on predicting the release and retention of plant nutrient cations.

Another excellent example relates to the use of $^{45}$Ca to determine exchangeable calcium in calcareous soils (Lahav and Bolt, 1964) for which a reliable and accurate method is lacking, and estimating the contribution of surface-adsorbed calcium as well as the amount of calcium of the calcite crystal exchangeable with $^{45}$Ca by diffusion into the crystal, which is a time-dependent process (Reiniger and Lahav, 1964, 1965). The referenced studies also revealed a "masking type" suppression effect of silicate impurities in the crystallites on the self-diffusion of calcium (Reiniger and Lahav, 1965).

The application of isotopic tracers in studies of soil chemistry of nutrient anions is best illustrated by examples drawn from the existing literature on the phosphate chemistry of soils.

It is well established that the concentration of phosphate in soil solution is governed by a dynamic equilibrium between the solid and solution phases, in which phosphate continually dissolves from and is resorbed by the solid phase. In the presence of the roots of plants that absorb phosphorus from the soil solution, this equilibrium is disturbed, and the soil solution is replenished by the continual dissolution of phosphate from the solid phase. Radioisotope $^{32}$P-aided studies have been undertaken to examine the kinetics of phosphate release from soil using a leaching technique (Fried et al., 1957) and an anion exchange resin as a zero sink for dissolved phosphate (Amer et al., 1955; Passioura, 1963; Olsen and Kemper, 1968). These studies have indicated that the potential rate of phosphate release from the soils as a whole was at least 250 times as great as the rate of phosphate uptake by a crop. However, since at any one time the roots of a crop feed from only a fraction of the total volume,
the effective soil volume from which roots absorb phosphate is less than 0.4% of the whole in situations where rate of phosphate release is limiting phosphate uptake. In a recent study on similar lines using anion exchange resin with a large number of British soils, it was demonstrated that the rate of phosphate release is proportional to the square-root of the release time and is diffusion-controlled (Cook and Larsen, 1965). Highly significant relationships were observed between the rate of phosphate release, total isotopically exchangeable phosphate in soil, and the quantity of phosphate taken up by ryegrass for contrasting soil types.

A recent study on characterization of calcium phosphates on calcareous soil by exchange with $^{45}\text{Ca}$ and $^{32}\text{P}$ has defined the limit of adsorbed phosphate above which octacalcium phosphate as a distinct surface phase can be confirmed (Amer and Ramy, 1971). Other studies on phosphate chemistry of calcareous soils have indicated that increasing the specific surface of the calcium carbonate crystallites in the soil, measured by $^{45}\text{Ca}$ exchange, decreased the self-diffusion of phosphate in soil (Talibudeen and Arrambarri, 1964).

Related evidence has also been obtained on the influence of polyvalent cations and anions present on the soil on the surface charge of calcites in soils and the resultant influence on self-diffusion of inter-crystalline phosphate in calcareous soils (Talibudeen, 1972). These studies indicate the potential of predicting the nature and extent of residual phosphates in calcareous soils with simple tracer studies using $^{32}\text{P}$ and $^{45}\text{Ca}$.

While the radioisotope $^{35}\text{S}$ with convenient half-life and beta-particle (radiation) energy is available, relatively little attention has been given so far to characterize soil sulphur, as has been done with soil phosphorus. Limited studies with virgin pasture and cultivated podsols in Canada show that isotopically exchangeable sulphur, which correlated significantly with sodium-acetate-extractable sulphur, was 8-10 times more in the B-horizon than in the A-horizon while total sulphur was more randomly distributed in the profiles (Mackenzie et al., 1967). Isotopic tracer studies offer particular advantage in studying sulphate adsorption in soils since due to negative adsorption of the divalent anion in negatively charged soils and clays, positive
adsorption is usually too small to be measured by chemical methods.

The use of radioisotopes in studies of chemical reactions of micronutrients in soil minerals and other solid-phase constituents of the soil matrix are restricted to concentration ranges in which negligible isotopic dilution occurs. This often limits studies at the concentrations relevant to soil reactions. However, radiotracer techniques have aided in measurements of the speciation of micronutrients in soil solution (Hodgson et al., 1966; Ellis and Knezek, 1972; Lindsay, 1972), providing a good example of the contribution of isotope-aided research to advancing our knowledge of the soil chemistry of micronutrients. In the referenced studies with neutral and calcareous soils where radioisotopes of zinc (\textsuperscript{65}Zn) and copper (\textsuperscript{64}Cu) were used, it has been shown that about 60\% of the Zn in the soil solution is complexed; the degree of complexing of zinc was correlated with soluble organic matter. In the case of copper, more than 98\% of the soluble copper was in an organic complexed form suggesting that in soils very small quantities of free or aquated Cu\textsuperscript{+} are available for adsorption reactions (Hodgson et al., 1966; Ellis and Knezek, 1972).

**ISOTOPE TRACERS IN STUDIES OF SOIL ORGANIC MATTER**

In recent years remarkable progress has been achieved through the use of isotopes in studies of the turnover of plant residues in soil, formation and decomposition of organic compounds and transformation of soil organic matter as related to the mineralization and immobilization of major plant nutrients (Flaig, 1977). Studies of organic-bound nitrogen, which plays a predominant role in the nitrogen cycle of the soil-plant system, are discussed in a separate section.

The turnover of plant residues in the soil has been extensively studied in recent years, and it has been observed that several factors, including soil properties, plant material and the environment, affect the rate of turnover. Plant material uniformly labelled with isotopes of carbon and in some instances, nitrogen, has proved very useful in such investigations (Talibudeen, 1972; Flaig, 1977).
Very recently, decomposition experiments with $^{14}\text{C}$-labelled plant material, carried out under field conditions using many different soils of temperate and tropical regions (Sauerbeck and Gonzales, 1977), indicated that, disregarding rapid losses of about 65% during the first year, the mineralization of the stabilized residues and turnover products followed a logarithmic function indicating half-lives between five and six years. Assuming a similar input and decomposition of plant residues annually, the calculated equilibrium concentration of recent humic matter was found not to exceed one-quarter of the total soil organic matter present; this assumption was supported by data from experiments with annually repeated additions of labelled plant residues. It is difficult to account for the actual carbon content of most field soils on the basis of the observed decomposition patterns, and these findings together with the results of $^{14}\text{C}$-dating (Martel and Paul, 1974), suggest the existence of two fairly independent organic matter pools in soils. The smaller labile fraction depends on the cultural practices used and includes both the plant residues and most of their humified turnover products. The larger stable phase appears to be a consequence of pedogenetic factors, and cannot be influenced to any great extent by cropping and manuring.

Other recent isotope-aided studies relate to the decomposition of plant residues in saline-sodic soils (Malik and Hyder, 1977), the identification of the chemical nature of organic materials released into soil from growing roots (Barber and Martin, 1976), and the transformation and humification of labelled sugars and starches in the soil (Flaig, 1977).

Besides the studies of overall transformation of plant residues, it is vital to follow, in relation to the fate of inorganic nutrients, the decomposition of specific organic compounds of which the residues are composed, or that are formed during their decomposition, including those produced by the metabolism of soil microorganisms.

$^{14}\text{C}$ and $^{32}\text{P}$ have been utilized in studies of organic phosphorus compounds in soil. These investigations included the isomerization of myo-inositol and the inhibition of microbial
oxidation by blockage of the hydroxyl group by interactions with other soil constituents (L'Annunziata, 1975). Other studies have indicated that the mineralization to inorganic orthophosphate of the most easily decomposable forms of organic phosphorus in soil takes about 45 days, and that increasing the temperature had a marked effect on the process (Ruiz and López Hernández, 1977).

In a comparative study of the mineralization of sulphur and nitrogen from soil organic matter in a number of pasture and continuously-cultivated arable soils, it was observed that sulphur is more refractory than carbon and nitrogen and tends to resist mineralization in the field (Kowalenko and Lowe, 1976; Swift, 1977).

Another noteworthy contribution of the isotopic tracer technique has been in studies of organic complexes attached by coordinate valency to, or precipitated on soil surfaces by adsorbed nutrient cations (Talibudeen, 1972; Stevenson and Adarkani, 1972). These studies (Schnitzer and Skinner, 1966) reveal that the valency and nature of the bridging cations is all-important in the decreasing order of complexing intensity Fe > Al > Ca > NH₄ > K > Na > H > Mg. Tracer studies also permit differentiating between functional groups in the soil organic matter that react with various intensities with soil cations (Saas and Granby, 1973), and derivation of stability constants of reactions of divalent micronutrients such as Cu, Zn, and Fe with fulvic acid (Stevenson and Adarkani, 1972; Schnitzer and Skinner, 1966; Rosell et al., 1977).

**ISOTOPE TRACERS IN STUDIES OF SOIL CHEMISTRY OF NITROGEN**

During the past decade, the isotope nitrogen-15 has been extensively used in studies on the chemistry and transformation of soil nitrogen. These studies encompass manifold aspects, including the mineralization and immobilization of N, nitrification from organic matter, denitrification, and ammonia fixation and volatilization. These topics have been comprehensively covered in recent reviews (Bartholomew, 1971; Hauck, 1971; Hauck and Bremner, 1976), and only an overview of these aspects where the use of N-15 has proved to be invaluable is included here.
Mineralization and immobilization of nitrogen are always taking place simultaneously under favourable growing conditions in field soils. The N present in any organic residue undergoing decomposition, along with mineral soil N (NO$_3^-$ and NH$_4^+$), is used by the involved microorganisms in building their own proteinaceous bodies. It is especially the addition to soil of low N residues of crops such as maize and small grains and rice, all commonly containing less than 1.5% N, that activates the immobilization process. Microbial numbers increase rapidly with corresponding N requirement in the presence of the organic energy material, but as the readily available portion of the energy source is dissipated the organism numbers drop off and some of the N in the microbial cells is gradually released as ammonium N. Obviously, it is of considerable practical import to know how soon any of the originally available mineral N so immobilized will be released again in plant-available form. By labelling the NO$_3^-$ or NH$_4^+$ being immobilized it has been possible to prove that the reconversion to the inorganic N form is very slow, requiring years or even decades for the total release (Broadbent and Nakashima, 1967). It has been demonstrated that essentially half of the labelled fertilizer N on incorporation into soil with barley straw was immobilized within a 15-day period with virtually no change in the subsequent 45 days (Broadbent, 1978). The mineralization of the unlabelled native soil N, however, was going on during the period of maximum immobilization and began leveling off after 15 days.

Increasing interest in the nitrogen fertilization of forests has made it important to obtain quantitative data on the transformation of soil and fertilizer nitrogen in forest soils. Investigations using $^{15}$N-labelled materials have supplemented studies made with labelled compounds (Leyton, 1972). $^{15}$N-labelled (NH$_4$)$_2$SO$_4$, Ca(NH$_3$)$_2$, NH$_4$NO$_3$, urea and CaCN$_2$ have been used in studies on forest soils with stands of Scots pine (Pinus sylvestris), Norway spruce (Picea abies), slash pine (Pinus elliottii), and black spruce (Picea mariana) (Nömmik, 1966; Björkman et al., 1967; Mead, 1971; Weetman, 1962; Overrein, 1969, 1970; Knowles and Lefebvre, 1972).
Recent field, greenhouse and laboratory studies (Knowles and Lefebvre, 1972) on the transformations of $^{15}$N urea in a boreal forest black spruce stand on a podsol profile have indicated that total uptake of nitrogen by the trees averaged around 10 per cent of the urea-N applied. Labelled N in the layers of humus decreased markedly with depth, and negligible quantities of $^{15}$N were detected at 15-cm depth and at a lateral distance of 5 cm from the edge of the plot. While there was a gradual transfer of labelled N from the NH$_4$-N to the residue-N fraction of humus, over a period of 84 days there was 15-35 percent of total labelled N present in NH$_4$-N fraction, suggesting continued availability of labelled N for tree nutrition.

In another study, transformation, vertical distribution and recovery of various sources of $^{15}$N-labelled fertilizer, nitrogen was examined in an iron-humus podsolic forest soil under a Norway spruce stand (Popovic and Nömmik, 1972). Of the Ca(NO$_3$)$_2$, (NH$_4$)$_2$SO$_4$ and urea-N added, the amounts recovered in litter, humus and mineral soil to 15-cm depth were at the end of 6 months 32, 80, and 78 percent, respectively. Corresponding figures for the inorganic form of labelled nitrogen were 9, 53, and 24 in the litter and humus layers; this was valid especially for urea, which was subjected to substantial immobilization.

On accumulation in any soil system from fertilizer application or nitrification of ammonium, NO$_3^-$ residence time will depend not only on the activity of crop roots in absorbing it and microbial demand in decomposing new residue additions, but the prevailing moisture regime as well. Leaching losses are assured if water from rain or irrigation percolates through and out of the rooting zone, there being essentially no soil adsorption of the NO$_3^-$ ion. Many investigations have been made during the past decade in following the transit of soil NO$_3^-$ to the ground water and in designating the source of that found in the water (Nielsen and MacDonald, 1978; Menzel, 1978; Olson et al., 1973; Wiklander, 1977). In lysimeter studies using $^{15}$N-labelled nitrogen fertilizers, Overeining (1968) has demonstrated that in forest soils only small leaching losses occur for added urea-N and (NH$_4$)$_2$SO$_4$-N.

Loss of NO$_3^-$N from a soil system also occurs through the process of denitrification. This occurs particularly under
excessively wet soil conditions where the soil has become anoxic. The organisms responsible for release of the N in gaseous form utilize some or all of the oxygen in the NO$_3^-$ for satisfying their own oxygen requirements. Denitrification occurs primarily in the surface horizon of most soils, where the carbon energy source for the anaerobes exists.

Many controlled laboratory studies involving closed systems and, more recently, field studies in open systems, have confirmed the denitrification process by direct isotope measurements. Maximum denitrification has been measured at 60-70°C and at high soil pH, with little or none at 60-70% water saturation, at low pH or at low temperature (Nömmik, 1956). Given proper conditions for denitrification to occur on moderately acid soil, sequential products have been observed with NO coming off first in small amounts followed by N$_2$O and the latter by N$_2$, which was by far the greatest in magnitude (Cady and Bartholomew, 1960). As each subsequent effluent grew in magnitude, the former dropped to nil. The $^{15}$N tracer technique and mass-spectrometry have also been used to examine the transformation of nitrite and nitrate during anaerobic incubation in an acid forest humus collected beneath a mature stand of Norway spruce trees (Nömmik and Thorin, 1971). The analysis of gases formed during incubation showed that the extent of nitrite decomposition was controlled to a large extent by soil pH. The results indicated that in non-sterilized humus the NO gas initially formed was gradually converted to N$_2$O and N$_2$. It was observed that, after 10 days incubation in the unlimed forest humus of pH 4.3, between 50 and 65 percent of added nitrite was immobilized as organic nitrogen; this reaction was largely non-enzymatic. The rate of biological denitrification of the nitrate form of nitrogen was extremely low in the acid humus, but was significantly increased by the addition of lime. The composition of the denitrification gases was highly dependent on both soil pH and the length of incubation and in some cases significant amounts of NO were formed during the nitrate reduction.

It is extremely difficult to measure denitrification under field conditions with a growing crop. Some attempts have been made in this direction by calculating the flux of $^{15}$N-labelled N$_2$
and N₂O gas by concentration gradients and diffusion coefficients, all highly dependent on an accurate assessment of the amount and nature of the air space of the system. In a recent study on an alluvial loam soil (Rolston et al., 1978) ¹⁵N-labelled nitrate was applied to laboratory columns and a field plot. The columns were maintained at soil-water pressure heads of -22 and -70 cm. The field plot was maintained at a soil-water pressure head of approximately -10 cm in the upper 10 cm of soil and was cropped with ryegrass (Lolium perenne). The concentration and isotopic ration of NO₃, N₂, and N₂O were measured as a function of soil depth and time and the gaseous concentration gradients and measured apparent diffusion coefficients were used to calculate the fluxes of ¹⁵N₂ and ¹⁵N₂O gas from the soil. Residual soil N, plant uptake, and leaching were also measured in order to calculate denitrification by difference. For the laboratory columns, the amount of denitrification determined directly compared favourably with that determined by difference. For the field plot, the disparity between denitrification calculated directly and by difference was attributed to the uncertainty in the gaseous concentration gradient near the soil surface and the spatial variability of the apparent diffusion coefficient near water saturation. Recognizing that much of the denitrification process takes place in the few surface cm of most soils, measurement thereof is also complicated because of alternate wetting and drying, which leaves microsites of anoxic soil between the larger pore spaces that presumably supply most of the air extracted by syringe sampling (Rolston, 1978).

The NH₄⁺ component of the N system is of extremely variable half-life in soils depending on soil physical and chemical properties. Substantial mineralization of organic N to NH₄⁺ form will occur under strongly acid conditions where the Nitrosomas, Nitrosococcus and Nitrobacter responsible for the final steps in oxidation of N will not function. Thus, NH₄⁺ tends to accumulate until removed by plants. Also, in submerged rice soils, the limited aeration of the soil inhibits the activity of the same groups of organisms, whereas many of the heterotrophs that bring about the initial organic matter decomposition and release of NH₄⁺ are not affected. Conversely, there may be minimal NH₄⁺ accumulation under well-aerated and neutral-to-alkaline soil
conditions because of rapid oxidation to $\text{NO}_3^-$ of any $\text{NH}_4^+$ produced from mineralization. Thus, a number of products have been developed in recent times to serve as nitrification inhibitors for extending the residence time of $\text{NH}_4^+$ in soil to minimize potential leaching that might occur with $\text{NO}_3^-$ (Hauck and Koshino, 1971).

The circumstances that can remove $\text{NH}_4^+$ through immobilization are identical to those for $\text{NO}_3^-$, viz., demand for additional N by multiplying numbers of soil microorganisms that attack and decompose added residues of low N content. The loss in this situation is not permanent for the soil, but may be of sufficient duration to be deleterious for an existing crop.

As far as plant uptake is concerned, the majority of crops utilize $\text{NO}_3^-$ and $\text{NH}_4^+$ with about equal facility (Schrader et al., 1972; Warncke and Barber, 1973). If there is a preference, it is frequently one of plants utilizing $\text{NH}_4^+$ somewhat better in early growth stages and $\text{NO}_3^-$ later. But for season-long growth the $\text{NO}_3^-$ affords greater accessibility to the root system because of the limited mobility of $\text{NH}_4^+$, very little of which exists below the surface 20-30 cm of soil. As the surface soil dries between rains or irrigation, root activity for nutrient uptake occurs primarily in deeper layers where moisture is present. The production of flooded rice, of course, is another matter for which much of N nutrition is accomplished in the surface few cm of soil and largely as the $\text{NH}_4^+$ ion (Patrick and Mikkelsen, 1971).

Clay fixation is another process responsible for immobilizing varying amounts of $\text{NH}_4^+$. This process occurs only in soils containing 2:1 clay minerals of expanding lattice structure. Fixation essentially eliminates the accessibility of $\text{NH}_4^+$ to plants, and the half-life of release must be very long since it is not isotopically exchangeable with a labelled $\text{NH}_4^+$ solution (Newman and Oliver, 1966). The majority of medium-to fine-textured soils containing 2:1 clays will contain in the order of 200 kg/ha cm $\text{NH}_4^+$-N fixed in the clay lattice. The real significance of this reserve N source to plant nutrition is, however, not clearly defined. Evidence has surfaced of its apparent nitrification over long time intervals and its resulting contribution to geologic $\text{NC}_3^-$ in deep mantlerock (Boyce et al., 1976).
In most soils the major portion of $\text{NH}_4^+$ coming from mineralization, if not absorbed first by plant roots, undergoes nitrification. The $\text{NO}_2^-$ stage is normally of such short duration that only rarely is any significant amount of it found in soil, which is fortunate since high $\text{NO}_2^-$ concentrations are toxic to plants as well as animals. Under conditions of strong acidity and high organic matter content a reaction can occur whereby a portion of $\text{NO}_2^-$ present is fixed in an organic complex and the remainder converted to gaseous forms (Bremner and Fuhr, 1966).

The major channel for loss of $\text{NH}_4^+$ from soil is that of volatilization as $\text{NH}_3$ to the atmosphere. Losses have been found to be most severe under conditions of high pH, particularly in calcareous soils, and with drying conditions when $\text{NH}_4^+$-containing or producing materials are applied to the soil (Myer, 1961; Fenn and Kissel, 1973). Similar volatilization loss can occur of $\text{NH}_4^+$ produced from mineralization of manure and other organic materials placed at or near the soil surface.

CHARACTERIZATION OF NUTRIENT SUPPLY MECHANISMS TO PLANT ROOTS

When plants are grown in soil, the inorganic nutrient ions absorbed by the roots must move to the root surface before they are available for absorption. As the roots extend through the soil they can intercept some of these ions. Further, because roots absorb water and transpire it from the leaf surfaces, they cause a flow of water which transports nutrient ions to the root surface by mass-flow. If these two mechanisms do not supply all of the plant's requirement for a nutrient, removal of the ions from the soil at the root surface because root absorption is occurring reduces the concentration at that surface, and net diffusion towards the root occurs along the concentration gradient that is established (Fried and Broeshart, 1967; Olsen and Kemper, 1968; Barber, 1962, 1966).

The amount of nutrients reaching the root surface by mass-flow can be estimated by multiplying the amount of water absorbed by the plant by the concentrations of ions in this water, which can be approximated by the concentration in the saturation extract of soil. The amount reaching the root by root interception can
be approximated by assuming it to be equal to the amount available in a volume of soil pore space equal in volume to the volume of the roots. The amount of ions reaching the root by diffusion can be estimated as the difference between the total uptake and the amount supplied by root interception plus mass-flow. The relative significance of each transport mechanism for supplying nutrients to the root can then be theoretically estimated by comparison of the uptake of nutrients in plants with the data on content of nutrients in the saturation extract and the "available" nutrient in the soil (Barber, 1966).

Table 2: The amounts of several nutrients supplied by three mechanisms to maize roots growing in a silt loam

<table>
<thead>
<tr>
<th>Ion Uptake* (0 - 20 cm)</th>
<th>Total available ions in soil (kg/ha)</th>
<th>Content of saturation extract (ppm)</th>
<th>Amount supplied by:</th>
<th>Amount supplied by:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>root interception</td>
<td>mass-flow diffusion</td>
</tr>
<tr>
<td>Ca 23</td>
<td>3300</td>
<td>50</td>
<td>66</td>
<td>175</td>
</tr>
<tr>
<td>Mg 28</td>
<td>800</td>
<td>30</td>
<td>16</td>
<td>105</td>
</tr>
<tr>
<td>K 135</td>
<td>190</td>
<td>10</td>
<td>3.8</td>
<td>35</td>
</tr>
<tr>
<td>P 39</td>
<td>45</td>
<td>0.5</td>
<td>0.9</td>
<td>1.8</td>
</tr>
<tr>
<td>Mn 0.23</td>
<td>6</td>
<td>0.015</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Zn 0.23</td>
<td>6</td>
<td>0.15</td>
<td>0.1</td>
<td>0.53</td>
</tr>
<tr>
<td>Cu 0.16</td>
<td>0.6</td>
<td>0.10</td>
<td>0.01</td>
<td>0.35</td>
</tr>
<tr>
<td>Fe 0.80</td>
<td>6</td>
<td>0.15</td>
<td>0.1</td>
<td>0.53</td>
</tr>
</tbody>
</table>

* Assuming a total yield of 15 680 kg/ha in the above ground portion of the crop.

Source: Barber (1966).

From the data on total uptake of nutrient ions by plants grown on a large number of soils, chemical analyses of available nutrients in soils, and the nutrient content of saturation extracts (Table 2), it has been estimated that much of the Ca and
Mg is supplied by root interception, and that very little P reaches the root surface by this mechanism; K is intermediate in this regard. Mass-flow can supply large quantities of Ca and Mg to the roots. Diffusion is usually an important mechanism for P supply and often for K. Any of the three mechanisms may be predominant for the supply of micronutrients in a particular situation because the amount required by the plant is small, and the levels of available micronutrients in soil and in the saturation extract vary over wide ranges of concentration (Barber, 1962, 1966; Oliver and Barber, 1966; Riley and Barber, 1966; Barber et al., 1963). A similar study on mineral cycling in a beech (Fagus silvatica) stand forest ecosystem on an acid Dystrochrept soil (Table 3) revealed that Mg, Mn, Cl, and S are supplied to the trees solely by mass-flow, whereas diffusion accounts for about 40% in the case of K, and P and 17% in the case of Ca. (Ulrich and Mayer, 1972).

Table 3: Annual balance of bioelement fluxes in a beech (Fagus silvatica) stand on a typical Dystrochrept soil (all values in kg/ha)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Plant uptake (kg/ha)</th>
<th>Mass-flow</th>
<th>Diffusion</th>
<th>Diffusion (as % of plant uptake)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>33.30</td>
<td>27.60</td>
<td>5.70</td>
<td>17</td>
</tr>
<tr>
<td>Mg</td>
<td>3.20</td>
<td>3.26</td>
<td>-0.06</td>
<td>0</td>
</tr>
<tr>
<td>K</td>
<td>45.90</td>
<td>27.70</td>
<td>18.20</td>
<td>40</td>
</tr>
<tr>
<td>P</td>
<td>4.89</td>
<td>2.86</td>
<td>2.03</td>
<td>42</td>
</tr>
<tr>
<td>S</td>
<td>35.80</td>
<td>35.30</td>
<td>0.50</td>
<td>1.4</td>
</tr>
<tr>
<td>Cl</td>
<td>27.50</td>
<td>26.40</td>
<td>1.10</td>
<td>4</td>
</tr>
<tr>
<td>Mn</td>
<td>6.03</td>
<td>6.00</td>
<td>0.02</td>
<td>0.3</td>
</tr>
<tr>
<td>Fe</td>
<td>3.70</td>
<td>2.20</td>
<td>1.50</td>
<td>41</td>
</tr>
</tbody>
</table>


Direct experimental evidence on the significance of the three mechanisms of supply for some of the nutrient ions is beset with
problems since it is often difficult in plant growth experiments to separate the ions supplied to the root by mass-flow from those supplied by diffusion.

An elegant isotopic tracer method which facilitates the identification of sources of supply of calcium uses the non-discriminatory uptake of Ca and Sr by tomato roots to determine the mechanisms supplying Ca and Sr to the root (Bole and Barber, 1971; Barber et al., 1972). In this method, soil Ca was labelled with $^{45}$Ca and soil Sr with $^{85}$Sr. Because of differential strengths of binding of Ca and Sr by the soil, the $^{45}$Ca:$^{85}$Sr ratio of the soil solution differed from the $^{45}$Ca:$^{85}$Sr ratio of the exchangeable cations. Some exchange materials adsorbed $^{45}$Ca preferentially to $^{85}$ Sr, whereas others adsorbed $^{85}$Sr preferentially to $^{45}$Ca. Plants were grown on two different exchange materials for six growth periods under varying humidity conditions which influenced the transpiration rate. Closely similar values of $^{45}$Ca:$^{85}$Sr ratio in plants to that in the equilibrium soil solution indicated mass-flow to be the predominant supply mechanism. When $^{45}$Ca:$^{85}$Sr ratio in plants was similar to the ratio on the exchange sites, the ions were transported to the root surface by exchange diffusion. These studies also provided evidence of accumulation and precipitation of ions around the root when mass-flow greatly exceeded the uptake of ions. Similar experimental approach which utilizes K and Rb pair of cations has been recently used for identification of the major supply mechanism of K to roots in different soils (Baliger and Barber, 1978).

An example of the use of isotopes for quantitative assessment of diffusion rates of nutrient ions in soils is the work of Lewis and Quirk (1962, 1965) who measured the diffusion coefficients of phosphate in soil and adopted a model root system to analyze diffusive flux of this anion to the root surface. The technique involved addition of $^{32}$P-labelled KH$_2$PO$_4$ solutions to soil, storage of soil at a given moisture stress for seven days, and measurement of $^{32}$P transported across the boundary of diffusion cells. Results indicated that, for the model systems considered, diffusion alone could supply the phosphate absorbed by plants, and further that diffusion through solution rather than surface migration is the important process.
Another good illustration of the use of isotopic tracers in the study of supply mechanisms of nutrients in soil is the work of Olsen and his co-workers who used two methods based on transient and steady-state systems for measuring the diffusion coefficient of P with the help of $^{32}\text{P}$ (Olsen, 1965; Olsen et al., 1965). These studies have demonstrated the application of diffusion coefficients to explain and predict the soil phosphate uptake by plants as related to soil differences (Olsen et al., 1965; Olsen and Flowerday, 1971).

A comprehensive $^{32}\text{P}$-aided study on quantitative aspects of diffusion mechanism has been carried out in British soils where the surface mobility of adsorbed ions is very low compared to their mobility in the soil solution. Under these conditions, the diffusion coefficient ($D$) is given by Equation 2:

$$D = D_1 v_1 f_1 \left(\frac{dc_1}{dc}\right) \quad [2]$$

where $D_1 =$ diffusion coefficient of the ion in the solution
$v_1 =$ moisture fraction by volume
$f_1 =$ impedance factor
and $dc_1/dc =$ the gradient of the isotherm of the relation between concentration of phosphate in the soil solution and the amount of phosphate desorbed into equilibrium soil solution from soil.

The concentration gradient of isotopically exchangeable phosphate, experimentally determined with the help of $^{32}\text{P}$, in the vicinity of roots (Farr et al., 1969) showed a fairly close relationship to that predicted on the basis of the above-mentioned isotherm (Russell, 1977).

Similar experimental verification of the movement of sulphate ions to root surface under conditions of high transpiration where mass-flow is the dominant supply mechanism has been achieved using the radioisotope $^{35}\text{S}$ (Nye, 1972).

Direct visual evidence of diffusion gradients of phosphate and rubidium ions around plant roots, and of accumulation of sulfate about roots as a result of mass-flow has been obtained
by autoradiographic techniques using $^{32}\text{P}$, $^{86}\text{Rb}$, and $^{35}\text{S}$ isotopes, respectively (Barber, 1966; Lewis and Quirk, 1965; Nye, 1972).

The importance of the diffusion mechanisms and root interception underlying the supply of important and often growth-limiting nutrient ions such as P, K, Ca, and Mg, has encouraged detailed studies directed to interpreting the role of roots and root hairs in absorption (Russell, 1977).

Methods commonly used in studies of the distribution of growing roots in glass-sided boxes (Asher and Ozanne, 1966; Muzik and Whitworth, 1962) permit serial observations on the same root system, but growing conditions at the viewing surface are often different from that in the bulk soil (Taylor and Böhm, 1976). Neutron radiography has been suggested as a potential technique for in situ studies on development of root systems (Willat et al., 1978; Willat and Struss, In Press). This recently developed technique is based on the preferential scattering of thermal neutrons by living roots whose volumetric water content (70-93%) is higher than that of soil at field capacity moisture status (5-30%). This greater attenuation by the roots effectively removes more neutron from a collimated neutron beam than the adjacent soil. This alteration in the neutron beam produces a radioactive image on a metal transfer screen (by producing a radioisotope of the metal) which can be transferred to X-ray film. The image of the root can then be seen in contrast to the soil on the processed film. In studies reported so far, elongation rates of soybean radicles and seminal roots of corn could be determined easily through 2.5 - 5.0 cm soil samples (Willat et al., 1978; Willat and Struss, In Press). While the present limit of resolution is roots of 0.3 mm diameter, it is likely that it can be further improved so that the development of smaller lateral roots and root hairs can be viewed.

Another development in relation to the diffusion and root interception mechanisms of the supply of nutrient ions is the recognition of the physiological role of root hairs and the rhizosphere microorganisms. Recent evidence from isotope-aided studies of Brewster et al. (1976) indicate that the possibility of exudation from root hairs exerting a significant effect on
the transport behaviour of diffusing ions such as phosphate in proximity to the root, needs to be seriously considered. At the same time, predictive models should be developed to describe the depletion of these ions in the soil and their uptake by plants (Russell, 1977).

The endotrophic mycorrhizae, whose hyphae enter roots either through the epidermis or root hairs and extend out into the soil from the root surface, have been implicated in the transport of phosphate to root surface considerably more rapidly than would be possible by diffusion through the soil. The first clear demonstration of this phenomenon was provided by Sanders and Tinker (1971, 1973), who found the inflow of $^{32}$P-labelled phosphate into mycorrhizal roots of Allium cepa to be over three times greater than in non-mycorrhizal roots that were absorbing at approximately the maximum rate that diffusion through the bulk soil could support. Other evidence of the importance of vesicular-arbuscular mycorrhizae in crop nutrition comes from the work of Hattingh et al. (1973) who showed, using phosphate labelled with $^{32}$P, that mycorrhizae could convey phosphate to the roots of plants from points in the soil about 2 cm distant; this was not observed when mycorrhizae were absent or when the hyphae were severed.

Considerable nutritional benefits to tree species in the field have been commonly attributed to the infection of the roots by ectotrophic mycorrhizae, and several isotope-aided investigations have helped to establish the enhanced ability of mycorrhizal woody species to absorb phosphate from the soil (Harley, 1969). These studies indicate that the fungal sheath around the root acts as a primary reservoir of accumulation from which phosphate passes steadily to the host plant. The transfer of other major inorganic nutrients such as nitrogen and calcium from the external milieu to the host root through the intervention of the ectomycorrhizal mycelium has been demonstrated in experiments employing $^{15}$N- and $^{45}$Ca-labelled compounds (Harley, 1969).

Isotope tracers have also been used to investigate the direct transfer of nutrient ions from one tree to another within a stand, via the roots. The occurrence of such transfer of
major plant nutrients in various woody species has been unequivocally established using $^{32}\text{P}$, $^{45}\text{Ca}$, $^{35}\text{S}$, and $^{86}\text{Rb}$ (Woods, 1970); however, the relative roles of mycorrhizae, root exudations or root grafting in such transfer are not yet clearly elucidated.

**DETERMINATION OF ROOT ACTIVITY PATTERNS**

Closely related to the characterization of nutrient supply mechanisms to plant roots discussed in the preceding section are the considerations of the distribution of active roots, location of zones where the density of absorbing roots is highest and how these vary with seasons. Quantitative data on these aspects are of direct value to efficient use of soil and applied nutrients by crops.

Prior to the application of isotopic techniques, studies on the rooting pattern of crops were based on direct visual observations of root systems or on the physical separation of roots from the soil by the root washing method (McCreary et al., 1943; Waver and Darland, 1949). Such techniques, apart from being laborious, can only provide a picture of the total root distribution - active, dormant, and dead. Moreover, it is sometimes impossible to distinguish roots of the crop under investigation from those of weeds and other plants. In contrast, isotope techniques offer a quick and reliable means for determining the distribution pattern of active roots.

Two approaches have been adopted in the development of tracer methodology for root activity studies. Several investigations (Racz et al., 1964; Rennie and Halstead, 1965; Subbiah et al., 1967; Russell and Ellis, 1968) have reported on techniques where $^{32}\text{P}$ or $^{86}\text{Rb}$ is injected into the plant stem and the pattern of root activity determined by taking soil-root cores and measuring the radioactivity in them. This method, however, may not reflect the ability of the roots to absorb nutrients from the soil at any given time since, for example, when soil moisture is limiting, $^{32}\text{P}$ injected into the stem can still be translocated into live, but dormant, roots that are unable to absorb nutrients from the soil due to moisture stress. In a more direct approach, radioactive compounds such as $^{32}\text{P}$-labelled phosphate are placed in the soil at the various
positions to be tested for root activity, and the amount of radioactivity taken up by the plant is used as a measure of the intensity of root activity. This technique has been extensively applied to agricultural crops (Hall et al., 1957; Lipps et al., 1957; Nye and Foster, 1960; Kafkafi et al., 1965; Bassett et al., 1970). The latter technique is more appropriate for delineating patterns of root activity in relation to the uptake of fertilizer nutrients under the soil and other environmental conditions prevalent during a specific period of time. Its application to a variety of tree crops was demonstrated in several preliminary experiments (Cornwell, 1957; Broeshart, 1959; Saiz Del Rio et al., 1961; Nethsinghe, 1965; Atkinson, 1974). Under an international coordinated research programme, the $^{32}P$ injection technique has been employed under field conditions for determining the root activity distribution of various tree crops of economic importance to developing countries (IAEA, 1975).

The seasonal root activity patterns of banana (in Uganda), citrus (in Spain and Taiwan), cocoa (in Ghana), coffee (in Colombia and Kenya), coconut (in the Philippines and Sri Lanka) and oil palm trees (in Malaysia and the Ivory Coast) were studied under this research programme. The $^{32}P$ contents of leaves of a defined age and morphological position were used as measures of root activity.

In most tree crops, root activity was highest near the soil surface, within the top 20 cm (Tables 4 and 5). The exceptions were orange trees in Spain, in which root activity was highest at 30 cm depth.

In general, banana, young orange trees in Spain, and mature coffee and coconut trees showed the highest lateral root activity within 30 to 100 cm distance from the trees (Tables 4 and 5). In young citrus trees in Taiwan, mature orange in Spain, and mature cocoa and oil palm trees in Malaysia, lateral root activity was highest at 100 to 300 cm distance. In the Ivory Coast the lateral root activity of mature oil palms was independent of distance from the tree within the 100 to 400 cm distance tested.
Table 4: Root activity of coffee trees - Kenya
Experiments in different seasons. $^{32}$P contents of young leaves, lower canopy, in counts/min per gram dry material x $10^{-1}$ (means of 3 replicates)

<table>
<thead>
<tr>
<th>Sampling interval (weeks)</th>
<th>Depth (cm)</th>
<th>Experiment 4: End of cool, dry season &amp; beg. of short rains</th>
<th>Experiment 5: Hot, dry season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rain-fall mm</td>
<td>Distance (cm) 30 82.5 135</td>
<td>Rain-fall mm</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1340 2084 293</td>
<td>1340 2084 293</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>1054 396 194</td>
<td>1054 396 194</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>75 2 1564 254 298</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>191 235 63</td>
<td>174 422 845</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>136 10 51</td>
<td>20 7 25</td>
</tr>
</tbody>
</table>

Source: IAEA (1975)

Table 5: Root activity of coconut trees - Sri Lanka.
Comparison of root activity as determined by $^{32}$P contents of sixth fully opened leaf - wet season, Mawatte. Data expressed as percentage of $^{32}$P content at 0.5 m distance, 12 cm depth.

<table>
<thead>
<tr>
<th>Sampling internal (days)</th>
<th>Depth (cm)</th>
<th>Distance (m) 0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12</td>
<td>100</td>
<td>108</td>
<td>90</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>49</td>
<td>100</td>
<td>60</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>47</td>
<td>39</td>
<td>42</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>62</td>
<td>74</td>
<td>30</td>
<td>21</td>
</tr>
</tbody>
</table>

Source: IAEA (1975).
In wet and warm seasons all crops showed more intense root activity than in dry and cold seasons. In dry weather, the differences between root activity near the soil surface and lower depths were less than in wet seasons. There were no marked seasonal variations in patterns of root activity. Experimental data indicate that patterns of root activity can vary with soil type, tree variety and age.

Fertilizer placement experiments using $^{32}$P-labelled fertilizers on coconut, citrus, cocoa and coffee trees showed that application within the zones of highest root activity resulted in highest utilization by both the treated tree and neighbouring trees.

The data of some of the tree experiments in the above-mentioned coordinated research programme revealed a high degree of variability of $^{32}$P activity between trees and between different leaves within a tree. In later studies (IAEA, 1975), a double-labelling technique using $^{32}$P and $^{33}$P was developed with a view to reducing the observed error variance. In this technique, $^{33}$P is applied to all experimental trees in a standard position with respect to the tree, and $^{32}$P is applied at locations corresponding to the different depths and lateral distances being compared. The treatment effects, namely, depth and distance, are expressed in terms of a ratio of the standard to the variable treatment. Experiments with Betula and Fraxinus trees clearly demonstrated that the double-labelling technique does not require the selection of leaf samples of a particular age or morphological position, and the error variance of $^{33}$P/$^{32}$P ratios is much less than that of $^{32}$P activities (Table 6). In other experiments (IAEA, 1975), a comparison between $^{32}$P and $^{15}$N as tracers for soil injection techniques with apple trees showed that similar results are obtained with the two isotopes; the error variance in the case of $^{15}$N is lower than for $^{32}$P (Table 7).

ISOTOPE TECHNIQUES FOR ASSESSMENT OF NUTRIENT AVAILABILITY IN SOILS

Isotopic tracer methodology has been applied to the measurement of the amount of inorganic mineral nutrient in soil that is available to plants. Of these procedures, the 'E' value
Table 6: $^{33}\text{P} / ^{32}\text{P}$ ratio in samples of different origin, derived from injections of $^{33}\text{P}$ mixed in the same ampoules

<table>
<thead>
<tr>
<th>TREE</th>
<th>SAMPLE LOCATION*</th>
<th>$^{33}\text{P} / ^{32}\text{P}$ RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraxinus</td>
<td>Adjacent</td>
<td>7.3</td>
</tr>
<tr>
<td>Betula</td>
<td>Adjacent</td>
<td>6.8</td>
</tr>
<tr>
<td>Betula</td>
<td>Opposite</td>
<td>7.6</td>
</tr>
<tr>
<td>Fraxinus</td>
<td>Adjacent</td>
<td>6.5</td>
</tr>
<tr>
<td>Fraxinus</td>
<td>Opposite</td>
<td>7.1</td>
</tr>
<tr>
<td>Betula</td>
<td>Adjacent</td>
<td>7.4</td>
</tr>
<tr>
<td>Betula</td>
<td>Opposite</td>
<td>6.5</td>
</tr>
<tr>
<td>Betula</td>
<td>Adjacent</td>
<td>7.2</td>
</tr>
<tr>
<td>Betula</td>
<td>Adjacent</td>
<td>6.9</td>
</tr>
<tr>
<td>Betula</td>
<td>Opposite</td>
<td>6.8</td>
</tr>
</tbody>
</table>

$\bar{x} = 7.0 \pm 0.37$, variation = 5%

* Adjacent = leaf samples taken from that side of the tree where the soil injections were made in a strip.

Opposite = leaf samples taken from the opposite side of the tree to where the soil injections were made.

Source: IAEA (1975)

(Russell et al., 1954) and the 'L' value (Larsen, 1952) are based on the principle of isotopic dilution while the 'A' value is based on the assumption that when a plant is confronted with two or more sources of a nutrient, it will take up nutrient from each source in direct proportion to the amounts available from each source.

The use of a radioisotope of a given nutrient enables the amount of that nutrient present in the labile or exchangeable form in a soil to be measured without using chemical extractants.
Table 7: The uptake by mature apple trees of nitrogen from $^{15}$N-labelled sodium nitrate applied at two depths (average of three replications)

<table>
<thead>
<tr>
<th>Time of sampling after soil injections</th>
<th>N uptake from the fertilizer</th>
<th>Coefficient of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper leaves</td>
<td>Lower leaves</td>
</tr>
<tr>
<td>days (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 10</td>
<td>0.40</td>
<td>0.31</td>
</tr>
<tr>
<td>20</td>
<td>0.74</td>
<td>0.32</td>
</tr>
<tr>
<td>60 10</td>
<td>0.33</td>
<td>0.21</td>
</tr>
<tr>
<td>20</td>
<td>0.80</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Source: IAEA (1975)

Measurement of the distribution of the tracer between the solid phase and the solution at "quasi" equilibrium

$$\frac{M \text{ (solid phase)}}{M \text{ (in solution)}} = \frac{^*M \text{ (solid phase)}}{^*M \text{ (in solution)}}$$

where $M$ and $^*M$ represent the nutrient and its isotope, respectively, provides the basis for measuring the amount of $M$ in soils available to the crop. The 'E' value method is a laboratory measurement in which the soil solution is sampled at a specific time. The 'L' value utilizes the plant to provide an integrated sample of the soil solution over the period of time the plant is grown. The 'A' value provides a measure of available nutrient in units of a fertilizer standard. The theoretical and experimental aspects of the 'E', 'L', and 'A' value measurements have been critically discussed by Fried (1964), Fried and Broeshart (1967), Rennie (1969, 1970), and Rennie and Fried (1971), and the reader is referred to these articles for extensive background material on this topic. The literature on the use of the above
techniques for assessment of availability of soil nutrients
during past two decades has become quite voluminous and in view
of limitations of space, only a brief résumé of the principles
and experimental approach, including advantages and limitations
of these techniques is presented here. While the discussion is
limited to examples from research into phosphate and zinc avail-
ability in soils, much of the discussion on soil phosphate is
relevant to soil nitrogen and other macronutrients, and that on
soil zinc would, in general, be applicable to other micronutrient
cations.

'E' VALUE

With reference to Equation 3 in the case of soil phosphorus,
the amount of $^{31}$P in the solid phase at equilibrium with the
phosphorus in solution can be calculated from Equation 4:

$$\frac{^{31}\text{P (solid)}}{^{32}\text{P (solid)}} = \frac{^{32}\text{P (solid)}}{^{32}\text{P (solution)}} \times ^{31}\text{P (solution)} \quad [4]$$

The 'E' value represents "labile-P" and includes $^{31}$P (solid) + $^{31}$P (solution) or total phosphorus in the system that undergoes
isotopic dilution. In practice, since a fraction of the $^{31}$P is
rapidly exchanged followed by a slower isotopic dilution process,
an arbitrary time is chosen for shaking the soil suspension and
the resultant value is termed $E_t$ (E for exchangeable and t for
time of exchange). Although the principle of obtaining the $E_t$
is equivalent to that of obtaining the 'L' value, identical
values should not be expected because the isotopic exchange occurs
in distinctly different environments. The time the suspension
is shaken, the exchangeable base status of the soil, the tempera-
ture, the time of shaking before addition of $^{32}$P and the soil:
solution ratios are required to be defined for $E_t$ values to be
considered a reliable and direct measure of the quantity of avail-
able phosphorus in different soils (1964).

The successful application of the 'E' value procedure depends
upon isotopic exchange between those components potentially avail-
able to plants, and the radioisotope added to the equilibrating
solution. Although this requirement seems reasonable in principle,
it is a major limitation in its general application to micronu-
trients. Zinc 'E' values could be measured on most acidic and
near-neutral soils, but erratic and unrealistic data were obtained on alkaline and other "fixing" soils (Rennie et al., 1971). The zinc 'E' values for acidic soils were reproducible, unaffected by variations in procedure and by amounts of carrier added, and were correlated with amounts of Zn removed by EDTA and MgCl₂ extraction. The 'E' value procedure, based on indifferent salt solutions, is generally experimentally unsuited for assessing the micronutrient status of soils. Isotopic exchange equilibrium can be assured by equilibration with solutions of dilute acids or complexing agents, and reproducible, acceptable 'E' values thus obtained. However, the resultant values, whether for example by DTPA (Lopez and Graham, 1970) or EDTA (Tiller et al., 1972), do not differ appreciably from that gained by simple extraction by the complexing agents themselves.

'L' VALUE

The 'L' value concept is based upon the assumption that labelled nutrient added to a soil is isotopically diluted with a clearly definable fraction of soil nutrient called 'labile soil nutrient'. In contrast to an 'E' value, the time span for dilution assessment is the growing season. Larsen (1952) used the equation (Eq. 5) for isotopic dilution to calculate the isotopically labile-P or 'L' value:

\[
'L' \text{ value} = \frac{(a_o - 1)}{(a_p - 1)} \times \text{fertilizer-P applied}
\]

where \( a_o \) and \( a_p \) are the specific activities (uCi \(^{32}\text{P}\) per g P) of the applied phosphorus and plant phosphorus, respectively.

Russell et al. (1957) modified Larsen's technique after showing that the 'L' value was independent of the amount of carrier phosphorus and of time of sampling, provided that the labelled phosphorus was thoroughly mixed with the soil. They concluded that it was best to use carrier-free \(^{32}\text{P}\) to prevent chemical reactions between the carrier and the soil that might reduce isotopic dilution. As stated by Fried (1964), the 'L' value is the amount of phosphorus in the soil and in the soil solution that is exchangeable with orthophosphate ions added to the soil as measured by a plant-growing system. Although conceptually
this involves the attainment of isotopic equilibrium, if isotopic
equilibrium is not attained, the 'L' calculated does represent
that amount of soil phosphorus that was exchangeable with solution
phosphorus over the time period and under the conditions of the
growth of the plant.

The 'L' value method, based on labelling with carrier-free
radioisotopes, provides a reliable reference procedure for the
measurement of the total quantity of available micronutrients.
'L' values for Zn were found to be unaffected by incubation of
the moistened, labelled soil, but introduction of radioisotope
with carrier increased the values (Tiller and Wassermann, 1972,
1973). 'L' values for zinc are unaffected by choice of plant
species as test plant, provided allowance is made for the con-
tribution of Zn from the seed when necessary (Tiller and Wasser-
mann, 1973). The 'L' values based on clover as the test plant
correlated well (p<0.001) with Zn extracted by both MgCl₂ and
EDTA from the soils of the pot experiment for a range of cal-
careous and acidic soils (Tiller et al., 1972), but not as well
with dilute HCl. Similar high correlations were obtained between
'L' values using rice under flooded conditions, and Zn extracted
by either EDTA or DTPA (Tiller et al., 1978).

Provided carrier is not used with the tracer, the 'L' value
procedure, for Zn at least, is not restricted to certain soil
types as was the case for the 'E' value approach (Tiller et al.,
1972). It applied equally well to soils in which Zn is strongly
bound, e.g. calcareous clay soils, where the 'Eₜ' value method,
based on indifferent salts, did not apply. This perhaps supports
the view of Fried and Broeshart (1967) that the 'L' value may re-
represent a more valid method of determining the 'E' value.

'A' VALUE

The 'A' value concept, widely applied to soil-plant nutrition
studies, is expressed in the following equation (Eq. 6) using P
as the plant nutrient:

\[ 'A' \text{ value} = \frac{\%Pdfs \times \text{Rate of P fertilizer application}}{\%Pdff} \ \text{(kg P/ha)} \]

where \( \%Pdff = (100 - \%Pdfs) \) and

\( \%Pdfs = \text{percentage of total P in the plant tissue} \)

\( \text{derived from the fertilizer} \).
'A' value data are quantitative criteria on which evaluation can be made to assess the comparative phosphorus (or other nutrient) fertility status of different soils.

The 'A' value serves as an availability index for either a fertilizer nutrient or a soil nutrient. The availability of soil phosphorus, for example, is measured relative to a standard fertilizer source. An accurate 'A' value is obtained when the reaction between the fertilizer standard and the soil phosphorus is minimal, or when the labelled carrier is banded.

'A' values depend not only on the amount of available soil phosphorus and fertilizer placement, but the plant root distribution and the form of phosphate fertilizer. The 'A' value concept is not restricted to growth chamber experiments, but is equally meaningful in field experiments. On the other hand, the 'L' value measures the total quantity of plant-available soil phosphorus and requires carrier-free $^{32}$P (or only a minimum of carrier) and uniform mixing with the soil. 'L' values are independent of the plant root distribution but cannot be determined in the field.

Extensive data support the observation that the limited soil-fertilizer contact afforded by band placement of the labelled phosphate fertilizer standard minimizes isotopic exchange and fertilizer-P fixation, which often occurs to varying degrees in different soils. Accordingly, 'A' values are a direct function of the P fertility level of the soils.

Provided that another nutrient such as nitrogen does not limit crop growth, previous experiments (Table 8) have shown that the placement of the labelled phosphorus standard with the seed of wheat results in an uptake pattern of soil and fertilizer phosphorus such that the 'A' value remains constant with increasing rates of fertilizer application (Rennie, 1970; Rennie and Fried, 1971). Two rates of labelled-P fertilizer applications may be used to ascertain whether they remain constant as rates of application are probably undesirable inasmuch as 'A' values may fluctuate when the ratio, % Pdfs/% Pdff, manifests extremely small or large values.
The 'A' value, using band placement of the phosphate fertilizer, affords a measure of the available soil phosphorus within the rooting zone. Therefore, under field conditions, where precipitation often varies widely, 'A' values can be expected to vary in accordance. This is illustrated in the data on contrasting Canadian soil types obtained from field experiments carried out in alternate years on the same field sites (Rennie, 1970). The uniformity of the Na₂CO₃ extractable phosphorus afforded a sharp contrast to the 'A' value data: The latter were consistently low under drought conditions, and high where favourable moisture conditions prevailed, while the former were constant. The 'A' value data suggest that the biologically available soil phosphorus is low under dry conditions, and, in comparison, high during wet years. This observation was supported by the percentage yield values.

The significance of the 'A' value concept (using band placement) as a means of assessing the phosphorus fertility status of soils is further illustrated in data reported by Rennie (1970) from experiments carried out both in the field and in the growth chamber on four genetic soil types: the Calcareous, Orthic, Illuviated and Humic Illuviated Gleysol. These four profiles
represent a catenary sequence that dominates the chernozemic soil area in western Canada. The 'A' value data obtained from this six-year study not only was of significance in evaluating the relative phosphorus fertility level of the four profiles in question but also provided data of value in assessing the effect of various growth factors that interact strongly with soil phosphorus, such as moisture, temperature and soil structure.

The determination of soil nitrogen 'A' values has been carried out on 12 widely differing soils by Legg and Stanford (quoted by Rennie(1970)). These authors concluded that from the results obtained there was no doubt that the 'A' value constitutes a precise standard for characterizing the nitrogen supplying capacity of soils. Data selected from the referenced study are given in Table 9. No evidence was found that the mineralization rate of soil nitrogen was influenced by the addition of fertilizer nitrogen; 'A' values remained remarkably constant with increasing rate of application.

Table 9: 'A' value as an index of the N-supplying capacity of soils

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Initial N (ppm)</th>
<th>AN value (ppm)</th>
<th>% Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evesboro sl</td>
<td>9</td>
<td>105</td>
<td>40</td>
</tr>
<tr>
<td>Redbay sl</td>
<td>50</td>
<td>122</td>
<td>49</td>
</tr>
<tr>
<td>Miami Sil</td>
<td>17</td>
<td>207</td>
<td>70</td>
</tr>
<tr>
<td>Elliot cl</td>
<td>110</td>
<td>271</td>
<td>79</td>
</tr>
<tr>
<td>Crosby cl</td>
<td>231</td>
<td>439</td>
<td>93</td>
</tr>
</tbody>
</table>

Source: Rennie(1970)

The most successful application of the 'A' value approach has been in nutrient availability research on macronutrients, especially nitrogen and phosphorus (Fried and Broeshart, 1967; Fried, 1964; Rennie, 1969, 1970; Rennie and Fried, 1971) but micronutrients such as zinc have also been studied in this way (Khasawaneh and Copeland, 1973).
In the case of nutrient ions such as phosphate and zinc, where diffusive flux through the soil solution is the principal supply mechanism and rate-limiting step governing the availability of these ions for root absorption (Lindsay, 1972; Barber, 1966; Olsen, 1965), a complementary approach describing the nutrient status of the soil is to stress the overall chemical interactions between solid and solution phases, and the parameters that affect this equilibrium.

The factors that control availability may be viewed in terms of (i) an extensive property, often termed the capacity or quantity factor (Q); (ii) an intensive property (I) such as concentration of nutrient in soil solution; and (iii) the slope of the relation between the two latter terms (Q/I).

The usual method of determining capacity factor in the laboratory is to determine the labile nutrient (for example phosphate) by isotopic dilution in a manner similar to the estimation of 'Et' value (Olsen, 1965; Olsen and Flowerday, 1971). The intensity factor (I) is the concentration of P in the soil solution. The term (Q/I) is described experimentally by the slope of the appropriate adsorption or desorption isotherm dc/dc or "buffer capacity" referred to in Eq. 2 (Nye, 1972). It is clear that these measurements are amenable to radioisotope techniques.

The work of Olsen et al. (Olsen, 1965; Olsen et al., 1965) and Olsen and Kemper (1968) have demonstrated the relative importance of the capacity and intensity factors together with the diffusion coefficient discussed earlier on the uptake of phosphate. These studies indicate that the higher rate of uptake of phosphate by corn plants from clay soils as compared to sandy soils with the same concentration of phosphate in the soil solution (intensity factor), can be explained in terms of higher capacity factor and diffusion coefficient of phosphate in the clay soil (Olsen, 1965; Olsen et al., 1965). In the referenced studies capacity factor was the slope of the linear relationship between labile P in soil volume and concentration of P in the soil solution.

More recently, Khasawneh and Copeland (1973) have characterized solid-phase phosphate supply in relation to surface chemical
reactions (adsorption-desorption phenomena) and proposed the term "supply parameter", which integrates the quantity and intensity factors and "buffer capacity" and shows a highly significant linear relationship with cumulative phosphate desorption in contrasting soil types.

The "buffer capacity" term for micronutrients has been estimated in recent studies using radioisotopes (Tiller et al., 1972; Tiller and Wassermann, 1972). The "buffer capacity" values for zinc on 25 Australian soils varied about 1000-fold; 25 other soils collected from 25 different countries showed a similar range of values. Corresponding values for cobalt varied only about 100-fold and the higher values were lower than those for Zn by approximately two orders of magnitude. Inclusion of the "buffer capacity" term helps to improve soil test correlations for micronutrients.

ISOTOPE TECHNIQUES FOR MEASUREMENT OF BIOLOGICAL FIXATION OF ATMOSPHERIC NITROGEN

In view of the energy costs of producing nitrogenous fertilizers, high priority is currently accorded to research aimed at more effective symbiotic and associative dinitrogen fixation by crops. This can reduce the need for nitrogenous fertilizers, especially in developing countries.

A major problem in symbiotic dinitrogen fixation by legumes has been the lack of an accurate method for quantitative estimation of the amount of N₂ fixed by crops grown in the field (Ham, 1978; Rennie et al., 1978). Isotopic tracer technique offers the possibility of measuring the contribution of fixed nitrogen to the crop over the entire growing season (Fried and Broeshart, 1975; Fried and Middleboe, 1977; Phillips and Bennett, 1978) which is another example of the tremendous versatility of this technique in nutrient availability research.

Since the atmospheric N₂ source cannot be isotopically labelled, the contribution of this unlabelled source is measured by adding a labelled common third source to the soil-plant system (Fried and Broeshart, 1975; Fried and Middleboe, 1977). This measurement can be made at any nutrient supply level and the only
assumption involved is that the added labelled source does not alter the relationship between the supply of nutrients from the other sources. In practice the uptake of nutrient from a labelled source is made in the presence and absence of the unlabelled nutrient source. In the case of a legume crop this would be in the presence and absence of nitrogen fixation as described in the following development (Fried, 1978).

Assume a case of two sources of a nutrient, namely soil (S) and unlabelled source of interest (X). An experiment will be initiated in which a labelled source of the nutrient in question (L) will be added in the one case to soil alone and in the other case to soil plus unlabelled source. Thus, the two treatments consist of (i) S + L and (ii) S + L + X. We can then conclude that

\[ s_1 + l_1 = 1 \]  
\[ s_2 + l_2 + x = 1 \]

where:

\( s_1 \) and \( s_2 \) are the proportions of the nutrient derived from the soil source in treatment (i) and (ii), respectively;
\( l_1 \) and \( l_2 \) are the proportions of the nutrient derived from the labelled source in treatments (i) and (ii), respectively;
and \( x \) is the proportion of the nutrient in the plant derived from the unlabelled source in treatment (ii).

Since the addition of \( X \) is assumed not to change the relationship between the soil source of the nutrient and the labelled source of the nutrient, e.g. if the two sources were equivalent in the absence of \( X \) they would also be equivalent in the presence of \( X \), then:

\[ \frac{l_1}{s_1} = \frac{l_2}{s_2} \]

Introducing Equation 7 into Equation 9:

\[ s_2 = \frac{l_2}{l_1} (1 - l_1) \]
Inserting Equation 10 into Equation 8:

\[
    x = 1 - \frac{\lambda_2}{\lambda_1}
\]  

[11]

In other words, the proportion of the nutrient derived from the unlabelled source equals one minus the ratio of the proportion of the nutrient coming from the labelled source in treatment (ii) to the proportion of the nutrient coming from the labelled source in treatment (i).

In practice the proportions represented by \( \lambda_2 \) and \( \lambda_1 \) have the same denominator, e.g. atom % \( ^{15} \text{N} \) excess in the labelled fertilizer applied. Thus the denominators of the ratios cancel out and only the atom % \( ^{15} \text{N} \) excess of the labelled nutrient in the plant is left. Therefore:

In the case of a stable isotope label

\[
    x = 1 - \frac{\text{atom % } ^{15} \text{N excess in the plant in the presence of X}}{\text{atom % } ^{15} \text{N excess in the plant in the absence of X}}
\]  

[12]

Since \( x \) can thus be determined experimentally and is the proportion of the nutrient in the plant derived from the unlabelled source it is only necessary to multiply by the total nutrient taken up by the plant to obtain the actual amount of nutrient derived from the unlabelled source. Source (X) and source (L) as well as the soil source (S) can also be compared quantitatively by using the 'A' value transformation (Fried and Broeshart, 1975).

Since the amount of standard fertilizer applied does not appear in Equation 12, it is not necessary to know how much labelled fertilizer is applied as long as the same amounts of the same material are applied in both treatments. In practice it may be necessary to know these amounts for other objectives of the experiment. (If different amounts of fertilizer are applied an 'A' value adjustment must be made (Fried and Broeshart, 1975).)
The only assumption involved is that the added labelled source does not change the relationship between the supply of nutrient from the other nutrient sources. Equation 9 derives from this assumption. This is a limited form of the consequence of the assumption that when a plant is confronted with two or more sources of a nutrient it will take nutrient from each source in direct proportion to the amounts available. The latter assumption is the basis for the 'A' value concept discussed earlier and has the mathematical consequence of constancy of 'A' value at different rates of fertilizer application.

The constancy of 'A' value can be tested by the addition of labelled fertilizer to the control plot: this will provide assurance that the assumption made is valid for the particular experimental conditions. Experimentally the labelled fertilizer should be mixed as thoroughly as possible with the soil. In measuring the amount of nitrogen fixed by a legume crop this control may be a non-nodulating strain of the same species, the legume nodulated with an ineffective rhizobium strain, the legume fertilized with high enough levels of N to effectively knock out N₂ fixation, or a non-legume. This approach has been used to calculate some of the data obtained in field experiments as part of an international coordinated programme on fertilization of legume crops. The data are presented in Table 10. These preliminary results, which show the amounts of nitrogen fixed by legumes as determined by the use of ¹⁵N-labelled fertilizer, illustrate the kind of information that can be obtained using the technique described above. Various cultural practices are indicated here as affecting the amount of nitrogen fixed in various locations. In Hungary, phosphorus fertilization was effective in increasing the amount of nitrogen fixed. In Sri Lanka, the incorporation of organic straw residue effected an increase in the amount of nitrogen fixed by soybean. In Ghana, the application of boron and molybdenum resulted in increases in the amounts of nitrogen fixed by inoculated soil under groundnuts.

**ISOTOPE TECHNIQUES IN EVALUATION OF APPLIED FERTILIZER NUTRIENTS**

While the scope of the present paper has been limited to discussion of the role of isotopic tracers in research into the
Table 10: The use of $^{15}$N-labelled (NH$_4$)$_2$SO$_4$ to measure the amount of nitrogen fixed by legume crops as affected by various cultural practices at different locations

<table>
<thead>
<tr>
<th>Crop location</th>
<th>Labelled starter N applied</th>
<th>Other treatments</th>
<th>N fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg/ha</td>
<td></td>
<td>kg/ha</td>
</tr>
<tr>
<td>Soybean</td>
<td>40</td>
<td>0 kg P/ha at planting</td>
<td>7</td>
</tr>
<tr>
<td>Hungary</td>
<td>40</td>
<td>35 kg P/ha at planting</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>70 kg P/ha at planting</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>105 kg P/ha at planting</td>
<td>71</td>
</tr>
<tr>
<td>Soybean</td>
<td>20</td>
<td>5000 kg straw at planting</td>
<td>41</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>20</td>
<td>Without inoculum</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>With inoculum</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Without inoculum</td>
<td>82</td>
</tr>
<tr>
<td>Groundnut</td>
<td>15</td>
<td>Inoculum on seed</td>
<td>94</td>
</tr>
<tr>
<td>Ghana</td>
<td>15</td>
<td>Inoculum in soil</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Inoculum in soil + B + Mo</td>
<td>106</td>
</tr>
</tbody>
</table>

Source: Fried (1978)

chemistry and availability of soil nutrients, many of the applications cited are equally relevant to studies on fertilizers applied to the soil.

Direct quantitative assessment of the applied nutrient for a given soil-crop combination in the greenhouse or under field conditions can be made by adding isotope-labelled fertilizers to
the soil and assaying the plant to determine the actual uptake of the nutrient from the labelled fertilizer. The literature abounds with the results of studies carried out over the past 25 years with isotope-labelled sources of phosphorus, nitrogen, calcium, sulphur, zinc, iron, manganese and other macro- and micronutrients. These have provided information of direct practical utility on the efficiency of different fertilizers, methods and timing of application of these nutrients, and the effects of different cultural practices on fertilizer efficiency under a wide variety of soil and crop conditions.

Many other agronomic problems can benefit directly from the isotopic tracer-aided ability to quantitatively separate added fertilizer nutrient from the nutrient already present in the soil. These include obtaining clear-cut answers to practical questions associated with the fertilization of tree crops through assay of the isotope label in leaves and other plant tissues, which obviates the need for the long-term studies of 5 years or more required in conventional field trials. The measurement of the residual value of applied fertilizer is another important example of studies directly amenable to isotope techniques. Isotope tracers permit the quantitative evaluation of the contribution to crop nutrition of nutrient sources that cannot be labelled. An example of this application is the use of nitrogen-15 in measurements of the amount of atmospheric nitrogen fixed by legumes over the entire growing season under field conditions described earlier. Another example, based on the same principles, is the quantitative evaluation of natural rock phosphates as sources of phosphorus for crops. These and other above-mentioned applications of the isotope technique in direct quantitative assessment of fertilizer management practices have been critically reviewed in a recent publication (Fried, 1972).

The literature surveyed in this paper and studies cited as examples of applications of isotope techniques in soil chemistry and nutrient availability research have been drawn largely from work carried out on agricultural soils. While this reflects the relatively limited application of the techniques to date specifically in forest soil investigations, the underlying concepts as well as many of the practical applications are equally relevant to agroforestry. It is anticipated that these versatile
techniques will continue to form an integral part of soils research activities at both national and international levels and, together with other conventional methodologies, contribute significantly to the advancement of our knowledge of the soil-plant system, and aid in obtaining effective and rapid solutions of problems of direct practical importance in agroforestry research.

**DISCUSSION**

*Dommergues*: What is the minimum level of inorganic N one can add to the soil without disturbing N₂ fixation?

*Fried*: You can add 1-2 kg N/ha, but this may be too low then to obtain any response with grain crops.

*Sánchez*: How do you reconcile the inherent differences between the non-legume and legume's N uptake in your N₂ fixation technique?

*Fried*: By measuring the ratio of N from isotope and non-isotope-treated soils you eliminate these differences.

*Sánchez*: Which non-legume crops do you use?

*Fried*: Non-nodulating soybeans, Sudan grass, and possibly small grains.
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RESEARCH STRATEGY FOR SOILS IN AGROFORESTRY

Bjorn Lundgren*

The formulation of a realistic research strategy for soils in agroforestry must be based on: (i) an identification of important interrelations between soils and crops that are typical for agroforestry land use systems, (ii) a synthesis of the state of knowledge of tropical soil/crop relations relevant to agroforestry, (iii) an identification of problems and bottlenecks particularly related to the study of soils in agroforestry, (iv) an identification of short and long-term aims of soil management under different agroforestry systems, and (v) a survey of available and potential resources for soil research in agroforestry, in terms of funds, manpower and scientific infrastructure. These points are briefly discussed in the paper. Aims and components of an agroforestry soil research strategy are tentatively proposed. Particular emphasis is given to the potential role of ICRAF in initiating and coordinating research and to provide continuous services to institutions, organizations and individuals involved in agroforestry research.

It is difficult, and even premature, to propose a detailed research strategy for soils in agroforestry before the background information and discussions that will come out of the present workshop are available. If a strategy is defined as "a plan to optimize resources (time, funds, manpower, institutions, etc.) to achieve certain aims", then an inventory of resources and a definition of the aims are necessary pre-requisites for the formulation of a strategy. Furthermore, the identification of priority aims of research must be based on a familiarity with the state of knowledge within the relevant subjects. All these aspects will be treated in other papers presented to this workshop. However, it would be too easy to escape the task like that. I do not think, for example, that it will be too controversial to formulate the overall, general aim for research on soils in agroforestry as: "to develop soil management methods which ensure the long term productive capacity of the site under agroforestry land-use systems".

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The difficulties are not over here, though. What is agroforestry and what justification is there to formulate a separate research strategy for soils in agroforestry? According to the ICRAF programme of work (King & Chandler, 1978), "agroforestry has been defined as a sustainable land management system which increases the overall yield of the land, combines the production of crops (including tree crops) and forest plants and/or animals simultaneously or sequentially, on the same unit of land, and applies management practices that are compatible with the cultural practices of the local population."

It is furthermore strongly suggested, in the ICRAF programme as well as in other texts and resolutions, that agroforestry as a form of land-use is primarily considered as a desirable replacement or improvement of land-use systems that are degrading under the pressure of increased population densities in areas with low inherent potential for intensive agriculture. In the humid tropics this is often synonymous with areas under various forms of shifting agriculture.

It is essential to elaborate on the implications of these definitions and limitations if the strategy for soil research is literally to be brought down to earth and justify being called an agroforestry research strategy. The risk is, otherwise, that conventional lists of research aims and priorities, and thereby strategies, will be produced that dutifully record all conceivable aspects of the study of soils but are equally relevant to any form of land use. To prevent this, I think that the formulation of a realistic research strategy discussed briefly below, must be based on:

a) an identification of important interrelations between soils and crops that are typical in agroforestry land use systems;

b) an identification of short and long-term aims of soil management under agroforestry systems;

c) a synthesis of the state of knowledge of soil/crop relations relevant to agroforestry;
d) an identification of problems and bottlenecks particularly related to the study of soils in agroforestry;

e) a survey of available and potential resources for soil research in agroforestry;

IDENTIFICATION OF INTERRELATIONSHIPS BETWEEN SOILS AND CROPS TYPICAL IN AGROFORESTRY

There are at least four such typical, though not necessarily unique, aspects that will influence the study of soils under agroforestry and have implications for the formulation of a research strategy.

THE TIME ASPECT

Unlike annual cropping systems where important trends in soil dynamics may be evident after only a few years, it will be exceedingly difficult, and often misleading, to draw conclusions about the long-term stability of agroforestry systems based on short studies. Regardless of whether the system is a sequential one (e.g. with "improved" tree fallows between food crops) or a simultaneous one (with mixed tree and food crops) the soil must be monitored over at least one rotation, i.e. the combined length of the clearing, cropping and tree phases, if any relevant conclusions are to be worthwhile. This may mean study periods of 10-20 years.

There are two main reasons why this is essential. The first is that, over the rotation, and depending on the crop, soil conditions will be affected by a number of different management activities and ecological conditions, e.g. clearing, hoeing, burning, felling, organic matter removal, shade and exposure, nutrient cycling, and various degrees of leaching. Some of these will have a positive influence on the soil, others a negative one. The important, and indeed difficult, thing is to establish the long-term trend that results from these short-term fluctuations.

The second reason is the importance of evaluating the effect on the soil of climatic extremes, e.g. the highest rainfall intensity or the longest dry period likely to be encountered over
a 10- or 20- year period. Indeed, in agroforestry such events should not be considered extreme since statistically they will occur once every rotation. If, therefore, conclusions on the soil stability under a system are based on short-term studies that do not include such climatic events, serious misjudgments may result concerning, for example, the systems' resistance against erosion or leaching losses.

TREES WILL MAKE UP AN ESSENTIAL COMPONENT IN AGROFORESTRY SYSTEMS

In the promotion of the agroforestry concept there has been no limit to the alleged positive influences of trees. Sometimes this has achieved almost mystical dimensions - the frequent talk about "miracle trees" is one aspect of this. Although it may sound like lack of imaginative thinking, it must be flatly stated that there exist no miraculous influences of trees on soils. It is often mistakenly supposed that any tree crop has the same stabilizing effect on the soil as a natural forest. This is as wrong as to say that a managed maize field is ecologically equivalent to a savanna.

No doubt, however, a number of trees possess a combination of qualities that make them suitable, and indeed necessary, components of any land-use system on freely-drained, low-base-status soils in the wet tropics, e.g.:

- they provide shade, thereby creating a more favourable microclimate and environment for soil organisms;
- they provide protection against the energy impact of raindrops, thereby reducing structural disintegration of the surface soil;
- they produce organic matter, some of which is added to the soil surface in litter fall and, in part, is subsequently incorporated into the humus fraction of the soil, thereby improving topsoil structure and water-holding and nutrient retention capacities;
- they store nutrients in their ligneous parts, thereby temporarily conserving these nutrients in the system;
their superficial roots will reduce nutrient and soil losses by leaching and erosion and improve porosity, infiltration and aeration properties, and their deeper roots will bring up nutrients from depth to be incorporated into the phytomass; and

- some trees are associated with symbiotic nitrogen-fixing bacteria, some have mycorrhizal associations, increasing their efficiency in nutrient uptake.

It is important, however, to stress the fact that these are qualities, the importance of which will depend on their efficiency (or magnitude) in relation to the magnitude of the ecological forces of degradation - compaction, erosion, leaching, removal, burning, etc. This obvious fact often seems to be overlooked when general statements are made on the soil-fertility-restoring capacity of trees. One quality trees certainly do not possess, for example, is the ability to synthesize minerals out of the air.

One crucial problem in research will be, therefore, to quantify the effect that different tree crops have on the inputs and outputs of nutrients and organic matter in the system during the rotation. This may involve more than conventional soil sampling and analysis, e.g. biomass flow studies, morphological and physiological studies of root systems, hydrological and microclimatological studies, etc.

AGROFORESTRY WILL MAINLY BE PRACTISED ON LAND THAT HAS LOW POTENTIAL

In practice, this means, among other things, that agroforestry will not be important on inherently homogenous or anthropogenically homogenized soils, e.g. alluvial deposits or soils that have long been under active tillage. Instead agroforestry land will typically have more-or-less broken topography, with soils varying both along catenal gradients and with important inherent local conditions - microtopographical, geographical, hydrological or biological. This will have important implica-
tions for research methodology, e.g. sampling intensities, comparability between treatments, area requirements for research, etc.

THE SOCIO-ECONOMIC AND CULTURAL CONTEXT

Although there may be exceptions, e.g. where some highly-priced cash crops can be successfully integrated in the system, most forms of agroforestry will be practised by farmers with limited capital available for inputs, such as fertilizers, herbicides, machine power, etc. The important implication of this is that active soil management research must aim at finding more or less self-maintaining land use systems. Or, in other words, the research must have a strong resource-conservation approach. I can see a potential difficulty here since most experienced researchers and well-established institutes in agriculture and forestry, which inevitably must be a major resource base also in agroforestry research, are biased toward high-input soil management systems.

IDENTIFICATION OF SHORT- AND LONG-TERM AIMS OF SOIL MANAGEMENT UNDER AGROFORESTRY SYSTEMS

Aims of soil research in agroforestry are discussed in another paper presented at this workshop. As a necessary prerequisite to formulate these aims and, subsequently, a research strategy, it is, however, relevant briefly to discuss the aims of soil management in agroforestry. Since agroforestry will mainly be confined to soils of low or medium fertility, the contribution of soil scientists must not be only to passively monitor the soils under systems that have been designed from promising agronomic, forestry or economic points of view. There must also be research on active soil management, i.e. the manipulation of soil conditions by means of crop selection, mulching, soil working, etc., all of course within locally realistic ecological and socio-economic limits. Such soil management aspects must play an important role even in the initial design of agroforestry systems.
If, for example, we are to design long-term successful agroforestry systems on latosolic soils in the high rainfall zone where leaching and, to some extent erosion are the major limiting soil-related factors, they must be based on the following soil management principles:

- maintenance of a plant or mulch cover during most of the year to protect the soil surface;
- maintenance of topsoil organic matter to improve nutrient retention and water infiltration capacities;
- maintenance of dense and efficient topsoil feeder root systems to prevent leaching of nutrients released upon decomposition, added by rain, and brought up from deeper layers;
- minimizing removal of organic matter and nutrients in harvests;
- minimize burning, to prevent nitrogen and organic matter losses as well as nutrient losses via leaching and erosion of minerals in the ash.

Similar sets of principles or aims can be worked out for soil management in other agroforestry situations, e.g. in mountain areas where water erosion is the major limiting factor, or in semi-arid lands, where drought and wind erosion are limiting the potential. The soil management principles thus defined will have implications for research methods and resources needed, and thereby it will influence the research strategy.

SYNTHESIS OF THE STATE OF KNOWLEDGE OF SOIL-CROP RELATIONS RELEVANT TO AGROFORESTRY

The rather recent and "explosive" appearance of the concept of agroforestry has led to a widespread belief that we are dealing with a completely new science, integrating components of forestry, agronomy, soil science, ecology, sociology, economy, etc. It is true that the design and study of agroforestry systems will require competence within all these fields if relevant answers are to be obtained. A multi-disciplinary approach is thus necessary. It is not true, however, that there is a well-defined science of agroforestry with its
own methodologies. Even if some problems are typical in agroforestry, as discussed above, they are not unique or completely separated from problems studies in other fields.

This is important to keep in mind when synthesizing the state of knowledge, since there is normally a considerable amount known within different sciences that is directly relevant to the study of agroforestry. To find this information and to evaluate it requires not so much a positive, "integrated" mind as specialized training and experience. Duplication of work, formulation of wrong hypotheses and strategies, or even serious mistakes, may easily result if a competent evaluation of the state of knowledge is not made. Even within a "narrow" sector like soil relations there is a wealth of relevant information spread over sectorial, institutional, linguistic and geographical boundaries.

Several important texts have recently synthesized the knowledge on soils and soil management in tropical agriculture (National Academy of Sciences, 1972; Sanchez, 1976; Greenland & Lal, 1977). Much less has been written on soil and fertility relations under tropical man-made forests (e.g. Lundgren, 1978; and Schutz, 1976), although relevant information is likely to come out of a forthcoming workshop on "Forest fertilization in tropical and subtropical areas" arranged in Brazil in October by IUFRO. Over the last ten years there has been an enormous increase in ecological research carried out by university institutions in both tropical and temperate regions. This research, much of which has been, or is being, coordinated within the IBP and MAB programmes, is highly relevant to agroforestry soil studies (see e.g. Brunig, 1977). Many large-scale studies directly related to agroforestry have been initiated by French research institutes, e.g. by CTFT in Madagascar (Bailly et al., 1974) and by ORSTOM in French Guyana (Aubert, 1977).

This list could be made much longer but it is not my task here to try to make it complete. The point I want to make is
that it is not entirely correct to say that we lack hard facts on agroforestry even if very little research has been carried out directly on agroforestry systems.

We may, for example, assume that it would be interesting to introduce a system of two years of food cropping followed by a 10-year planted *Pinus caribaea* fallow in areas now under a bush falling system in West Africa. It is entirely true that no studies of the long-term productivity of such a system have been made, but we may still obtain important indications by combining results from other studies as shown in Table 1 below:

<table>
<thead>
<tr>
<th>Table 1: Compilation of data from separate sources which are relevant to an assessment of an agroforestry system involving food crops and a <em>Pinus caribaea</em> fallow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Removal of nutrients (kg ha⁻¹ yr⁻¹)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>N</strong></td>
</tr>
<tr>
<td><strong>Maize</strong> (grain only, medium yield) 63 12 30 8 6 Sanchez (1976)</td>
</tr>
<tr>
<td><strong>Cassava</strong> (roots only, low yield) 64 21 100 41 21 &quot; &quot;</td>
</tr>
<tr>
<td><strong>Pine</strong> (<em>P. patula</em>) (stem wood + bark only, high yield) 40 4 23 25 9 Lundgren (1978)</td>
</tr>
<tr>
<td><strong>Leaching losses/yr during the two years of cropping after a nat. forest fallow</strong> - - c100 c700 c250 Nye &amp; Greenland (1964)</td>
</tr>
<tr>
<td><strong>Approx. total removal in a 12-y cycle, assuming burning of nat. fallow, 1 crop maize, 1 crop cassava + 10 y pine fallow</strong> &gt; 500 &gt; 75 550 1700 600</td>
</tr>
<tr>
<td><strong>Input in rain during 12 yr</strong> 90 - 50 120 25 IITA (1975), Ibadan</td>
</tr>
<tr>
<td><strong>150 20 150 45 20</strong> Boyer (1973), Yaoundé</td>
</tr>
</tbody>
</table>
Although Table 1 is only a compilation the individual results are real and all come from tropical environments with medium-to-high rainfall and freely-drained kaolinitic soils. We may draw some conclusions from it that are relevant to our planned system:

- leaching during the cropping phases is extremely important;
- the removal of nutrients from a fast-growing timber fallow is substantial, even if only stem wood and bark are removed from the site;
- if such a land-use system is to be stable, the leaching and/or removal of nutrients must be reduced, or we must be certain that the nutrient pump effect (i.e. the uptake of nutrients from depth and their retention in the system) compensates for the losses.

This realization will, of course, substantially improve our ability to establish relevant aims and priorities for our soil management and research in this particular example. I am convinced that similar guidance may be obtained in many other agroforestry situations.

IDENTIFICATION OF PROBLEMS AND BOTTLENECKS PARTICULARLY RELATED TO THE STUDY OF SOILS IN AGROFORESTRY

Many of these problems have been touched upon in the previous text but it is worthwhile to list them in a comprehensive form:

1. Soil research on agroforestry systems will normally require a long time to yield relevant results.

2. There is a strong sectorial bias in most competent research currently carried out on tropical soils and land use.

3. The rather vague definitions of agroforestry in combination with its strong political appeal in international organizations, with consequent prospects of large funds being made available, will probably lead to a "join the bandwagon" trend among scientists and research institutes. It will require competence and hard scrutiny of research proposals by funding
agents like ICRAF, FAO, IDRC, etc., if much wastage of funds due to irrelevant and infeasible projects is to be avoided.

4. Research on agroforestry will take place mainly on heterogeneous land where inherent soil conditions vary and the number of management variables influencing soil conditions will be large. To achieve comparability between treatments within one study or between studies, the size of the study areas must be big and sampling intensive.

Together, these four problems imply one very important conclusion for the formulation of a research strategy: there are few institutions or organizations that are, today, capable of undertaking a full-scale, long-term research project on soil management and soil dynamics under various agroforestry systems.

SURVEY OF AVAILABLE AND POTENTIAL RESOURCES FOR SOIL RESEARCH IN AGROFORESTRY

With the concluding point above in mind, it is obvious that an institutional resource is not synonymous with just any research institute equipped with good will and a soil laboratory. Expertise must also be available in agronomy, forestry and other relevant fields; continuity in staffing and funding must be guaranteed; there must be large field-research areas situated in ecologically and socio-economically relevant environments available, where full managerial control is ensured. It is only the well-established international or regional research institutes and organizations that more-or-less meet these requirements, even if most of them are traditionally biased toward some sector of crop production. Potential resources also exist if cooperation can be initiated among sectorial national research institutes or university departments. International cooperation, e.g. between institutions in temperate and tropical regions, is another possible resource.

Since knowledge of these institutional resources is a necessary component in a detailed strategy, it is essential that a survey be undertaken as soon as possible. To avoid misunder-
standing, it should be stressed that the above points concern "total" systems research on agroforestry. Naturally, there are numerous relevant aspects that not only could but, preferably, should be carried out by specialized research institutes. This may, for example, include comparison of the rooting habits of different tree species, determining nutrient content of various crops, quantifying erosion under various crops and coverage, etc.

A FRAMEWORK FOR A RESEARCH STRATEGY

The strategy on soil research in agroforestry, which hopefully will come out of the present workshop, would thus be based on, among other things, an identification and evaluation of the points discussed above. It should suggest answers to a number of questions on the use of resources to achieve the aims decided upon, as shown in Figure 1 below:

Figure 1: Plan for evaluation, strategy, formulation and execution
As stated initially, it would be premature to go into details on the answers to these questions. In order to structure the discussion, the following simple framework is proposed as a basis (Table 2). Many of the "boxes" are already discussed in the ICRAF program of work (King & Chandler, 1978), other points may need further elaboration and still others may have to be added before a relevant and feasible strategy for soil research in agroforestry can be formulated. I have not tried to fill the boxes with my own ideas, only indicated some fields where ICRAF has an obvious role to play.

Table 2: A framework for a research strategy on soils in agroforestry

<table>
<thead>
<tr>
<th>Activity (what should be done?)</th>
<th>Initiating research</th>
<th>Raising and providing funds for research</th>
<th>Co-ordination of research</th>
<th>Implementing research</th>
<th>Dissemination of research results</th>
<th>Services to research workers and institutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aim (why should it be done?)</td>
<td>To ensure financing of research</td>
<td>To ensure optimum use of resources, prevent overlap</td>
<td>To ensure quick practical use of results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enacting body (who should do it?)</td>
<td>ICRAF, IDRC</td>
<td>National and international aid agencies</td>
<td>ICRAF, MAB</td>
<td>Res. institutes, IDRAF, national universities, consultants</td>
<td>ICRAF, Unesco consultants</td>
<td></td>
</tr>
<tr>
<td>Time span of activity (when and how long?)</td>
<td>Contacts, meetings, scholarships</td>
<td>Expert consultations, newsletters, meetings, courses</td>
<td>Newsletters, meetings, courses</td>
<td>Databank, library, state-of-knowledge reports</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methods (how should it be done?)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
DISCUSSION

Uriyo: To advocate the retention of an approach that will keep a low income system prevailing in the tropics is, surely, not what you intend?

Lundgren: Certainly not! Agroforestry land-use systems, as I understand the concept, are meant to improve or maintain the productivity of land that otherwise will have a decreasing productivity under the present land-use systems with existing and future pressures from increasing populations. Wherever and whenever inputs, such as fertilizers, are economically feasible, they should be used to increase land productivity. Over large areas and for many countries, large-scale inputs — and they must be large-scale since we are dealing with many people — are simply not available, for various reasons.

Lal: Our strategy should be based on what we should optimize. The optimizing criterion will depend on specific problems of a given agro-ecosystem. In some ecological zones soil and water conservation will be more important, whereas improved productivity per unit land area or unit time will be important in others.

Huxley: Before designing strategies for practical agroforestry systems, there should be a very clear appreciation of the fundamental ways in which, for the cropping components of any land-use system, the annual (or seasonal) components differ from the perennial (mainly woody perennial) ones. These two components can have quite different behavioural characteristics and, therefore, will need very different management practices. For this purpose, studies on some high-input systems may well assist.

Tejwani: To understand and finalize the strategy for research, it will be necessary to appreciate the approach at various levels of land management; for example, we can generalize that: (a) agroforestry will be mostly on wasted lands as identified by ICRAF; (b) by and large, lands available for agroforestry will be in difficult, inaccessible, problem areas and often not suited for agriculture; (c) while we may do research with high inputs, by and large, we will have to develop a package of low inputs, especially for trees, less dependence on fertilizers, weedicides, pesticides, and more dependence on better land management and compatible tree species, etc.; (d) emphasis will be on production combined with conservation, as conservation by itself will be difficult to sell; and (e) it may be difficult to specify what can be done in any specific project areas with respect to optimization of land or water or type of crop, or emphasis on conservation, etc.

Fried: What should be the relative weight placed on the production aspects of agroforestry and the conservation aspects?

Lundgren: When I spoke about research considerations I referred to those soil resources essential to the production of crops and trees, i.e. nutrients and water. The agroforestry system must adopt soil management practices that conserve these resources, by protecting them from being lost in erosion, leaching, etc., the aim, of course, being that they should be available for crop production. There is, thus, no conflict between the production and conservation aspects, the conservation part being necessary to maintain or increase production over a long time.
Sanchez: To simplify the strategy question, it might be better to divide it along ICRAF's four major ecological areas of interest (tropical rainforest, savannas, highland, and semi-arid tropics) and devise more specific strategies for each.

King: You stated that all agroforestry research should be done on a catchment basis. I can envisage the use of other units of land that will well prove useful when considering agroforestry systems.

Lundgren: Not all agroforestry research, but long-term studies on the whole system's ability to sustain or improve yields should preferably be done on a catchment basis.

Poulsen: Could Dr. King define the agroforestry aims for maximizing benefits while maintaining long-term ecological stability? I wish to point out that planted tree fallows may serve principally to rejuvenate soil productivity.

King: I do not think that we can enunciate a principle in this regard. One cannot say that in agroforestry systems either conservation or production should be given preference. This will depend on the prevailing conditions. For example, in the Himalayas conservation must be given priority, but attempts to increase food production should be made in the "conserved" system. In the arid savannas the priority would be to increase productivity.

Pereira: Are we paying enough attention to the desired crop output? Most tree crops involve some form of processing or marketing for food or industrial production if we are aiming to break out of rural poverty rather than to perpetuate it. Organization through such processing centres permits credits for inputs. We saw good examples on our tour of the Kikuyu highlands.

Lundgren: The crop/commodity output should indeed be the main priority in agroforestry. Trees should ideally have the dual role of producing a commodity (rubber, nuts, fruits, fodder) and at the same time minimize losses through leaching and erosion. The Kikuyu highlands are an exception from many points of view. Both soil fertility and climate are favourable, also small farmers have been able to cultivate profitable cash crops in sufficient quantities.
LITERATURE CITED


STANDARDIZATION IN SOIL RESEARCH METHODOLOGIES AND STRATEGY IN AGROFORESTRY

H.O. Mengi, S.O. Keya and P.M. Ahn

ABSTRACT

To the extent that agroforestry is a new discipline, or at least a new emphasis, there are no long-accepted, agreed methodologies. The methods "agroforesters" can choose from one largely the existing ones of soil science, agriculture, and forestry. The main emphasis in soil sampling is on the bulk sampling of the 0-15 cm topsoil horizon in which changes can be expected to be more marked than in the lower soil horizons at times related to the sequence of operations such as fallow and cropping. Biological activity as an index is best measured in terms of CO2 production, though biomass changes, nitrogenase and dehydrogenase activity form other useful parameters. Methods of determining soil moisture characteristics are now fairly standardized, but infiltration rates and structural stability are determined by a range of methods with little standardization as yet. The measurement of bulk density changes is particularly useful. Analytical methods for soil chemistry and fertility are particularly varied. Soil organic matter levels are of practical importance, and are frequently determined by the well-known Walkley-Black method. Soil fertility evaluations and research approaches in agroforestry should be concerned with influences on the total available nutrient pool in the soil and in the biomass, and its movements and changes under different vegetation types, crops and cropping sequences. Soil survey and description methods are becoming more standardized, however, problems still arise due to the variety of soil classification systems extant and the difficulties in equating soil categories between systems applied particularly to taxonomic classifications. Comparisons are made between the French, Brazilian and FAO systems, and the USDA Soil Taxonomy system, as examples. Other, more practical systems of soil classification and capability are often very useful, supplementing the taxonomic classifications. Among these, it is necessary to select classifications which are not only standardized and widely used, but which stress soil properties relevant to agroforestry.

Agroforestry has come into prominence relatively recently, and therefore has no long-accepted methodologies. It is our purpose to discuss methodologies for it and to make recommendations. Nevertheless, it might be argued that agroforestry is not so much

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a new subject as a new emphasis: its methodologies are to some extent the existing ones of agriculture, of forestry and of soil science. To what extent are these existing methodologies varied, and to what extent do these differences make the interpretation and correlation of results difficult?

Soil scientists, among others, have long been aware that differences in sampling methods, analytical procedures, and soil classification have made the comparison and evaluation of work in different areas difficult. This paper considers a number of aspects of soils research, relevant to agroforestry, in which standardization problems occur. It discusses the progress made in moving toward commonly accepted methods, and draws attention to problems still remaining due to the continued use of different methods and classification systems, as well as suggesting ways in which research strategy in agroforestry might be coordinated.

SAMPLING PROBLEMS

Fundamental to all work on soil assessment is correct sampling. It has been said that the analysis is no better than the sample, meaning that if the sampling is done poorly it is little use analyzing that poor, unrepresentative sample with great accuracy.

In agroforestry work it is necessary to give particular attention both to accurate sampling and to the standardization of methods so that results are comparable. The soil must be sampled as well as the vegetation or crop. The latter samples may include determinations of total or above-ground biomass and the extent of the root system.

In soils work, we may distinguish between the sampling of a soil profile and the bulk sampling of a particular layer of a plot or field. Soil profile sampling, usually for pedological investigations and soil classification, involves the digging of a pit and the sampling of the soil according to its natural horizons. The pit represents the soil at the sampling point only. The pedologist refers to the soil pedon, the minimum soil area that appears to be uniform, and this can be as little as 1 - 10 square metres (Buol et al., 1973).

Bulk sampling is to be preferred for work involving soil monitoring, and for soil fertility assessments. It involves the
collection of a relatively large number of core samples taken to a carefully standardized depth and mixed together to give a sample representative of a plot or area in which soil type and history are fairly uniform. An analysis of individual cores before they are bulked can give additional information on soil heterogeneity and allows a more statistical evaluation of the results. A common error is to take too few cores. With an increasing number of core samples, the percentage error variance decreases with the factor \(1/\sqrt{n}\). With only four core samples it is 50%; with 15 core samples it is 26%; and with 40 core samples it is down to 16%, which is considered the practical lower limit since further increases in the number of subsamples will decrease the sample error only very slightly (Hauser, 1973).

Of particular importance to the standardization of soil sampling in agroforestry investigations is the depth of sampling. The effect of a particular treatment, such as a planted tree fallow, or of a particular tree species, is often more on the topsoil than on the lower horizons of the soil. Any changes that occur are more likely to be detected in the upper few centimetres of the soil than at depth. Recognition of this fact does not, in any way, minimize the importance of the lower soil horizons or of the movement of nutrient ions from these lower horizons to the topsoil via litter fall. Nutrient cycling of this type is one of the main benefits provided by trees in a mixed system or in a tree fallow. However, roots in the lower horizons are relatively sparsely distributed and feeding may be from localized sites (Lundgren, 1978). Changes in the lower horizons may be slight and difficult to detect, and a better approach is usually to concentrate on the net result of the translocations and other changes by monitoring changes in the agriculturally important topsoil. This horizon is also the most accessible: it would be more difficult to take bulk samples of a horizon two or three metres below the soil surface.

There would be a strong case for sampling a thin upper layer of the soil, such as 0 - 5 cm, based on the belief that soil changes are usually most marked and easily detected in that layer most affected by litter fall, the topsoil root mat, and biotic activity. However, in the interests of standardization and simplification, there is an even stronger case for recommending that the
main emphasis should be on the sampling of a thicker topsoil to a standard 0-15 cm. Much work has already been done and reported on this layer (and on the very similar 0-6 inch layer), and it is very difficult to compare results for layers of other thicknesses because of the often rapid change with depth in the upper part of the soil. It is suggested, therefore, that for routine work on chemical analyses, attention be concentrated on a standard 0-15 cm layer, supplemented, where required, by the additional sampling of the 15-30 cm layer. Other work, such as the taking of core samples for bulk density, can be carried out on subdivisions of these layers in such a way that results can be calculated for the same depths, e.g. three 5 cm layers can be summed to give information on the 0-15 cm layer.

Some degree of standardization and agreement is also desirable regarding the timing of sampling, i.e. when, and at what intervals, samples are best taken in order to monitor a changing situation. Most investigators would agree that, where natural vegetation or fallow is cleared prior to planting, an initial sampling is needed before clearing is done. Major soil changes may occur during clearing and burning, due to the effects of the heat of the burn and the production of ash. The ash acts as a dose of fertilizer and it may raise the soil pH markedly for some time, on some soil types. The second sampling, therefore, might usefully be performed immediately after clearing and burning or at planting time. In selecting sampling times after this, attention will have to be given to what soil changes are expected, and when. In an investigation on planted tree fallows, for example, further soil sampling would be indicated when cropping ceases and the fallow is planted. From then on, the fallow would be expected to bring about certain soil changes resulting in improved productivity. In monitoring these changes, subsequent sampling would be desirable at intervals, with an absolute minimum of sampling at the end of the fallow period when the fallow is cleared or coppiced.

Soil sampling for biological studies raises special problems. Such sampling must be done aseptically in order to avoid soil contamination by unwanted groups of microorganisms. This is important, because the organisms investigated must be present at the time the soil was sampled, and must not be aerial or laboratory invaders coming in afterwards. As a result, the air drying
of soil samples normally carried out for routine laboratory fertility determinations is usually avoided by microbiologists. Drying of the soil is, in any case, undesirable since it results in the death of many microorganisms. It is usually best to store the sample at the same moisture content it had on sampling.

SOIL BIOLOGY

Biological factors both influence and reflect soil fertility. Whereas the pedological features of a soil, however, may appear uniform over short vertical and horizontal distances, biological aspects are extremely heterogeneous both in time and space. This heterogeneity is due to the occurrence of microhabitats whose chemical, physical and nutritional conditions fluctuate greatly. Soil organisms also display marked differences in size and physiology. Special methods are necessary if they are to be observed and studied without disturbing their soil environment. It is often not possible to examine them alive.

The nutritional parameters are the most important of the environmental changes affecting microorganisms, and these cannot be studied directly. Laboratory media are not equivalent to what the soil furnishes. Problems of standardization in soil microbiology are related to the fact that experimental conditions are artificial, so that results obtained can have little more than a comparative value. In the laboratory, organisms are kept in what are judged to be optimum thermal, nutritional and environmental conditions, so that even non-sterile soil, in the laboratory, is not the same as in the field.

The isolation and enumeration of various groups of soil organisms is commonly reported. Very few of the existing methods are strictly ecological in the sense that the soil is studied in its natural state, so that most of the counts are based on laboratory methods. These methods vary from organism to organism, depending on the activity of the functional group studied. The value of a total microbial count is doubtful, because counts are affected by the season, the methods employed and the individual experimenter, and repeatability may thus be poor. The evaluation of the total microflora remains an unsatisfactory method with presently available techniques for judging the activity of a soil community.
Since total counts do not give us the information we need, emphasis is now more on measuring the activity of soil organisms as reflected in nitrification, carbon dioxide evolution, and nitrogen fixation.

The activity of the microbial population is best evaluated in terms of production of carbon dioxide, the end product of the process of oxidation of the carbon-containing substrate. The decomposition of soil organic matter and other carbonaceous materials added to the soil has been monitored mostly by looking at carbon dioxide production and/or oxygen consumption. If it is necessary to distinguish between carbon dioxide released from native soil organic matter and that released from added material, this can be done by using labelled carbon.

The mineralization of soil organic matter is principally a microbiological process, and the rate of mineralization and the amounts of N and other plant nutrients released are important in relation to agriculture and fertilizer use. Although mineralization rates must vary from soil to soil, it is thought that increased standardization of the methods used to determine mineralization rates would narrow down the presently reported range of 2-10% per annum.

The biological fixation of molecular nitrogen has received wide attention due to its importance to food production. There are at present at least 14 methods of measuring biological nitrogen fixation, of which three stand out: the old established Kjeldahl method of determining total nitrogen and the more recent methods using $^{15}$N and acetylene reduction.

In recent decades concern has been expressed regarding the use of pesticides, and their persistence, degradation and effects on microbiota. Although pesticides may be essential to maintain yields in agroforestry, their use raises issues relating to microbiological, ecological and environmental balances. Considerable study has been devoted to the effects of pesticides on microorganisms and microbial processes in the soil, but the results are sometimes difficult to compare and evaluate because of the range of methods used, and these, therefore, need to be standardized.

Soils usually possess a definite level of enzymatic activity. Soil urease, dehydrogenase and phosphatase are often measured as
parameters of biological activity. Skujins (1973), for example, found that dehydrogenase activity correlated with a number of other biological activities. The methods of estimation of enzymatic activities in soil must meet the general requirements placed on enzyme tests. Incubation time must be short, and microbial growth prevented. The extent of the enzyme reaction must be directly proportional to its concentration, and the reaction rate must be constant in time. The enzyme assay should not be influenced by soil properties such as sorption of the product or dispersion of clay during colorimetric determinations. The earlier methods did not always fulfill these requirements, but current techniques show improvements.

SOIL PHYSICS

The problems facing soil physicists who have sought to monitor and characterise soil physical properties in the field have included:

(a) difficulties in correlating laboratory measurements of such soil properties as structural stability and infiltration rates with field conditions and with the behaviour of soils when cultivated, and

(b) the very great variations over short distances often encountered when soil properties such as infiltration rates are measured in the field, so that a large number of determinations may be needed to obtain an acceptable average. As a result, it is generally agreed that the monitoring of soil physical changes, during cropping or fallow periods for example, is relatively difficult.

SOIL MOISTURE RETENTION AND AVAILABLE WATER

The amount of water held by a soil at a given tension is related to the amount of colloids in the soil and their type, and to the capillary porosity. It is now standard practice to determine water contents at 1/3 and at 15 atmospheres and to equate these with moisture held at field capacity and at wilting point, respectively, and to consider that the difference between the two amounts represents the water available to plants. These are convenient assumptions, but we know that the water held at field capacity, i.e. the water left when the surplus, gravitational water has
drained downwards, may be more than that held at a tension of 1/3 atmosphere.

In some highly-weathered tropical soils, the microaggregation of the clay fraction to silt and the presence of sand-sized microaggregates (Ahn, in press) improves the drainage but lowers the amount of available water held, and results in the fact that the water held at field capacity is more like that held at 1/10 or 1/20 of an atmosphere than that held at 1/3 atmosphere (Wolf, 1975; Sharma and Uehara, 1965; Maclean and Yager, 1972). This is because a well-aggregated clay oxidic soil behaves somewhat like a sand, draining its macropores at about 0.1 bar, and thus reaching field capacity at a lower tension than it would have done if not so well aggregated. Similarly, the water still left in the soil when plants wilt may be less than that held at 15 bars if the plants concerned can exert greater suctions than normal, as may be the case with many savanna plants with deep root systems which can exert greater suctions than the sunflower plants originally used to determine "wilting point". Thus, in many tropical situations, available water may be more than that held between 1/3 and 15 atmospheres. Nevertheless, the standard adoption of this convention and of standardized pressure-plate and pressure-pot techniques for determining water held at different tensions is very useful for comparative purposes.

In some agroforestry situations, it might be important to monitor changes in the available water storage capacity of a soil. These changes might be due to: (a) changes in the capillary porosity of the soil and/or (b) changes in the type and amount of colloids, including increases or decreases in organic matter content. These two aspects may be closely related, since porosity is related to soil structure, and structure is related to organic matter contents, particularly in the topsoil, and to the amount and nature of the clay minerals.

SOIL INFILTRATION RATES

A number of methods are in use for measuring soil infiltration rates, of which the most popular is probably the double ring infiltrometer, in which water infiltrating from the outer ring is relied on to minimize or eliminate any lateral movement of water from the inner ring, so that only the downward infiltration
rate from the inner ring is being measured. Initial rates may be high, followed by a rapid fall, so that accurate timing is needed at the beginning. The major difficulty encountered is that referred to above, namely that readings may vary widely between points in the same plot or area. This variation is due to the natural heterogeneity of the soil. One would hardly put the infiltrometer in position over a rat hole or a termite mound, but even if obviously unsuitable spots are avoided, it is not easy to avoid cracks and smaller holes which may give rise to large infiltration rate differences. Small undisturbed core samples can be taken to the laboratory for infiltration and other tests (Pereira, 1956), but it is difficult to correlate such laboratory tests with what happens under natural conditions. Rainfall simulators used in the field may indicate how an area of soil actually behaves when rainfall of a known intensity and amount is applied under standard conditions, but such apparatus, and the water it uses, may raise transportation problems (Barber et al., in press). Rainfall simulators are available at present in a number of types, and are far from standardized.

SOIL POROSITY AND AERATION

Changes in soil structure and porosity are particularly useful parameters in relation to the effects of particular crops or agricultural practices such as tree fallows and grass leys. Changes in soil structure may be difficult to monitor directly, but an indication of the effects of such changes on total porosity can be obtained by determining the bulk density of the soil. This can be done fairly reliably with a core sampler, dividing the soil volume by its weight, and, if undisturbed core samples are taken, these can, in combination with moisture determinations, give an indication of capillary and non-capillary porosity. Another method of determining bulk density is to coat individual clods with a water-repellant layer (such as the plastic, Saran), weighing them and determining their volume by immersing them in water. Both methods require careful sampling if the samples are to be representative, and soil heterogeneity would require conclusions to be based on a relatively large number of samples. Alternatively, a relatively large but known volume of soil can be carefully removed from, for example, a square metre dug to
standard, carefully-measured depth, and then simply weighed. Since total porosity can be easily calculated from bulk density if the specific gravity of soil particles is known or assumed, and bulk density and porosity reflect the effects of other important soil properties such as structure, which are more difficult to monitor directly, bulk density determinations are particularly useful: they should be carried out even if no other physical determinations are included in the soil monitoring activities.

SOIL TEXTURE

Although the term "soil texture" implies the "feel" of the soil, and is related to consistency and handling properties, soil texture now refers simply to the relative percentages of sand, silt and clay in the fine earth fraction of the soil. Changes in soil texture can occur through migration of clay or other particles either down the profile, from A to B, for example, or laterally downslope. These are often thought of as being relatively slow processes, but they may be speeded up by cultivation. Apparent changes in the texture of the upper soil horizon may occur due to erosion, topsoil removal and profile truncation, exposing material of a different texture at the surface.

Methods of determining texture are usually based on one of two methods, the pipette and the hydrometer. The former is more accurate, the latter easier and quicker, but both methods are accurate enough to be comparable. Difficulties arise mainly with the prior dispersion of the soil. Dispersion of some tropical soils high in iron and aluminium oxides is sometimes relatively difficult, and many early analyses underestimated clay content due to incomplete soil dispersion. Nowadays these problems are widely recognized, and a combination of a chemical dispersing agent (usually sodium hexametaphosphate, often with some sodium carbonate) with mechanical shaking or stirring is generally adequate. Dispersion can be tested by ascertaining if the clay content is increased by removing iron and aluminium oxides, and a rough check can be made by comparing the clay content with the water held at wilting point.

The classification of the soil into textural classes (clay, clay loam, etc.) is done in different ways in different areas.
The widely used USDA textural classification, which appears in many textbooks written in English, divides soils into 12 textural classes based on the relative proportions of clay (less than 2 microns), of silt (2-50 µ). Differences between this system and other systems of textural classification, such as that used in francophone areas, are due to (a) different definitions of the silt and sand fractions and (b) the use of a different total number of textural classes and/or of classes with different limits. In the French system, for example, there is the heavy clay class (*argile lourde*), with over 60% clay, whereas in the USDA system there is no subdivision of soils with over 40% clay based on clay content. Even when comparing soils for which actual sand, silt and clay percentages are given, the definitions of the silt and sand fractions should be checked.

**STRUCTURAL STABILITY**

In agroforestry, interest often centres not only on soil structure but also its stability, *i.e.* its persistence as a soil is cultivated or used in other ways. Structural stability has long attracted the attention of soil physicists, but all structural stability determinations are empirical, and a wide variety of methods have been employed, so that this is an area of investigation where standardization is particularly needed. Some workers have been concerned with all aggregates above sand size, others with various larger aggregates, while the work in francophone West Africa by Dabin (1970), using the methods of Henin (*Henin et al.*, 1958) is based on aggregates over 200 µ in diameter that survive a standard number of rotations of the sieve in water.

Some workers have stressed the practical importance in many tropical soils, particularly the more highly weathered ones, of stable microaggregates of silt- and sand-sized dimensions. One method of assessing water stable microaggregation that gives reproducible results is to carry out two parallel sets of mechanical analyses, with and without a dispersing agent (Ahn, 1968). Microaggregation to silt- and sand-sized aggregates alters the apparent texture of the soil and effects its handling qualities and water relationships. It accounts for the fact that many clay soils feel and handle like loams. The very productive Kikuyu friable clays in the highlands of Kenya form a good
example of a soil whose excellent physical properties are associated with a high degree of microaggregation (Ahn, in press).

SOIL CHEMISTRY

Because of limited resources, it is sometimes necessary to confine analytical work on soils to those elements suspected to be in short supply, so that, to some extent, the chemical properties to be determined will vary according to the nature of the problems met or suspected in the field.

PHOSPHORUS

Phosphorus is thought to be a very widespread limiting nutrient in the tropics. Most high-base status soils of the Oxisol, Andept, Ultisol and Vertisol orders of the Soil Taxonomy (USDA, 1975) are thought to be deficient in phosphorus (Sanchez, 1976). High-base status soils are generally rich in calcium phosphates, while the Andepts, in particular, are rich in calcium, aluminium and organic phosphates. In low-base status soils, phosphates generally form compounds with iron and aluminium. In Oxisols, a good proportion of the phosphorus may be organic.

Phosphorus testing of soils for agroforestry should include the determination of (a) organic phosphorus, and (b) "available" or extractable phosphorus. The latter should be determined by the Bray I, dilute acid-fluoride method (Bray and Kurtz, 1945) for soils high in calcium phosphates (generally those with a pH above 6.0), while for those soils high in iron and aluminium phosphates (generally below pH 6.0) the North Carolina method using dilute HCl and H₂SO₄ is preferable (Nelson et al., 1953). These methods have been widely used in the tropics, especially in South America, and have given reasonably good correlations with plant response in many instances. Other researchers, however, have advocated the use of the Olsen sodium bicarbonate method for both high and low pH soils, claiming that it gives a good indication of likely responses to phosphorus for a wide range of soils.

NITROGEN

Determinations of soil nitrogen should normally be confined to total nitrogen, and to inorganic, mineralized N (i.e. the sum
of NO$_2^-$, NO$_3^-$, and NH$_4^-$N). The total amount of inorganic nitrogen in the soil at any one time is usually very small, and the amounts may fluctuate in short periods of time. These changes can be grouped into those that are: (a) due to seasonal changes, such as the upward movement of NO$_3^-$ in the dry season, and downward in the wet (Greenland, 1958; Birch, 1960; Semb and Robinson, 1969; Wild, 1972; Hardy, 1946); (b) due to mineralization flushes which occur when a dry soil is wetted (Birch, 1960; Semb and Robinson, 1969), and (c) due to other causes such as volatilization, "fixation", crop removal, run-off and leaching (Hardy, 1946; Wild, 1972; Singh and Kanehiro, 1969; Kinjo and Pratt, 1971; Mongi, 1974; Mongi et al., 1974; Greenland, 1958; and Terry and McCants, 1970).

Although it may be of some value to monitor short-term inorganic nitrogen changes, because of the limitations of resources referred to above, it may in practice be necessary to concentrate on determining total and mineralized, inorganic nitrogen at the beginning and end of set periods in a cycle, e.g. at the beginning and the end of a fallow or a cropping season.

Total nitrogen is normally determined by some type of Kjeldahl digestion, of which the modified regular macro-Kjeldahl method described by Bremner (1965) is to be recommended. This modification removes most of the nitrite and nitrate-N without prolonging the digestion period. Total mineralized N can be determined by the simple steam distillation method of Keeney and Bremner (Bremner, 1965).

**EXCHANGEABLE CATIONS**

The determination of the exchangeable cations in the soil, particularly of Ca, Mg and K, is needed in order: (i) to assess the availability of these nutritional elements to plants, (ii) to study the balance between different cations, and (iii) to calculate the percentage base saturation of the soil (TEB/CEC).

Although plants can obtain potassium from forms additional to the exchangeable potassium, the latter is nevertheless considered to give, for practical purposes, a good index of K availability to plants (Doll and Lucas, 1973; Pratt, 1965). The determination of exchangeable Ca, Mg and K can routinely be made
by extracting with 1 N \( \text{NH}_4 \text{Ac} \), and then determining K by flame photometry (Pratt, 1965) and Ca and Mg by atomic absorption spectrophotometry (Heald, 1965).

**EXCHANGEABLE ALUMINIUM**

The determination of 1 N KCl-extractable aluminium (McLean, 1965) gives a good measure of exchangeable aluminium, as well as of the acidity that needs to be reduced by liming and/or the application of organic manures (Kamprath, 1970). The relationships between soil pH, CEC and nutrient balances in highly-weathered tropical soils are complex. They have been studied in relation to crop production by numerous investigators (McLean, 1971; 1972; Kamprath, 1971; Kinjo and Pratt, 1971; Mongi, 1974; van Wambeke, 1974). These studies suggest that liming should be in relation to the effective CEC on the basis of 1 N KCl-extractable aluminium, but more work is needed in different situations, to elucidate the factors involved and to provide a basis for soil management advice.

**ORGANIC MATTER**

The soil organic matter is extremely important in relation to the properties and value of tropical soils due to its great effect on the improvement of the physical, chemical and biological properties of the soil (Black, 1968; Sanchez, 1976; Greenland, 1977). Organic matter is important in increasing the fertility and productivity of tropical soils of low base status and CEC in particular, so that some investigators take the view that in the case of highly-weathered tropical soils the management of soil organic matter is almost synonymous with the management of CEC (Sanchez, 1976, p. 155). Decreases in organic matter in such soils may lead to marked reductions in CEC (Brams, 1971). The progressive and often drastic decrease in the yield of crops following forest clearing on highly-weathered soils has been associated with, and related to, a corresponding decrease in soil organic matter (Lundgren and Lundgren, 1972; Nye and Greenland, 1960; Brinkman and Bascimento, 1973). The importance of organic matter in "no-fertilizer" agriculture has been well presented by Greenland and Dart (1972).

The determination of soil organic matter is normally carried out by determining organic carbon and then multiplying by a
factor based on the assumed average carbon content of soil organic matter. Organic carbon determination is satisfactorily carried out by the widely-used modified Walkley-Black wet-combustion method in which easily oxidized carbon is oxidized with potassium dichromate in the presence of sulphuric acid (Walkley, 1946). The usual conversion factor of 1.724 assumes that organic matter contains 58% carbon. This factor was found to be low for some temperate soils (Broadbent, 1965) and may require verification for tropical soils in different situations, but nevertheless this simple, standardized and well-known method has gained very general acceptance and allows soils to be compared with reasonable confidence. In conjunction with a Kjeldahl determination of total nitrogen, the organic carbon determination is used for calculating the C/N ratio of the soil organic matter, a useful parameter for comparing its approximate composition.

SOIL FERTILITY EVALUATION

The important question of soil fertility evaluation is discussed in more detail in other papers (Singh, 1979; Kamprath, 1979; Fried and Mistry, 1979). A wide range of methods is available for diagnosing soil fertility and soil nutritional problems, but in the tropics they have been applied systematically only in a few areas. Soil fertility evaluations have been carried out on a fair scale in Latin America (Sanchez, 1976), but less experience has been gained in Asia and in Africa where "no-fertilizer" agricultural production systems are still very widespread. No soil fertility evaluation system valid for multiple cropping systems has yet been developed that has gained wide acceptance. Such a tool would certainly be of value to agronomists in developing and adapting such systems.

Research strategy in agroforestry (King and Chandler, 1978) must take into account the fact that in multiple cropping systems the relationship between crops may be competitive, non-competitive or synergistic (Trenbath, 1974; Hall, 1974a; 1974b) and that in agroforestry the aim is: (i) to exploit the non-competitive and synergistic aspects of this relationship and (ii) to minimize the competitive aspects with special reference to the soil and other factors that contribute to or influence it. Soil fertility evaluation in relation to agroforestry should thus examine both
the influence of various crop mixtures on the soil and the influence of soil characteristics on the first and subsequent crops or crop mixtures in relation to various population densities and management practices.

Under intercropping conditions, the total nutrient requirements will not necessarily be the sum of the individual crop needs when grown separately. Allelopathy (the effect of root exudates) may complicate the interpretation of nutritional effects (Evenari, 1959; Tukey, 1969), and competition for light may adversely affect nutrient uptake by individual plants. The influence of individual crops on the soil and on the ambient microclimate will also influence the availability of soil nutrients. Crop species and crop varieties differ in their ability to extract the less easily available nutrients, e.g. "fixed" forms of K and P, and the nutrient element needs of plants grown in various combinations and spacings may differ from the pattern under monoculture. These are some of the considerations relevant to soil fertility investigations in relation to agroforestry.

Biomass studies, including the determination of C:N, C:N:P and C:N:P:S ratios and total content of major and minor elements in the biomass or subdivisions of it, would help to elucidate the potential contribution of a particular crop, tree or plant association to the soil. In more detailed studies, which might be excluded by the resource considerations referred to at the beginning of the section on Soil Chemistry, above, an investigation might include an attempt to quantify the potential transfer from the vegetation to the soil in the various forms of litter fall, prunings or lopped material, timber fall, root decomposition and rainwash, taking account of losses from the system in the harvested material. Such an investigation would have to be repeated at intervals at appropriate points in the cycle.

Under a well-established tropical forest, nutrients circulate in an almost closed cycle between soil and vegetation. Losses from such a system might be very slight and might be balanced by additions from the atmosphere and from the deeper soil layers. The total nutrient pool circulating between soil and vegetation might thus be built up over a period (Nye and Greenland, 1960). Nutrient losses might be considerable
however during the initial clearing, or clearing and burning, prior to the establishment of an agroforestry system (Saubert, 1975). Once the system was established, an estimation of continuing losses due to crop removal, leaching, run-off, erosion, volatilization and denitrification would assist the study of management systems and their long-term viability. The root distribution patterns of both the annual crop and tree components of the system, and of a tree fallow, if employed, would be relevant to the study of nutrient movements from various soil layers. Although there has been some study of root systems in the tropics (e.g. Lundgren, 1978), far more fundamental basic information on root systems and how they vary in different soils and in different competitive situations is needed.

SOIL SURVEY AND CLASSIFICATION

The methods of soil survey appropriate in any particular situation depend largely on the scale of the map produced and on local conditions. From the point of view of correlation, the exact nature of the field methods employed is relatively unimportant, provided that the soils are: (a) described according to accepted norms, and (b) classified according to a widely accepted system, and sufficient basic information is given to enable the soils to be classified according to other systems if required.

In general, methods of soil description are now fairly standardized, but several prominent systems of classification are used in different areas, and it is not always easy to equate one with the other.

SOIL DESCRIPTION

It is now widely accepted that a standard format for describing a soil sample or soil horizon should deal with colour (as defined with a colour chart; and including the colour of any mottles present), texture, structure (type, size and grade), consistency (usually for the moist soil, but also for wet and dry soils when there are marked consistency differences in these states), content of coarse material and presence of cutans, porosity, roots, pH, and the nature of the horizon boundary, often in that order. Information on the site is normally also
given (location, elevation, landform, gradient, vegetation, land-use and climate), as well as an indication of the soil parent material. Standardized methods of soil description are usefully presented in a booklet issued in English, French and Spanish by FAO, the English version of which is entitled "Guidelines for Soil Description".

There should be no difficulty describing soils in a uniform way so that two people describing the same profile independently should arrive at virtually the same description. The main difficulty encountered when reading many papers and reports on agronomy and soil fertility is simply that the description and classification of the soil are given inadequate attention or may be lacking.

SOIL CLASSIFICATION

Soils are classified for various reasons, and a range of different types of soil classification, some complex and some simple, are available to meet this range of requirements.

A distinction can be made between simple, practical classifications, sometimes assessing the suitability of soils for a specific crop, or for a specific type of agriculture (such as irrigation), and more fundamental taxonomic classifications. The latter seek to include all the world's soils, putting each into its appropriate place in the system, and these fundamental taxonomic systems can be compared in some respects to those used by botanists and zoologists to classify plants and animals. Such soil systems usually emphasize soil genesis, or at least those soil properties held to reflect genesis, and it is important to remember that they often do not, therefore, emphasize those particular properties that may be particularly relevant to the productivity or agricultural vocation of the soil.

Taxonomic soil classifications differ in their arrangement (number and types of categories and subcategories) and in the criteria emphasized when dividing soils at any particular level. As a result, it is often difficult to equate a subdivision in one system with the appropriate subdivision in another system. Soil correlation work in the tropics has been made difficult for this reason. During the 1950's, for example, soil correlators
in Africa had to contend with the fact that different classifications were in use in East Africa, South Africa, the English-speaking West African territories, Francophone West Africa, the then Belgian Congo, the Portuguese-speaking territories, and North Africa. The first attempt to correlate these diverse systems and to produce a soil map of Africa with a common legend was that of a Belgian pedologist working for the SPI (Service Pedologique Interafricain), Jules d'Hoore, who produced a soil map of Africa on the 1:5 000 000 scale with an explanatory monograph in 1964. D'Hoore evolved his own legend, which was his personal synthesis of the other systems, and his system was then adopted and used in Nigeria and elsewhere, thus actually increasing the number of different classifications used by different adherents, though nevertheless providing a very useful common denominator for all of them. D'Hoore's work and the map he made drew attention to correlation problems and stimulated discussion regarding differences in approach.

A much greater stimulus to discussion and work on the classification of tropical soils was provided by the publication of the USDA "Seventh Approximation" in 1960 and of the supplement to it in 1967, works that eventually resulted in the publication of the USDA Soil Taxonomy (USDA, 1975), which is the most complex and detailed world soil classification system yet to appear. Although it has not been accepted by scientists — in some parts of the world in particular — as their preferred system of classification, and has been much criticized, it is nevertheless becoming increasingly well known to soil scientists. As a result, though many soil reports may classify soils according to another system, they now also include a classification according to Soil Taxonomy.

A number of attempts have been made to correlate the categories of different taxonomic systems. A recent paper (Beinroth, 1975) on the relationship between the Brazilian Soil Classification System, the U.S. Soil Taxonomy and the FAO/UNESCO soil map of the world mapping units concluded that these three systems, the most extensively used in tropical America, differ in structural organization, precision of definition and number of taxa, choice of differentiating criteria and nomenclature. The result of
this comparative study was that unequivocal correlation of the
three schemes cannot be achieved with accuracy in many cases,
and that only approximate equivalents of higher category classes
can be established (Table 1). Of the three systems, the preci-
sion of definition of lower categories was highest in Soil
Taxonomy, and such detail, it was maintained, is indispensable
if taxa are to be established that are sufficiently specific to
be useful for the transfer of agricultural experience.

While many other users of the Soil Taxonomy system might
agree with Beinroth that precise and detailed definitions of
lower classification units are essential to enable practical
agricultural experience to be applied to similar soils elsewhere,
they might nevertheless argue that the distinguishing criteria
applied at various levels in Soil Taxonomy are often more oriented
to soil genesis than to soil characteristics of relevance to
practical agriculture. They might suggest that, if a classifi-
cation scheme were to be drawn up with the latter in mind, some-
what different criteria might be emphasized. What, for example,
is the practical significance to the cultivator of a distinction
between more than or less than 1% of clay skins in the B horizon?

In Francophone West Africa, soils are classified and mapped
according to the French classification system of Aubert (Aubert,
1965 and 1968). A 1:5 000 000 map of West Africa showing soils
mapped according to this system was published in 1971 by the OAU
in their West African Atlas (Atlas de l'Ouest Africaine). This
map is on the same scale as the FAO soil map of the same area,
and a direct comparison can therefore be made between the two
maps and classification systems as applied to West African soils.
Making this comparison, Ahn (1977) found that the 10 orders of
the French classification system could each be equated with 1-6
of the 26 major FAO mapping units. Conversely, the FAO mapping
units were sometimes mapped as the equivalent of up to four
French soil orders, suggesting considerable divergence between
the two systems. Ahn's findings are summarised in a cross key
between the two systems in Table 2.

The FAO/UNESCO soil map of the world deserves special mention
since it has now provided, in a number of map sheets supported
by explanatory monographs, a soil map at the 1:5 000 000 scale
Table 1: Approximate correlation of taxa of the highest category of the US Soil Taxonomy, the Brazilian classification system and the FAO/UNESCO soil map legend (Beinroth, 1975)

<table>
<thead>
<tr>
<th>U.S. Soil Taxonomy (USDA, 1975)</th>
<th>FAO/UNESCO Soil Units (predominant Units are italicized)</th>
<th>Brazilian classification (Bennema, 1966)</th>
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<tr>
<td>Alfisols</td>
<td>Luvisols, Planosols, Nitosols, Podzoluvisols, Solonetz</td>
<td>Non-Hydomorphic Soils with Textural B Horizons, CEC&gt;24 meq/100 g, base saturation &gt;35% (class III) Soils with a Hardpan (Class VI) Hydromorphic Soils (Class XII)</td>
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<td>Arídisols</td>
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<td>Soils with Solonetzić B Horizons (Class IV) Soils with a Hardpan (Class VI)</td>
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<td>Fluvisols, Lithosols, Regosols, Gleysols, Arenosols</td>
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<td>Non-Hydomorphic Soils with Incipient B Horizons (Class V) Hydromorphic Soils (Class XII)</td>
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<td>Mollisols</td>
<td>Chernozems, Phaeozems, Kastanozems, Greyzems, Haplustels, Gleysols, Planosols, Solonchaks, Solonetz</td>
<td>Non-Hydomorphic Soils with Textural B Horizons, CEC&gt;24 meq/100 g, base saturation &gt;35% (Class III) Hydromorphic Soils (Class XII)</td>
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<td>Oxisols</td>
<td>Ferralsols, Gleysols</td>
<td>Soils with Latosolic B Horizons (Class I) Hydromorphic Soils (Class XII)</td>
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<td>Vertisols</td>
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Table 2: Cross key, showing the correlation between the French soil orders and the major FAO soil mapping units in the West Africa Sahel and savanna zones (Ahn, 1977)

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covering the whole world—a major achievement. The FAO/UNESCO system is not a classification system as such, but simply a legend to the soil map that divides all the world’s soils into 104 units without further subdivisions. The aim and great merit of the FAO/UNESCO system is that, like the earlier work of d’Hoore in Africa, it synthesizes other systems and indicates, at the level of detail dictated by the scale of the map, those areas of the world where soils are comparable. It is considered by users to be a relatively practical system, easier to understand than some more complex systems, and local users are always free to make subdivisions of the 104 units mapped at the 1:5 000 000 scale for work on larger scales. The system has been adopted by the Tanzania National Soil Service and the Kenya Soil Survey.

It is suggested that where soils are classified in agroforestry investigations, they should be classified in both the FAO/UNESCO system and according to the U.S. Soil Taxonomy, as well as in the local system of soil classification where this differs from these two. This will enable the soils to be correlated according to these systems with similar soils in other parts of the world. At the same time it should be realized that these classifications might not, of themselves, give the user much information on the agricultural value of the soil. For this, other more practical systems of assessing soil capability might be used in addition, supplementing the taxonomic ones. In adapting a widely-used soil capability classification such as the U.S. land capability classification, which puts land into eight classes according to an increasing degree of limitation, particular stress might be laid on properties relevant to agroforestry, such as pH, depth, content of organic matter, content of weatherable minerals, CEC and percentage saturation, texture, aeration, permeability, drainage and other factors.

One might summarize these remarks on soil classification systems in relation to agroforestry by stressing:

(a) that taxonomic soil classifications divide soils mainly according to criteria thought to relate to mode of formation, and distinctions may not be particularly relevant to the practical value of the soil in relation to agroforestry and other uses of it;
(b) that it is frequently impossible to equate the classification given to a soil in one system with an exact category in another system: the soil has to be classified afresh in the second system, and this can only be done if sufficient basic data on the soil, local climate, etc., are given; and

(c) that for practical agroforestry purposes it is usually desirable to assess the soil further by classifying it according to criteria selected for their relevance to plant growth rather than soil genesis, and there is considerable scope and need for standardizing such a practical capability classification for agroforestry work.

DISCUSSION

Nyandat: There are two considerations. One is a soil map and the other is an interpretative map for agroforestry. The former is essentially for communication and all that is required is to follow with analyses for soil. ICRAF can have a vital role to play with regard to the development of interpretative maps for agroforestry. There is need to work for a framework document for interpreting soils for agroforestry. But I must stress that this will only be a broad framework outlining the important parameters to be taken into consideration. Interpretative maps cannot be standardized over a wide area as some parameters will be relevant to some areas and not to others. Interpretation must be localized although fitted within an overall framework.

Ahn: Agreed. A technical practical classification stressing soil aspects of relevance to agroforestry would be helpful in deriving the interpretative map from the basic soil map.

Huxley: The new FAO publication defining agro-ecological systems may also be useful for defining areas of similar potential for the production of particular crops.

Ahn: The FAO study seeks first to define the climatic needs of a range of important crops (making important assumptions that must be kept in mind and may not apply in specific areas) and then, in a very broad way, whether the 104 mapping units shown in the FAO 1:5 million World Soil Map
are "suitable", "marginally suitable" or "unsuitable". The exercise runs into the basic problem of using a taxonomic soil classification in order to assess agricultural suitability and, obviously, this is a rather "coarse-mesh" and, hence, approximate approach. I think the FAO study is a very useful initial attempt to quantify and define the soil-climate requirements of specific crops, but the problem is not static: breeding is constantly enlarging the areas that can be profitably used by specific crop varieties, for example.

Goosen: The structure of a soil map should be based on landscape properties (micro-relief, meso-relief). The taxonomic classification system classifies internal properties of soil profiles. Small changes in topography affect hydrology (ground water movement, etc.) important for plant growth within short distances, as in agroforestry systems.

Sánchez: It is necessary to emphasize the need for natural and technical soil classification systems. Soil taxonomy is probably the best natural system because it is the most quantitative. If possible a technical classification system could be based on Buol's Soil Fertility Capability Classification and expanded to include properties more relevant to geography. The USDA land-use capability system is of very limited value in the tropics.

Ahn: I fully support these views. A soil fertility classification system suitable for agroforestry is needed and if such a classification were to receive just a fraction of the international attention given to the taxonomic systems so far, it should become a practical tool quite quickly. The USDA Land Capability Classification system is essentially negative since it emphasizes limitations and it does not emphasize positive qualities sufficiently. Our experience is that it has to be drastically adapted to be useful in a context outside of that in which it was developed. In "no-fertilizer" agriculture in the tropics, for example, inherent soil fertility is still very important, whereas in the USDA capability classification it is taken into consideration only where it is so low that it is a "limiting factor". Many steep lands in the tropics are highly prized because nutrients are being liberated within the crop root depth. Soil capability classification must be adapted to ecological areas and to different land-use systems and economic frameworks.

Pratt: Several studies at various levels in California have shown us that the only way really to know how to sample is to take some samples with each core or keep sub-samples separate, so that each can be analyzed separately. Statistical analyses of the data can then tell us how to sample the area or plot.

Ahn: I agree that it is very useful to look at the cores before they are bulked both in order to decide how many cores are needed to achieve a desired level of accuracy and to serve as a measure of "soil heterogeneity". The important point, though, is that soil heterogeneity varies according to the particular property looked at, so that the number of samples needed would also depend to some extent on why you were sampling and which soil properties you were looking at.

Keya: The Australian approach where the land system is used is probably a better approach which has successfully been applied in tropical America.

Goosen: The land system approach of CSIRO Australia is indeed a very useful one. CSIRO has done some pioneering work, and many soil survey groups in The Netherlands are using a soil map-unit classification similar to the land system approach.
In the tropics a useful concept in both soil mapping and in the development of viable production systems is the soil catena. A catena is a fairly regular sequence of soils related to relief, often forming a pattern repeated over well-defined areas. Rational land-use recommendations should consider the whole catena, not just single soils within it. Different soils in the catena might best be used in quite different ways depending on different physical and chemical properties, broadly related to differences in drainage.

The methods for the investigation of root system development have not been discussed.

Root system studies, in general, have been neglected because of the labour and difficulties involved. The total mass per defined layer is not enough; roots should at least be divided into diameter classes even if actual lengths are not worked out (as by the method suggested in Rosemary Bradley's paper). We are interested in the extent of the system and its activity, and changes of these in time. The latter aspect is particularly difficult.

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SOIL RESEARCH IN AGROFORESTRY

P.F. Pratt*

ABSTRACT

The International Council for Research in Agroforestry (ICRAF) has opportunities to provide an alternative to standard agronomic cropping and to shifting cultivation in the development of forested areas and savannas, and to provide improved production systems for arid and mountainous areas of the tropics. As a mission-oriented entity, ICRAF should focus on strategic research and the development of a training programme for personnel who will do the needed tactical and operational research at the local level. Along with research and training programmes, ICRAF should develop an information accumulation and dissemination programme. The author's top priority for soil research within ICRAF is to develop systems of production that will restore and protect the physical nature of the soil.

Within the total research programme of the International Council for Research in Agroforestry (ICRAF), soil studies must be one of the central themes. The soil is the natural resource that can be most difficult to restore or improve once it has been damaged by mismanagement or, in the extreme, once it has been removed by erosion, leaving an unproductive landscape of bedrock or raw soil materials. King and Chandler (1978) broadly described the research programmes of ICRAF as consisting of: (1) the investigation of agroforestry methods on which to base improved farming systems to replace shifting cultivation in the tropics, (2) the development of agroforestry pastoral and cropping systems for the prevention of desertification and the rehabilitation of arid and semi-arid ecosystems, (3) the application of agroforestry systems to the maintenance and improvement of the quality of tropical pasture land, and (4) the investigation of agroforestry systems for rehabilitating vegetative cover to ameliorate and upgrade degraded land in mountain ecosystems. Soil studies have an important place in each of these programmes. In fact, King and Chandler list soil studies as one of the core activities that applies to each of the proposed programmes.

PROBLEM-SOLVING RESEARCH

The objectives and programmes of ICRAF imply that the land will

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be managed to produce food, fibre and fuel for the benefit of people and to restore and/or conserve the soil resource so it will produce for future generations. In this context, the research to be done must consider soils, plants, plant protection, economics, and social systems. To be effective, this research must focus on solutions to problems. Because solutions usually involve several aspects of the whole system, the research must be multidisciplinary. The need for inputs from a number of disciplines, e.g., soil science, plant science, entomology, forestry, horticulture and economics, demands either a team consisting of several researchers from different disciplines or a generalist who has sufficient command of a sufficient number of disciplines to solve the problem. The generalist has a place and a role to play in directing and implementing phases of the ICRAF programmes. However, in this day of specialization, the reasonable approach for problem-solving research is to assemble a team of specialists covering the complete set of required specialties.

The education and training of research scientists must necessarily produce specialists. To obtain a research degree in one specialty, to gain sufficient knowledge and experience in one specialty, and to qualify as a researcher in that specialty by the time a person is in his late twenties or early thirties, requires all his time and effort. During the period of education and training, attempts can and should be made to give the young scientist a broad view of other disciplines, but there is not sufficient time to produce a young generalist with in-depth knowledge of a number of specialties. Thus, the generalist must be produced from the specialist and the problem-solving research team must be created from specialists.

Problem-solving research can be demanding, exciting and rewarding. But before a scientist can successfully pursue it, he must be weaned away from his discipline or specialty so that he is willing to delve into other disciplines or to cooperate with people from other disciplines. On the other hand, problem-solving research sometimes requires the development of fundamental or basic information that is at the forefront of a specialty or discipline. The main point is that problem-solving research focuses first on the problem and then looks for the solution, which might be found in application of existing knowledge, in knowledge that must be developed, or in concepts or relationships yet unknown.
MULTIDISCIPLINARY RESEARCH

Multidisciplinary research occurs when several people of differing disciplinary backgrounds jointly plan and accomplish research. With this definition, any individual may do his thing as a disciplinarian, in his own way, independently from his colleagues if the research is jointly planned and his thing contributes to the success of the project. In the Department of Soil and Environmental Sciences at the University of California, Riverside, a good example was provided by a team, consisting of a soil physicist, a soil chemist, a soil morphologist, and a soil microbiologist, that developed a successful method for the direct measurement of denitrification in the field (Ryden et al., 1979).

When the author became chairman of a university department in 1965, Dean A.M. Boyce's advice on cooperative projects was that: (1) an administrator cannot force multidisciplinary research, (2) the best he can do is to get people together to talk with the hope that cooperative projects will develop, and (3) the administrator can develop and manipulate resources so that multidisciplinary research is encouraged. In the author's experience, the key is to get resources allocated to a problem-solving mission and then invite people to join in planning and conducting the needed research.

To get successful multidisciplinary research, the members of the team need to understand each other and the basic nature of the problem, the objectives and the approach. This understanding will insure that each member knows how his part fits into the whole, will give him a feeling that he has something to contribute and will prevent him from wasting time on unproductive sidelines. In the development of understanding, there is no substitute for time spent in verbal communications and lively discussions. The worst thing than can happen in a group is that the members are so polite to each other that there is little or no challenge. This does not suggest that the members must be mean or abrasive but that they must challenge each other to communicate well and explain ideas in language understandable to others of different disciplines. One has to be able to say "I don't understand. Please explain in simpler language," and to accept and respond to the same words from others.
The wider the spread of disciplines in a group, the more time should be used to develop the understanding needed to plan and coordinate research. With soil scientists of various kinds, the team may already have a basic core of understanding common to all members and thus require a minimum of time. But if economists, hydrologists, engineers, and crop and soil scientists are involved, the required time might be an order of magnitude greater. An example is provided by a group of 18 people who accepted the task of making a nitrogen balance of the Upper Santa Ana River Basin in California (Ayers and Branson, 1973). The participants consisted of soil and crop scientists, horticulturists, waste management and soil and water engineers and hydrologists. The group met for two days twice per month for a period of four months. Even though all had agricultural backgrounds, four days of meetings were required before their understanding reached the level where sound concepts of what was needed were developed. The process of challenge and development of ideas and concepts through lively discussion continued throughout the entire period. Some people responded positively to the challenge, whereas others responded negatively and made fewer contributions.

Multidisciplinary group discussions, if done properly, are hard work and, because of this, most people do not ordinarily seek them. The tendency is for most people to gravitate back to their disciplinary group, where communication is easier. Thus, some mechanism is needed to keep the interdisciplinaty group going. The successful group will have: (1) a strong leader selected by the group or appointed by consent of the group, (2) ample resources, (3) sound objectives, and (4) an approach that allows each person to contribute and get recognition for his contribution. The factor that most effectively holds the group together is nearly always the resources, but this alone is not sufficient to ensure success. Recently a member of a successful research team was asked if the group would stay together if the resources from a granting agency were to be withheld. His response was that he thought the individuals would all gravitate back into their respective disciplines and that the mechanism for keeping them together was the grant. However, if the grant were to be terminated, various subgroups might be formed as the larger group ceased to be a viable unit.
The research environment created by ICRAF should be one in which soil scientists can apply themselves to problem-solving research and where they can interact with others in multidisciplinary teams. Hopefully, the environment will also be such that the soil scientist can forget his soil specialty and learn sufficient about all phases of soil science that he becomes a generalist in soils and then learns enough about agroforestry systems to become somewhat of a generalist in agroforestry.

SOILS IN THE TROPICS

The focus of ICRAF as explained by King and Chandler (1978) is on the lands of the tropics. Thus, a brief discussion of soils in the tropics seems appropriate.

The term "tropical soils" has been criticized by Drosdoff et al., (1978) and by Van Wambeke and Dudal (1978) because it gives an unrealistic impression and/or misconception that soils in the tropics consist of a group of soils with common properties. This conception is of soils having the same red colours, kaolinite and oxide minerals, acid pH values, and a set of nutrient deficiencies, whereas, in reality, the tropics contain as many different kinds of soils, if not more kinds, than the temperate zone. According to Sanchez (1976), the only property common to all soils of tropical regions is a uniform temperature throughout the year. Van Wambeke and Dudal (1978) stated that the isotherm concept (a difference of less than 5°C variation between summer and winter temperatures at the 50-cm soil depth) is the most effective differentiating tropical characteristic.

Climatically, the area referred to as the tropics is defined as that part of the earth's surface between 23.5° north and 23.5° south of the equator. This area contains 38% of the earth's land surface (about 5x10^9 ha). According to Sanchez (1976), 87% of the area in the tropics consists of tropical lowlands which have high temperatures throughout the year. Because of these high temperatures and the absence of glaciation during recent geological time, the proportion of extremely old and highly-weathered soils in tropical regions would be expected to be much higher than in temperate regions. There are large areas of highly-weathered mineral-deficient soils in the Central
Plateau and the Amazon Basin of Brazil. Extensive areas of similar soil conditions are found in other continents. Sanchez (1976) indicated that 30% of the tropics consists of tropical rainforests, 45% of savannas and 15% of semi-deciduous and deciduous plant cover. With such large areas in forests and savannas on old landscapes, it is natural to think of the typical soil of the humid lowland tropics as having yellow and red colours, acid pH values, highly-weathered minerals, oxide and kaolinitic clays and a given set of mineral element deficiencies. The soils of the savannas of Central Brazil have deficiencies of calcium, magnesium, nitrogen, phosphorus, potassium, sulphur, zinc and boron. Thus, though the use of the term tropical soils is not justified, there are large areas of these red, acid, mineral-deficient soils in the tropics. Comparable soils exist in only small areas in temperate regions.

According to the U.S. President's Science Advisory Committee (1967), about 50% of the world's 3.19x10^9 ha of potentially arable land occurs in the tropics. According to Uehara (1976), 5x10^8 ha of underutilized, potentially arable land exist in humid and subhumid tropics. The soils on these lands are described as either highly-acid and leached or highly-weathered or both. The development of these lands is hindered by the high costs of providing mineral fertilizers. These soils represent a challenge to all agricultural scientists. Perhaps agroforestry rather than conventional development into croplands can provide better systems for development at lower economic costs with greater protection of soil resources.

An example of the potential for development of savannas is found in Brazil, where it is estimated (EMBRAPA, 1977) that the development into cropland of one-third of the 180x10^9 ha of the savannas (cerrados), which comprise 21% of the national territory, would increase the cultivated cropland in Brazil by about 170%. The amount of cultivated cropland in Brazil in 1970 was estimated as 34x10^9 hectares. Successful research by ICRAF can offer the Brazilians and others some viable alternatives to solid plantings of soybeans, wheat, rice, maize, sorghum, and other agronomic crops.
CONCEPTUAL PROBLEMS

A discussion of several philosophical or conceptual problems related to research on soils in the tropics, within the focus of ICRAF, is justified on the basis that soil studies are to be one of ICRAF's main activities. The ideas presented in this section are taken from the paper "Some Major Fertility Problems of Tropical Soils" by Fox and Kang (1976).

Fox and Kang list three concepts that to some extent prevail in professional circles in the tropics and influence decision-making about agricultural development. These are: (1) the majority of subsistence farmers cannot afford cash inputs and even if they could, the necessary infrastructure is usually not established to provide their needs or utilize their products, (2) the first increment of an input provides the largest increment of yield, which justifies emphasis on a programme of minimum inputs, and (3) what is needed is a new variety, or still better, a new crop that can thrive on soil infertility.

It is often assumed that in tropical agriculture fertilizers are expensive and the crop produced is cheap. Thus, much higher crop responses per unit of fertilizer are needed in the tropics if fertilizers are to be profitable. But this conclusion is true only if the assumption is valid. It is not always correct to assume that the crop produced in the tropics is cheap on an absolute basis or on a relative basis.

Subsistence agriculture in much of the tropics is already operating against soil fertility constraint. It cannot generate the capital required for long-term fertility building; and without fertility inputs there is little chance of increased production. The phrase "an operation bootstrap cannot succeed in a land where there are no shoes" describes the condition of the subsistence farmer. He cannot invent soil fertility. It must be supplied. Thus, fertilizers to provide the basic mineral nutrients should be subsidized as an essential infrastructure is developed so that an operation bootstrap can work. The danger in the concept that fertilizers will not pay in tropical agriculture is that it might be used as an excuse to avoid finding and developing the necessary conditions to make them useful in agricultural development.
The second concept assumes that the Mitcherlich yield-response curve is concave downward through its entire range. This is not always the case. Whenever the soil microorganisms or weeds compete strongly for the first increment of nutrients applied, the first increment can give very little response.

There is a desperate need for yield-response curves covering the most important nutritional problems. The experimental work should meet the following specifications: (1) the rates of fertilizer elements should cover the range from zero to excess, (2) enough experimental points should be obtained to define the yield-response curve throughout its range, (3) the agronomic practices should be adequate to provide possibilities for acceptably high yields, (4) the experimental treatments should not be confounded with other variables, (5) the field plot design should provide adequate replication and randomization, (6) relevant collateral information should be collected, especially on soils and weather, and (7) the experiments should be conducted for sufficient time for residual effects of fertilizers to be measured.

Most agriculture in northern Europe and in North America could not remain competitive without large inputs of plant nutrients and soil amendments—high-yielding varieties and all other technology notwithstanding. And yet the prevailing philosophy in agricultural production in the tropics is one of minimum inputs of fertilizers. Because large areas of the tropics cannot be continuously cropped without mineral inputs, it is clear that research on fertilizers and soil amendments must be part of any overall research programme on production systems for tropical areas.

Relative to the concept that we should develop crops or varieties of crops that are adapted to the soils on which they are to be grown, we must consider that the history of crop production runs counter to the idea that quality crops can be grown on infertile soils. We must beware lest we begin to believe that through breeding we can accomplish the impossible of developing a crop that can utilize nutrients that are not there.

There is yet another idea that may tend to seduce research workers and many others. That is a child-like faith that a major breakthrough is imminent, a breakthrough that will solve all our
problems. The danger is that in searching for a breakthrough, we neglect the mundane things that work for sure.

RESEARCH IN AGRICULTURAL DEVELOPMENT

According to Wortman and Cummings (1978), successful efforts to increase the pace of agricultural development must involve the simultaneous provision of all necessary services, locality by locality. These services are markets, prices, input supplies and research. Also, they propose that the transfer of research information from developed countries cannot provide the needed research information for developing countries. Thus, the research to be delivered at the local level must be done at the local level.

SPECTRUM OF RESEARCH

Research has been classified in many ways for many purposes. For the purposes of agricultural development, the classification of Wortman and Cummings (1978) is perhaps the most useful. They listed categories of: (1) operational or farm-level research, (2) tactical research, (3) strategic research, (4) supporting research, and (5) basic research. Operational or farm-level research is defined as the identification, through experimentation on farms, of the combinations of crop and animal production practices that provide high productivity and profitability on those farms. Tactical research is defined as the identification of improved components of farming systems through work at local experiment stations to support farm-level research. Strategic research is defined as biological, chemical, physical or social research aimed at solving major problems affecting several areas of a country or region. This research is in direct support of scientists involved in tactical research. Supporting research is defined as investigations whose usefulness can be only partially foreseen. This research is mostly focused on given problems but has a longer-range focus than strategic research. Basic research is that which develops knowledge with no predetermined use necessarily in mind.

Examples of the research spectrum are presented in Table 1. We can easily recognize the difficulty of always placing any one research project nicely into one of the categories. The project
may involve two or more categories. However, the spectrum has a great conceptual utility in planning and in reviewing research operations. For example, let us assume that strategic research on the question of soil stability in the humid tropics has indicated that the maintenance of 8 to 10 tons of organic mulch/ha keeps the physical conditions of the surface soil at reasonable levels. If this is a sound general principle, tactical research is needed to find the mulch materials to be used and how local crops can be grown in the mulch. Operational research is needed to fit the mulch management idea into farmers' operations.

RESEARCH PRIORITIES

The establishment of research priorities by groups of individuals of diverse disciplines is usually difficult. When the priorities involve specific disciplinary projects such as nitrogen fixation, mycorrhizal associations, phosphorus fertility, water infiltration or plant breeding, the established priorities are biased by the particular mix of disciplines in the group. Even when priorities involve multidisciplinary programmes, the group selection of priorities is biased because various programmes favour one discipline or another. Thus, research priorities, particularly in the case of mission-oriented research centres, must be selected by management.

Table 1: Examples of the spectrum of research as defined by Wortman and Cummings (1978)

<table>
<thead>
<tr>
<th>Research spectrum</th>
<th>Development of Mexican wheats*</th>
<th>Potassium fertilization of crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Basic genetics and plant physiology</td>
<td>Mineralogy, essentially of mineral elements</td>
</tr>
<tr>
<td>Supporting</td>
<td>Genetics of wheats, nature of resistance, diseases, physiology of wheats</td>
<td>Soil mineralogy, plant physiology, function of K in plants</td>
</tr>
<tr>
<td>Strategic</td>
<td>Breeding of wheats for a given climatic region</td>
<td>Potassium reactions in soils, soil and plant analysis, response to K fertilizers</td>
</tr>
<tr>
<td>Tactical</td>
<td>Management factors, planting dates, fertilizer rates, etc.</td>
<td>Soil tests, rates, sources, timing and placement of K fertilizers</td>
</tr>
<tr>
<td>Operational</td>
<td>Fit the new varieties into a farming system</td>
<td>Trials on farmers' fields and local experimental farms</td>
</tr>
</tbody>
</table>

*Taken from Wortman and Cummings (1978).
The research spectrum of Wortman and Cummings (1978) can be used to recommend broad programmes of research and training. Within this spectrum, ICRAF, as a mission-oriented and problem-solving entity, should focus on strategic research with some overlap into supporting and tactical research. An accompanying training programme should prepare personnel for tactical and operational research at the local level. The strategic research of ICRAF should focus on multidisciplinary research to develop and test the productivity, maintenance and/or improvement of soil quality by agroforestry systems. The supporting research should meet the special needs of the strategic research. This can be done by members of the strategic multidisciplinary teams or it can be done under contract to other research centres or to universities. The tactical research should focus on sufficient field testing in a few areas to insure general applicability of systems developed by strategic research. These tests can be performed under contract to national research centres with cooperation of members of the strategic research teams.

Assuming adequate resources, ICRAF research and training operations should consist of: (1) contracts for strategic research in agroforestry production systems in forests, savannas, arid and mountain areas of the tropics, (2) supporting research at universities and other research centres, (3) a training centre to prepare personnel for tactical and operational research, and (4) an information accumulation and dissemination programme. The main focus in this overall plan is on strategic research and on training personnel to do tactical and operational research to provide research inputs needed on a local basis. An alternative plan would be to make extension the main focus, in which case the operations would consist of: (1) information accumulation and dissemination with a special library plus an information dissemination vehicle, (2) a training centre for extension and local research personnel, and (3) contract research to meet the needs of the training centre and for the extension activities.

PERSONAL RESEARCH PRIORITIES

After reading all of the papers in this consultation and after some consideration of the problems and needs, my priorities for research in soils within the total research programme of ICRAF are as follows.
The first priority is to develop or select systems of production of food, feed, and fibre that maintain or restore the physical properties of soils, i.e., the maintenance and/or improvement of water infiltration and transmissivity and soil stability for protection against soil erosion. The second priority is to support the first priority as needed depending on the soil, the climate and the cropping system, with studies on (1) nutrient cycling, (2) nitrogen fixation and transformations, (3) fertilizer use and use efficiency, and (4) microbiological associations and soil-born diseases. The third priority is to collect sufficient site information on soils, landscapes, climate, weather and other site characteristics in all studies to ensure transferability of information to other sites.

Discussion

Nyandat: I agree that protection of the soil should receive the highest priority. But perhaps the next priority should be rehabilitation.

Pratt: The soil programme of ICRAF will, and should, include rehabilitation of poor soils.

Nyandat: Is there a difference between multi-disciplinary and trans-disciplinary? In view of the practical difficulties, which is the more desirable?

Pratt: We need to have multi-disciplinary research teams and we need generalists (trans-disciplinarians). Both have a place. The generalists can man the tactical and operational research with help from specialists.

Nyandat: Priority of programmes for strategic research should not necessarily be based on whether the problem is widespread. It should be on the basis of whether the problem has serious effects on the quality of life.

Pratt: If each level of research supports the next, in going from supportive to operational research, the serious problems in local areas will receive attention. Communications up and down the research spectrum should help to get attention paid to problems at all levels.

Sánchez: The low input vs high input approaches can be easily reconciled by: (1) studying the whole range of the response curve, but adding more points at the low end of the curve; (2) considering farmers' risks and infrastructure limitations to fertilizer response; and (3) comparing varietal response differences where they exist. A major trap is the "soil mining" argument which needs hard data to quantify it. Evidence with cassava at CIAT has shown increases in available P rather than "mining". We should keep an open mind and relate the alternatives to realistic, economic, infrastructural and marketing constraints.
King: At Berkeley (University of California) there is training at the graduate level which encompasses several biological disciplines together with socio-economic courses. These graduates have had no difficulty in obtaining employment.

Kamprath: Some scientists have given the impression that the problem of food production in tropical areas can be solved by selecting varieties that can exist at low levels of nutrient supply, and can utilize relatively insoluble forms of soil nutrients. Eventually the soil will be mined and the problem will be more severe than originally.

King: I do not deny that you cannot remove from a site more than you put in plus what is there already. However, most of the nutrients in certain areas are lost through leaching and through erosion. These leakages can be minimized. Moreover, there is, I believe, some slight evidence that certain tree species bring nutrients from layers of soil not normally tapped by agricultural crops.

Fried: Many have said that tree crops remove nutrients from greater depths bringing them up to the surface. There is very little hard data on this subject, and since it is so relevant to the agroforestry system, it is one thing that badly needs investigation.

Lundgren: Low input systems should, of course, not be an aim in themselves; but it is a more realistic approach to consider these for large areas in the tropics. In the long run it is quite obvious that the nutrient balance is negative in any crop and/or tree production system on tropical soils of low fertility. In many areas soil management aimed at minimizing erosion and leaching is a more feasible short-term measure for keeping up productivity than to apply fertilizer.

LITERATURE CITED


### List of Participants

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<thead>
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<td>Dr. S.O. Keya Senior Lecturer, Dept. Chairman and Director, MRCEN Project</td>
<td>Department of Soil Science University of Nairobi P.O. Box 30197 Nairobi, Kenyan</td>
</tr>
<tr>
<td>11.</td>
<td>Dr. Rattan Lal Soil Physicist IITA</td>
<td>P.M.B. 5320 Ibadan, Nigeria</td>
</tr>
<tr>
<td>12.</td>
<td>Dr. Björn Lundgren Senior Consultant Swedforest Consulting</td>
<td>17193 Solna, Sweden</td>
</tr>
<tr>
<td>13.</td>
<td>Mr. Albert L.D. Mongi Adviser to UNEP's ROA</td>
<td>P.O. Box 30552 Nairobi, Kenya</td>
</tr>
<tr>
<td>14.</td>
<td>Dr. Jacqueline Roy-Noël Maître de Conférences Faculté des Sciences</td>
<td>Laboratoire d'Ecologie et d'Environnement Université de Dakar B.P. 206 Dakar, Senegal</td>
</tr>
<tr>
<td>15.</td>
<td>Mr. N.N. Nyandat Assistant Director of Agriculture (Land Development)</td>
<td>Ministry of Agriculture P.O. Box 30028 Nairobi, Kenya</td>
</tr>
<tr>
<td>16.</td>
<td>Sir Charles Pereira, F.R.S. Consultant in Tropical Agriculture Peartress,</td>
<td>Fairlawn Teston, Maidstone Kent ME18, 5AD, United Kingdom U.K.</td>
</tr>
<tr>
<td>17.</td>
<td>Mr. Gunnar Poulsen Senior Research Advisor (Forestry)</td>
<td>P.O. Box 30677 Nairobi, Kenya</td>
</tr>
<tr>
<td>18.</td>
<td>Dr. Parker F. Pratt Professor of Soil Science and Soil Chemist</td>
<td>University of California Riverside CA. 92521, U.S.A.</td>
</tr>
</tbody>
</table>
19. Dr. J.P. Redhead  
Professor of Forest Biology  
Division of Forestry  
University of Dar es Salaam  
Morogoro, Tanzania

20. Prof. Pedro A. Sánchez  
Soil Scientist and Coordinator  
Tropical Pastures Programme  
CIAT, A.A. 67-13  
Cali, Colombia

21. Dr. B.R. Singh  
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Department of Soil Science  
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22. Dr. K.G. Tejwani  
Director  
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23. Dr. Andrew Paul Uriyo  
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24. Dr. Matuka Kabala  
Science Officer  
Environment Programmes  
UNESCO  
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25. Dr. Oscar von Borries  
Programme Officer (Forestry)  
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26. Dr. K.F.S. King  
Director-General  
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Nairobi, Kenya

27. Dr. P.A. Huxley  
Senior Research Scientist  
ICRAF  
P.O. Box 30677  
Nairobi, Kenya

28. Dr. H.O. Mongi  
Senior Research Scientist  
ICRAF  
P.O. Box 30677  
Nairobi, Kenya
### Table 3. Production of sorghum and sesame at El Dali Mechanized Production Scheme, 1960-1978

<table>
<thead>
<tr>
<th>Year</th>
<th>Sorghum - Durra</th>
<th></th>
<th></th>
<th>Sesame</th>
<th></th>
<th></th>
<th>Ann.</th>
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<tr>
<td></td>
<td>Area Cult. (ha 10&lt;sup&gt;-3&lt;/sup&gt;)</td>
<td>Total Prod. (t 10&lt;sup&gt;-3&lt;/sup&gt;)</td>
<td>Ave. Yield (t ha&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>Area Cult. (ha 10&lt;sup&gt;-3&lt;/sup&gt;)</td>
<td>Total Prod. (t 10&lt;sup&gt;-3&lt;/sup&gt;)</td>
<td>Ave. Yield (t ha&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>Rain fall (mm)</td>
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<tr>
<td>60/61</td>
<td>8.3</td>
<td>19.5</td>
<td>0.43</td>
<td>172</td>
<td>34</td>
<td>0.20</td>
<td>481</td>
</tr>
<tr>
<td>61/62</td>
<td>17.2</td>
<td>20.1</td>
<td>0.86</td>
<td>113</td>
<td>36</td>
<td>0.32</td>
<td>814</td>
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<tr>
<td>62/63</td>
<td>17.6</td>
<td>24.0</td>
<td>1.36</td>
<td>349</td>
<td>245</td>
<td>0.70</td>
<td>486</td>
</tr>
<tr>
<td>63/64</td>
<td>21.0</td>
<td>22.3</td>
<td>1.06</td>
<td>550</td>
<td>188</td>
<td>0.34</td>
<td>661</td>
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<tr>
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<td>18.2</td>
<td>1.16</td>
<td>227</td>
<td>36</td>
<td>0.16</td>
<td>575</td>
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<tr>
<td>65/66</td>
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<td>22.0</td>
<td>0.86</td>
<td>756</td>
<td>162</td>
<td>0.21</td>
<td>572</td>
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<tr>
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<td>14.6</td>
<td>0.54</td>
<td>796</td>
<td>170</td>
<td>0.21</td>
<td>487</td>
</tr>
<tr>
<td>67/68</td>
<td>39.6</td>
<td>63.4</td>
<td>1.60</td>
<td>2633</td>
<td>845</td>
<td>0.32</td>
<td>406</td>
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<tr>
<td>68/69</td>
<td>30.0</td>
<td>11.8</td>
<td>0.39</td>
<td>3499</td>
<td>957</td>
<td>0.27</td>
<td>562</td>
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<tr>
<td>69/70</td>
<td>24.3</td>
<td>10.2</td>
<td>0.42</td>
<td>1556</td>
<td>260</td>
<td>0.17</td>
<td>477</td>
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<tr>
<td>70/71</td>
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<td>10.9</td>
<td>0.67</td>
<td>189</td>
<td>4</td>
<td>0.02</td>
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<tr>
<td>71/72</td>
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<td>9.9</td>
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<td>588</td>
<td>205</td>
<td>0.35</td>
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<tr>
<td>72/73</td>
<td>9.4</td>
<td>4.7</td>
<td>0.50</td>
<td>974</td>
<td>252</td>
<td>0.26</td>
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<tr>
<td>73/74</td>
<td>9.8</td>
<td>4.3</td>
<td>0.43</td>
<td>1046</td>
<td>224</td>
<td>0.21</td>
<td>*</td>
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<tr>
<td>74/75</td>
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<td>77.1</td>
<td>0.65</td>
<td>1104</td>
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<td>0.14</td>
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<td>75/76</td>
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<td>0.92</td>
<td>1202</td>
<td>443</td>
<td>0.37</td>
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<td>76/77</td>
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<td>0.97</td>
<td>1831</td>
<td>764</td>
<td>0.42</td>
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<tr>
<td>77/78</td>
<td>14.6</td>
<td>13.3</td>
<td>0.94</td>
<td>2541</td>
<td>515</td>
<td>0.20</td>
<td>*</td>
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</table>

* Data not available

Source: Annual Reports, Department of Agriculture, Khartoum (1960-77)

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### Table 1. Production of groundnuts and sesame in Northern Kordofan province, 1960-1973

<table>
<thead>
<tr>
<th>Season</th>
<th>Groundnuts</th>
<th>Sesame</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area Cult. (ha 10&lt;sup&gt;-3&lt;/sup&gt;)</td>
<td>Total Prod. (t 10&lt;sup&gt;-3&lt;/sup&gt;)</td>
</tr>
<tr>
<td>60/61</td>
<td>77.3</td>
<td>73.0</td>
</tr>
<tr>
<td>61/62</td>
<td>94.5</td>
<td>103.2</td>
</tr>
<tr>
<td>62/63</td>
<td>75.6</td>
<td>63.7</td>
</tr>
<tr>
<td>63/64</td>
<td>84.3</td>
<td>59.8</td>
</tr>
<tr>
<td>64/65</td>
<td>92.2</td>
<td>72.0</td>
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<tr>
<td>65/66</td>
<td>99.5</td>
<td>63.3</td>
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<tr>
<td>66/67</td>
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<td>45.7</td>
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<td>67/68</td>
<td>73.4</td>
<td>43.4</td>
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<td>90.0</td>
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<tr>
<td>69/70</td>
<td>126.0</td>
<td>69.7</td>
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<tr>
<td>70/71</td>
<td>93.5</td>
<td>42.0</td>
</tr>
<tr>
<td>71/72</td>
<td>353.0</td>
<td>76.4</td>
</tr>
<tr>
<td>72/73</td>
<td>340.5</td>
<td>73.7</td>
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</tbody>
</table>

Source: Annual Reports, Department of Agriculture, Sudan (1960-73)

### Table 2. Production of gum arabic (tons) in Kordofan and Darfur provinces (QOZ* soils) 1968-1973

<table>
<thead>
<tr>
<th>Season</th>
<th>Kordofan province</th>
<th>Darfur province</th>
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<tbody>
<tr>
<td>68-69</td>
<td>21,773</td>
<td>9,858</td>
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<tr>
<td>69-70</td>
<td>14,667</td>
<td>8,655</td>
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<td>70-71</td>
<td>18,950</td>
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<td>71-72</td>
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<td>72-73</td>
<td>6,730</td>
<td>5,734</td>
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</table>

Source: Annual Reports, Forest Department, Sudan

* Sandy soils