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Contribution of soil organisms to the sustainability and productivity cropping systems in the tropics

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ABSTRACT

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Research to identify appropriate means of sustaining tropical soil productivity has intensified during the last 2 decades and promising technologies such as minimum tillage, herbaceous and tree based systems, and improved fallows have been identified. This paper discusses the contribution of soil microorganisms to the sustainability of such cropping systems in the tropics. A favourable environment for biological activity is promoted by management practices which: (1) maintain continuous vegetational cover of the soil and extensive perennial root growth; (2) encourage the return of plant litter to the soil; (3) support a diversity of plants (preferably and including legumes) and thence of litter inputs; (4) minimize soil disturbance (e.g. by tillage). It is concluded that although the importance of biological processes for soil fertility conservation is increasingly recognised there is still little understanding of these processes in tropical cropping systems.

INTRODUCTION

Intensive cultivation in response to increasing populations has led to reduced soil fertility and increased soil erosion in many areas of the humid and semi-arid tropics. Despite selection of highly productive plant genotypes, population growth is now outstripping increases in agricultural productivity in 35 out of 41 sub-Saharan African countries (FAO, 1989). Evidence from many parts of tropical Africa indicates that it is becoming harder and/or more expensive to maintain the soil fertility of crop land. Changes in land productivity are often considered as physiological responses to changes in the physical environment. In this view, the impacts of cropping systems are evaluated as they affect levels of nutrients, light and water, either increasing or decreasing land potential to generate food production (Allison, 1973). Land produc-

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tivity is pictured as decreasing as withdrawals of nutrients exceed their inputs. Maintaining long-term site productivity, therefore, requires that cropping system management activities minimize withdrawal of site resources and, when necessary, replenish depleted resources with inputs.

In the past, intensive use of industrial fertilizers was advocated to alleviate soil nutrient deficiencies for maximum food crop yields. Only in some cases however, could declining soil fertility be arrested by addition of chemical fertilizers and from a financial view point this is not a solution for the great majority of farmers in developing countries. Unfortunately, this conventional approach also fails to recognize the diversity and activity of soil organisms that influence the total reservoir of resources determining long-term cropping system productivity. In the last decade the search for more appropriate means of sustaining soil productive capacity has intensified, and promising methods have been identified. There is now greater recognition that biological factors influence soil nutrient and physical status and that the management of biological processes could be one pathway to restoring and sustaining soil fertility.

Low input technology suitable for rural agriculture in the tropics includes legume intercropping, minimum tillage with efficient residue management, and tree-based systems. All these approaches emphasize the importance of biological processes for soil fertility conservation, but biological activities and their changes under cultural practices have been little studied in tropical agriculture.

The objective of this paper is to evaluate the role and contribution of soil organisms to the sustainability of cropping systems in the tropics. The potential of some management practices used in cropping systems which influence soil fertility through biological processes will be reviewed.

BIOLOGICAL PROCESSES IN TROPICAL CROPPING SYSTEMS

Within the soil a diverse series of biological processes occur, the rate and type of which control plant growth both directly and indirectly. A soil biological process of central importance is that of the decomposition of the organic matter input from plants in the form of litter, dead roots or crop residues (Swift et al., 1979). Additional inputs resulting from management practice may take the form of mulches or manures. Soil micro-organisms are also responsible for specific processes (Dommergues and Diem, 1982) such as nitrogen fixation, a variety of transformations of inorganic elements and for facilitating nutrient uptake by plants. Soil biological processes (particularly microbial) are also responsible for the formation and decomposition of humus fractions (Allison, 1973).

Faunal activities may furthermore be important in the distribution of organic and mineral material within the soil profile (Lavelle, 1933). The activities of micro-organisms, fauna and roots also modify the physical structure of soil and hence regulate the rates of movement of nutrients, water and gases. Soil micro-organisms may also play important roles in controlling plant pathogens and degrading phytotoxic substances in the soil.

Soil biological processes, mediated by roots, micro-organisms and fauna, are thus an intimate part of the function of natural and managed systems. Current understanding of the functioning of these processes is now outlined in this paper within two main contexts — their influence on nutrient cycling and on modification of the physico-chemical properties of soil.

Nutrient cycling

The role of biological processes in nutrient cycling is first considered in relation to the factors determining nutrient retention and release from organic matter; second, a brief account is given of some specific microbial transformations of nutrient elements; third the biological influence on the uptake of nutrients by plants is discussed.

Decomposition

Soil biomass and organic residues constitute the main source of plant nutrients. During decomposition soil animals intervene in the process with the mechanical breakdown of plant and animal residues in the topsoil.

During decomposition the physical structure of the resource is changed through comminution. Complex organic molecules are enzymatically degraded and soluble fractions may be leached. Concurrently, new organic matter components are synthesised in the production of animal and microbial cells and in the formation of amorphous soil organic fractions (humification).

Decomposition also results in the release of inorganic nutrients which may be recycled within the soil biota, retained within the soil matrix by exchange or other phenomena, absorbed by plants roots or lost from the soil by leaching, gaseous or aerosol outputs or erosion. Removal by harvest can also be an important loss from the system. The regulation of decomposition and the varying pathways of nutrient flux under its control thus determine the long-term nutrient capital of an ecosystem and the rates of supply of nutrients to the plants. These regulatory controls vary with differing vegetation and soil types.

The rate of decomposition of any resource (i.e. any individual unit of organic matter available to the decomposer organisms such as a leaf, fruit, twig, root or faecal pellet) is controlled by the physico-chemical environment and by its intrinsic properties (resource quality). Both environment and resource quality act through the soil micro-organisms and fauna.

Detailed monographs have been published on decomposition in terrestial ecosystems with chapters on the process in tropical environment (Swift et al., 1979).

The kinetics of plant material decay in agricultural systems can be studied by measuring weight loss of the material contained within nylon bags or by assessing the $^{14}CO_2$ from ^{14}C-labelled plant materials. Nylon bags of different mesh size treated with selective pesticides provide an opportunity to monitor the contribution of groups of soil organisms to the process. Few investigations have been conducted in tropical Africa (Cook et al., 1979; Mulongoy, 1983; Yamoah et al., 1985; Wilson et al., 1986). Most studies have dealt with leaf decomposition, but very little or no attention has been directed to the turnover of root nutrients particularly after land clearing and in systems such as alley cropping in which pruning hedgerow trees is expected to bring about changes in the normal pattern of root development.

To obtain accurate data with the litter bags and to monitor decomposition of buried plant materials, it is necessary to make use of ^{14}C and/or ^{15}N plant materials. Jenkinson and Ayanaba (1977) used ryegrass uniformly labelled with ^{14}C and showed that the decay patterns were similar in Nigeria and in England, but that decomposition under tropical conditions was four times faster than in temperate regions. Evaluation of decomposition of crop residues, mulch materials, cover crops and restorative trees in agroforestry systems will generate information that would justify the inclusion of these materials in agricultural practices to improve soil organic matter. The International Union of Biological Sciences recently stressed the importance of standardised methods to study decomposition processes, as a prerequisite to clarify and manipulate biological activities for improved tropical soil fertility (Swift, 1984).

Mineralisation and immobilization

Decomposition processes are intimately coupled to mineralisation and immobilisation of nutrients. Mineralisation is the conversion of organic molecules to inorganic ionic states readily available for plant use. It is carried out by a diverse range of soil organisms including bacteria, fungi, protozoa and invertebrate animals. These organisms release inorganic N, P, S and many other elements from soil organic matter. In natural ecosystems, these processes are the major ways, excluding biological N fixation, in which the essential elements are made available to the plant. Yet they have been studied even less than mycorrhiza, probably because plant nutrient uptake from inorganic fertilisers bypasses the biological pathways. However, development of low input agriculture for farmers in developing countries cannot rely on expensive inorganic fertiliser inputs (Swift and Sanchez, 1984).

During decomposition and mineralisation processes, recalcitrant molecules such as lignin are left over. They constitute the basic components for humus synthesis. The biochemistry of this largest fraction of the soil organic content is yet to be elucidated. In natural systems, the main value of humus is its sustainability over long periods of time by an equilibrium between formation and breakdown (Swift and Sanchez, 1984). Humus is fundamental to soil fertility. It acts as a reservoir of mineralisable plant nutrients.

In soils, the rates of nutrient mineralisation or immobilisation are usually determined by N availability. The C/N ratio has been used to draw up some simplified generalisations. When the ratio is relatively high, microbial populations tend to multiply and immobilise nutrients, at least temporarily. When the ratio is relatively small, mineralisation becomes prevalent (Mulongoy and Gasser, unpublished data). Manipulation of these two microbial processes can help to minimise nutrient leaching and to maximise the efficiency of mineralisation reactions and plant nutrient uptake. Models have been set up to predict the actual and potential release of some plant nutrients, such as N, based on the pattern of climatic and edaphic factors, but spatial compartmentalisation of the processes in the soils does not allow straightforward extrapolation of data from controlled conditions to the field.

Farming systems that build up soil biomass content, in particular efficient uses of crop residues and mulching practices, will promote temporary immobilisation of plant nutrients in the soil biomass which acts as a sink, but rapid turnover makes the soil biomass a source of readily available plant nutrients. Investigators (e.g. Ladd et al., 1981) have confirmed these observations unequivocally. Microbial biomass value as a source of plant nutrients is further stressed by Lynch (1983) when the presents data indicating that biomass N can be released during the spring when the crop is most in need of it. Immobilisation in winter would prevent leaching during this season. Similarly, soil organisms can immobilise for their own growth nutrients that are released in secretions and excretions, and during decomposition of their dead bodies. For example, earthworms contain 10% N and 0.7–0.9% P and S (Syers and Springett, 1984). Also their casts contain more, N, P, C and cation exchange capacity (CEC) than the underlying soil, and they are less prone to erosion as they have more water-stable aggregates (e.g. Lal and De Vleeschauwer, 1982).

If immobilisation is a useful process in reducing nutrient losses through leaching, volatilisation and erosion, there can be instances where soil biomass competes with the plant for nutrients. This biological nutrient 'tie-up' may create and intensify soil nutrient deficiency. Tinker (1984), however, considers biological tie-up of nutrients as being of little significance in natural ecosystems because microbial turnover is rapid.

Soil biomass mediation in plant nutrient uptake

From seed germination, plant root systems develop in association with microbial populations. These organisms may be free-living or symbiotic. Their role is essentially to produce chelating agents and plant-growth regulators, promote active ion transport and absorption in the root zone, redistribute nutrients in the soil profile for increased plant-use efficiency, and to channel nutrients into the plant roots in the case of symbiotic associations.

Rovira et al. (1979) have reviewed and classified the organic materials and the organisms present in the rhizosphere. Soil conditions and the substrates present in the rhizosphere will greatly influence the composition of the soil community. Barber (1978) described a heat-labile substance of microbial origin that increased root uptake of manganese. Powell et al.. (1980) also described siderophores that are bacterial compounds with a strong affinity for iron. Their significance in plant nutrition is being studied extensively (Tinker, 1984). They probably solubilise ferric oxides to make iron available to plant roots. By doing so, they may deprive some plant pathogens of iron for the benefit of plant growth (Lynch, 1983). Microorganisms can also improve plant growth rates by producing plant hormones and antibiotics controlling soil-borne pathogens. Microbial products can also have inhibitory effects on beneficial microorganisms and on the plant roots (Lynch, 1983). Waid (1984), for instance, noted the microbial formation in the soil of substances that increased root cell permeability and caused leakage of organic substances into the root zone.

Soil biomass, particularly the mesofauna, can redistribute nutrients in the soil profile. The feeding habit of earthworms clearly illustrates this action. Some worms feed on plant residues at the soil surface, others rely on decomposed organic materials within the soil profiles for their food. During burrowing and casting activities, earthworms distribute nutrients in the soil profile. Syers and Springett (1984) also showed that transfer of nutrients from the soil surface to the root zone increased the effective use of nutrients. This is particularly true for low water-soluble materials such as lime and rock phosphate. The agronomic effectiveness of surface-applied rock phosphate increased by 15–30% in a glasshouse experiment with ryegrass when earthworms were introduced (Mackay et al., 1982). While soil organisms are mixing soil in the profile, their guts show increased microbial population sizes and activities (Parle, 1963).

Biological N_2 fixation has been the most studied microbial activity because of its potential for a low cost source of N. It is the process whereby atmospheric N_2 is reduced to combined N. Only some species of bacteria and blue-green algae possess naturally the nitrogenase enzyme catalysing this reduction. Biological N_2 fixation is highly energy demanding. It is therefore restricted to environments where the N_2-fixing bacteria can find readily available sources of assimilable C compounds. Of all N_2-fixing systems, the symbiosis between *Rhizobium* and leguminous plants is the most familiar and the most beneficial to food production. Biochemistry, physiology and genetics of both partners have been studied extensively. Manipulation of the system has permitted the maximisation of N_2-fixation in agricultural systems. Inoculation with effective and adapted strains is carried out when the indigenous rhizobia are ineffective or lacking. Mutants have been produced to introduce superior strains in terms of N_2-fixing ability and competitiveness. The host plant has also been modified to accept the effective native strains, and yield more than unimproved varieties. Some woody dicotyledonous plants nodulate with the actinomycetes *Frankia*. This association has only recently attracted much attention when it became possible to make inoculants with pure cultures of *Frankia*. Nitrogen-fixing plants particularly nodulating legumes can be cropped for their high protein value and/or as sources of organic N for the benefit of non-N_2-fixing crops grown in association or in rotation. Nitrogen fixation is therefore a major thrust of resource-poor farmers for developing low input agriculture.

Nitrogen-fixing bacteria can also live freely but in close association with the roots of several other plants. It has been conclusively demonstrated that members of the family Graminae can support populations of free-living N_2-fixing bacteria. These micro-organisms obtain the energy needed in the form of root exudates. They, in turn, enrich the soil in the plant root vicinity with N. Nitrogen fixation by free-living heterotrophs is more significant under anaerobic conditions (Tiedje et al., 1984). Recent works suggest maximum fixation rates in the range of 30 kg N ha^{-1} $year^{-1}$ (Tinker, 1984). This may be important for natural vegetation but not for intensive agriculture.

Mycorrhizal development, which is almost universal in the roots of plants in the tropics (Janos, 1983) is very important in increasing the efficiency with which root systems can acquire phosphorus, nitrogen and possibly water. This increase arises from the external hyphal system around the roots to exploit a very large proportion of the soil volume (Harley and Smith, 1983). In addition, in natural ecosystems significant associations between roots, mycorrhizal fungi and decomposing organic materials can be observed. By this means plants can achieve a very close contact with sites where nutrients are being released by the processes of decomposition.

There is some evidence that in certain cases, mycorrhizal fungi may directly recycle nitrogen and phosphorus from litter. In addition there is evidence that roots influence decay rates. It is therefore important to define both the magnitude of these effects and the circumstances under which they operate. It has become clear that many important crop plants such as cassava are completely dependent on their mycorrhizal association for adequate supplies of phosphorus when no phosphorus fertiliser is applied.

Modification of soil physico-chemical properties

This section considers the major effects of organisms on the soil physico–chemical properties.

Surface properties and structure of soil

Fine-textured soils have a tendency to develop soil caps or crusts, which reduce water infiltration. Plant litter which prevents the development of soil caps and the accumulation or maintenance of a litter cover is of major significance in semi-arid regions (Kelly and Walker, 1979). Infiltration is also promoted by the activities of soil fauna.

Soil organic matter, particularly the short-lived fraction, increases soil particle aggregation, for example by the presence of binding molecules of mucopolysaccharides, which in turn increases porosity. Porosity is also increased by the activities of soil fauna, especially earthworms and termites (Lee and Wood, 1971; Edwards, 1977) and by the growth and decomposition of plant roots. The effects of fauna and roots lead to macro-pore development, which has various consequences such as increased water absorption, and therefore reduced run-off and erosion, reduced waterlogging, changes in the distribution of water in the soil profile, thus altering the competitive balance between plants with different rooting depths.

Soil water and chemistry

Water is essential for soil organisms, for plant growth, and as a medium for nutrient transport. In the humid tropics it is largely the movement of nutrients which is of concern, apart from soils where waterlogging is a problem. In drier tropics available soil water is generally the major determinant of ecosystem structure and function. For any particular rainfall pattern the soilwater regime is determined by the infiltration rate, the water-holding capacity of the soil, soilwater conductance, and soil depth.

The indirect effects of soil biota on water dynamics operate mainly through the increase in water-holding capacity associated with soil organic matter accumulation and soil porosity. This is of particular importance in sandy soils in the sub-humid tropics. The main direct biotic effect on the water dynamics is the uptake of water by plant roots. The greater the uptake the less the risk of leaching, or in soils with impeded drainage the less the likelihood of waterlogging.

BIOLOGICAL PROCESSES IN RELATION TO MANAGEMENT

A number of key biological processes affecting soil fertility and sustainability have been identified in the preceding paragraphs. Each of these processes is affected in some way by agricultural management practices. Some practices promote the biological contribution to soil fertility, others suppress or disrupt it.

Management practices which may result in uncoupling include stimulating the decomposition rate by selection of high quality crop monocultures, burying crop residues by ploughing, and fertilisation with inorganic nutrients. Application of pesticides or low quality mulches may, however, delay the onset of nutrient release. Alternatively, any mixed cropping practice will spread the period of plant demand as well as widening the spectrum of resource quality in the input.

Some technology options for sustainable production systems

Cultivation

It is well established that arable practices generally result in a reduction of soil organic matter content, with associated changes in cation exchange capacity, water-holding capacity and aggregate stability (Sanchez, 1976), but there is little understanding of the biological processes involved, or the indirect biological consequences of these changes. The exposure of surface litter to high-intensity solar radiation accelerates decay rates by initiating biochemical depolymerisation of structural carbohydrates as well as by volatilisation of simple aromatic molecules or inactivation of other modifiers of decomposition.

In a seasonal environment litter decay and plant growth are initiated by the onset of rain (Swift et al., 1981) and a major pulse of nutrient release may occur before the rooting system of the crop can respond. The timing of litter inputs to the soil in relation to climate or irrigation, and the manipulation of decay rates to coincide with crop demand, clearly requires an integrated knowledge of soil processes and crop phenology.

Land clearing and cutting

In the humid and sub-humid tropics, land clearing for cultivation requires the removal of trees and shrubs. After cutting, bush and forest slash is either left to decompose in situ or is burned. In both cases, the largest trees may be left standing. Alternatively, in more intensive continuous cropping systems, vegetation may be clear-felled and bulldozed from the site. This is a particularly destructive method of forest clearance, since most of the nutrient capital held in vegetation and even topsoil is deposited outside the plot.

On small and medium-sized farms, land clearing is done manually. This has an advantage over machine-clearing since the problems of soil compaction and erosion are reduced. The drudgery involved, however, makes some degree of mechanised clearing an attractive alternative.

In the sub-humid tropics, where there are fewer trees, mechanised land clearing is becoming more common on large commercial farms. Research by the International Institute of Tropical Agriculture (IITA) has shown that when heavy equipment is used, soil disturbance and subsequent erosion can be kept to a minimum with implements such as the shear blade, which cuts the vegetation at ground level. Minimum or zero-tillage with use of cover crops, mulches, and herbicides are necessary when the land is cleared in this way.

This system conserved soil and water and maintains lower soil temperatures and higher levels of soil organic matter (Lal, 1974). However, further agronomic and economic analysis is needed to determine the conditions under which it would be most practical for small-scale farmers.

In the slash and burn system fire is used both for site clearance and to mobilise plant nutrients from vegetation and litter. Some of the nitrogen capital of the natural system is inevitably lost as smoke during burning. Losses of nitrogen associated with felling, and immediate post-fire leaching, may amount to 1000 kg ha^{-1} $year^{-1}$ when humid forests are cleared, but in West African savanna ecosystems, containing comparatively low nitrogen standing crops, losses of 12–15 kg N ha^{-1} $year^{-1}$ appear to be compensated by atmospheric input and nitrogen fixation in algal crusts (Rosswall, 1980).

Under higher rainfall regimes, some of the potential benefits of N mineralisation may be lost by leaching and denitrification prior to establishment of the root network of the crops.

The benefits of litter input to the soil, in terms of soil organic matter formation and associated soil physico-chemical properties, are also lost by burning. On the other hand, ash reduces exchangeable aluminium to below toxic levels in acid soils so that more extensive rooting systems of crop plants can develop (Sanchez, 1976).

Application of fertilisers and pesticides

Fertiliser. Application of fertilisers may contribute to increased rates of soil organic matter decomposition, though this effect has not been clearly distinguished from those associated with tillage practices. Crop plants, particularly fertilised crops, have high resource quality characteristics and generally decompose faster than natural vegetation under comparable conditions. Grain crops differ from fodder or root and tuber crops in the distribution of resource qualities in different parts of the plant. Hence the consequences of harvest on nutrient balance of the system are different for different crops.

In extremely phosphorus-deficient soils, phosphate fertiliser is needed but the rate of application is reduced if crop roots are infected with mycorrhizal fungi at the start of the growth cycle (Ganry et al., 1982). The use of nitrogen-fixing plant species for cropping, interplanting or as green manures is spread and, for providing organic matter inputs as well as nitrogen, reduces leaching losses even when supplemented with fertilisers. The accumulation of nitrate in soil can, however, inhibit root nodulation and the use of stem nodulated species provides a method of increasing input of biologically fixed nitrogen to soils even when the nitrogen content of the soils is high (Dreyfus and Dommergues, 1980; Sanginga et al., 1986).

Pesticides. Pesticides have a direct effect on the soil biota and indirectly modify rates of decomposition. Bacteria, fungi, and algae however differ in their response to pesticides. Responses are often related to the biochemical mechanisms of action of the pesticide and pesticide concentrations in the soil. Total microbial populations in soils are often unaffected or only slightly affected by pesticide applications, but populations and activities of individual species or groups (e.g. cellulose decomposers) of microorganisms may be greatly affected. Pesticide concentrations, greater than those resulting from field applications, can cause interruption of microbial activities and shift in populations. Most pesticides used at field rates do not appear to cause significant lasting effects on the microbial activities most related to soil fertility. In general, the changes in microbial populations due to pesticide applications are no more severe than changes caused by natural environmental stresses. The effects of pesticides on crop residue decomposition, nutrient cycling, and root symbionts have been extensively reviewed with respect to production practices.

Fallow management

Maintenance of crop cover and organic matter in the topsoil is crucial for sustainable management of the soil in the tropics. Two methods for providing organic matter with which IITA has worked are herbaceous and woody fallows.

Herbaceous fallows. Early attempts to use planted fallow in the tropics were dominated by the use of herbaceous legumes for production of green manures. Later studies indicated that green manuring with herbaceous legumes was not compatible with most tropical climates, especially in areas with long dry periods which precede the main planting season (Wilson et al., 1986). In Asia, green manures (including *Azolla*) are commonly used for lowland rice.

Following the introduction of herbicides and no-till crop establishment in the tropics, some cover crops were found capable of producing live mulch or in situ mulch for minimum tillage conditions. The live-mulch system is a crop production technique in which food crops are planted directly in a low-growing cover crop with minimum disturbance (Akobundu, 1980). Annual dry-matter yields of legumes that are useful in live and in situ mulch systems range between 1500 and 7500 kg ha^{-1} in Africa (Skerman, 1977; Mulongoy and Akobundu, 1985), with N yields ranging from 30 to 300 kg ha^{-1} $year^{-1}$.

The soil restorative and protective value of organic mulches is well known (Lal, 1974). Results of a series of continuous cropping experiments using leguminous cover crops, particularly *Mucuna pruriens* (mucuna) conducted in Ibadan, Nigeria, from 1922 to 1951, showed that mucuna improved soil properties but that its effect was not long-lasting. Studies by Lal et al. (1978) and Wilson et al. (1982) also showed improvement in soil physico–chemical properties and biological activities as measured by earthworm cast production, under *Stylosanthes guianensis, Centrosema pubescens, Pueraria phaseoloides* (pueraria) and *M. pruriens* grown for only a short period, as compared with natural fallow. The cover crop improved soil bulk density and soil moisture retention and gave better protection against erosion.

A number of reports have also indicated that leguminous cover crops increase the organic matter and N contents of the soil. Jaiyebo and Moore (1964) found that organic matter accumulation in the top 10 cm of soil was in the following order: bare soil less than mulch of *Imperata cylindrica* less than star grass less than pueraria less than bush treatments. Observations by Lal et al. (1978) and Wilson et al. (1982) showed small increases in soil N content ranging from 0.01 to 0.06% over a 2 year period under various herbaceous legumes.

Another benefit from leguminous cover crops used in rotation and intercropping systems is the sustained and high crop yields with minimum N fertiliser input. Work with cover crops at Moor Plantation in Ibadan, Nigeria, from 1922 to 1951 (Faulkner, 1934; Vine, 1953) showed that, though the cover crops have no long-lasting effect, inclusion of mucuna in the rotation system, supplemented with low fertiliser rates, could maintain adequate maize yields. Faulkner (1934) estimated that the increase in yield of a maize crop following mucuna was in the order of 700–900 kg grain ha^{-1}. Kannegieter (1966) also reported increases in crop yield in Ghana following a short-term fallow on which pueraria was grown. Wilson (1978) reported increased yield and improved quality of tomatoes grown with an in situ mulch of pueraria. Lal et al. (1978) also observed that, after 2 years, in situ mulches of *C. pubescens*, *P. phaseoloides* and *S. guianensis* increased the yields of cowpea, soybean, maize and cassava.

The intensity of labour involved in clearing cover crops will greatly determine the acceptability of the cover species. Farmers may not be willing to invest scarce cash in herbicides for killing the cover crop, and farmers using herbicides and mechanical planters may find poor emergence in heavy mulch unacceptable. It should also be noted that in developing the mulch, the land is left under fallow cover for at least 1 cropping year. This is a disadvantage where land is limited. But the improvement in soil properties and the increase in crop yield resulting from the mulch can give adequate compensation.

Legumes used for live and in situ mulch should be easy to establish and produce sufficient biomass in a short time with little or no fertilizer input. Species that grow rapidly and vigorously will be able to smother weeds effectively. They should nodulate effectively with indigenous rhizobia and fix atmospheric N. They should not increase pest and disease incidence. Finally, they should be easy to eradicate by inexpensive means. For the live-mulch system, they should also be perennial and should not compete with the associated crops.

Woody fallows. As early as 1928, Misum and Bunting (quoted by Akobundu (1980)) suggested that herbaceous legumes were not very suitable sources of green manure in the humid tropics. Rather they believed that perennial shrubs like *Crotalaria* sp. and *Cajanus cajan* were more suitable. Since then, various reports have shown that trees and shrubs with their deeper root systems are more effective in taking up and recycling plant nutrients from greater depths than herbaceous or grass fallows (Nye and Greenland, 1960; Jaiyebo and Moore, 1964; Lundgren, 1978; Jordan, 1985). *C. cajan* with its deep roots survives most dry seasons. At the start of the rains it has abundant litter and leaves to contribute as green manure. Planted fallows of shrub legumes such as *C. cajan* are already used by some traditional farmers and were sometimes found to be more efficient than natural regrowth in regenerating fertility and increasing crop yields (Nye, 1958; Webster and Wilson, 1980). Some investigators even suggested a cut-and-carry method in which leaves from special green manure plots would be used to manure other plots on which crops would be grown.

At IITA, substantial resources are devoted to research on alley cropping, an agroforestry system in which the shrubs and trees grown in the hedgerows retain the same functions of recycling nutrients, suppressing weeds, and controlling erosion on sloping land as those in the bush fallow. (Kang et al., 1984). Desirable characteristics for the hedgerow trees include easy establishment, rapid early growth, high biomass production, deep rooting, and ability to coppice and to fix atmospheric nitrogen. Various trees adapted to the soils in the sub-humid region have or are being tested (Kang et al., 1984). They include nitrogen-fixing trees like *Albizia lebbeck, Calliandra calothyrsus, Cajanus cajan, Flemingia macrophylla, Gliricidia sepium, Leucaena leucocephala, Sesbania grandiflora, Sesbania sesban,* and *Sesbania rostrata* (Mulongoy and Kang, 1986), and non-nitrogen fixing trees like *Cassia siamea, Cassia spectabilis, Alchornea cordifolia* and *Acioa barterii.*

Prunings from the trees and shrubs are a source of mulch and green manure. Leguminous woody species also add atmospheric nitrogen to the system. *Leucaena leucocephala, Gliricidia sepium* and *Sesbania rostrata* have been shown to fix at least 45% of their N from the atmosphere in the forest/savanna transition zone at IITA (Mulongoy, 1986; Sanginga et al., 1986; Mulongoy et al., 1988). Prunings from leguminous species can provide as much as 40–70 kg N ha^{-1} (Mulongoy, 1986; Sanginga et al., 1986). The alley cropping technique can, therefore, be regarded as an improved fallow system with the following characteristics and potential advantages: (1) cropping and fallow phases are combined; (2) longer cropping periods and increased land-use intensity are possible; (3) soil fertility regeneration is rapid with more efficient plant species; (4) requirements for external inputs are reduced; (5) the system is scale neutral, being flexible enough for use by small-scale farmers and for large scale production; (6) the hedgerow trees provide numerous other benefical outputs such as animal fodder, staking materials and firewood (Kang et al., 1984). When the hedgerows are planted on the contour lines of sloping land, they can also help prevent erosion. Compared with N fertiliser application, alley cropping with hedgerows of *Leucaena leucocephala* or *Gliricidia sepium* has been shown capable of producing relatively high yields of maize and other crops on Alfisols and related soils in the subhumid region with or without N fertiliser and on a sustainable basis (Kang et al., 1984).

By integrating small-ruminant production with alley cropping, the International Livestock Centre for Africa project in Ibadan, Nigeria, has developed the alley-farming concept (Sumberg and Okali, 1983) in which prunings from the hedgerows also provide high-quality supplementary fodder. Alley farming can thus be defined as the planting of arable crops between hedgerows of woody species that can be used to produce mulch and green manure for improved soil fertility, and high quality fodder. Sunberg and Okali (1983) recommended the use of alternating hedgerows of *Leucaena* and *Gliricidia* for alley farming in order to offer mixed foliage to animals and to minimise the possibility of livestock toxicity due to high intake of *Leucaena*.

Improved fallows. A limited amount of research has been done on developing improved fallow management practices that will be more efficient in restoring soil fertility than unmanaged bush fallows. Some of the species used in alley farming experiments, such as *Leucaena*, can be beneficial in a managed fallow system. Moreover, there are areas in which farmers already plant or select certain fallow species, especially in the humid forest zone (Kang et al., 1984). This can provide the basis for further work, although the particular mix of species used may be quite site specific. We have started a number of long-term fallow management trials at IITA involving herbaceous and woody species.

Cropping systems

A common feature of traditional farming systems in tropical Africa is the production of several crop plants on each farm or by each farmer. The success of multiple cropping by African farmers is due to a judicious choice and arrangement in time and space of various crops to suit their changing micro-ecological conditions and maximise crop production with minimum risks. It also involves location spacing of plants in such a way as to ensure that crop cover is adequate to effectively control soil erosion and weeds (Okigbo, 1978).

The 'Green Revolution' in Asia was associated with high-yielding varieties, sole cropping monoculture and enormous inputs of non-renewable resources to extend the cropping season, increase soil productivity and control pests. The failure of the Green Revolution in Africa has led developers to revise their approach for the promotion of food production in the tropics. A lot of research has been initiated in the area of multiple cropping for crop production stability, resource conservation, reduction of inputs and more complete use of resources. Development of technologies suitable for small farmers should be within the context of multiple cropping systems.

SUMMARY AND CONCLUSION

In this paper, sustainable systems have been defined as those characterised by stable production. The general hypothesis of TSBF used provided a succinct statement of the current understanding of the role of soil biological processes in soil fertility and their relationships to management practices. It has been shown that the maintenance of fertility through soil biological processes requires management practices which control the quantity, quality and timing of decomposition of plant residues.

Stability is a property derived, at least in part, from the presence of feedback mechanisms within the system (e.g. nutrient cycling) and the development of component interdependence (e.g. symbioses).

Soil organisms may contribute to this in a number of ways: (i) improving and stabilising input of nutrients to plants by symbiotic associations of N-fix and mycorrhiza. (note also plant–plant bridges in mycorrhiza); (ii) stabilising nutrient cycles, e.g. provision of temporary and long-term (soil organic matter) immobilisation pools which inhibit nutrient loss from soil and operate in synchrony with plant demand (because they are regulated in similar manner); (iii) enhancing soil physical structure (soil fauna) and water regimes.

The capacity for this stabilising effect will be enhanced by greater diversity in the soil microbial and faunal community. The conditions which promote this diversity will have stabilising effects: e.g. diversity in the plant community leading to a wide range of substrates for soil organisms, improving soil microclimate, etc.

A more favourable environment for promotion of biological activity may be created by cultivation practices which (i) maintain continuous vegetational cover of the soil and extensive perennial root growth; (ii) encourage the return of plant litter to the soil; (iii) support a diversity of plants (preferably including legumes) and thence of litter inputs; (iv) minimise soil disturbance (e.g. by tillage); (v) minimise use of toxic chemicals.

Low-input technology suitable for rural agriculture in the tropics includes legume intercropping, minimum tillage with efficient residue management, and agroforestry combinations. It emphasises the importance of biological processes for soil fertility conservation at relatively low economic cost. Biological activities and their changes under these cultural practices have been little studied in tropical agriculture in spite of their importance in soil fertility management. Various models of biological processes have been proposed. They should be adapted to the conditions of the tropics. They will then form a basis for the understanding and improvement of soil fertility in this part of the world were food production has become the most critical factor of development.

The first steps should consist of a comparison in fertile and infertile soils of various soil factors including biological parameters, such as microbial biomass, soil respiration, urease, phosphatase, glucosidase, dehydrogenase, mineralisation potentials, lytic activities, earthworms casting, organic matter decomposition pattern, and numbers of important soil organisms.

Factors that will be highly correlated with soil fertility measured in terms of crop growth and yield for instance will be retained. Multiple regression tests would then be applied to appraise the interactions between these factors, and the effects of the interactions on soil fertility parameters. The most sensitive factors would be used to monitor soil fertility in experimental plots when soil degradation following land clearing and cultivation or where evolution of degraded soils under improved farming systems would be monitored. Once correlations between levels of the selected physico–chemical and biological factors and the levels of soil productivity are established, predictive models could be derived using the chosen factors for rapid assessment of soil fertility changes under various land management and cropping systems. Our knowledge of the influence of biological processes on soil fertility will undoubtedly form the basis for major changes in farming practices in the future.

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