

**INFLUENCE OF BIOLOGICAL PROCESSES ON SOIL FERTILITY: A RESEARCH  
PRIORITY FOR SUSTAINED CROP PRODUCTION IN THE TROPICS**

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**Introduction**

The most important groups of soils used for crop production in tropical Africa are Alfisols (FAO: luvisols; French: sols ferrugineux), Ultisols (FAO: acrisols; French: sols ferralitiques) and Oxisols (FAO: ferralsols; French: sols ferralitiques fortement desatures). They have low activity clay, very low inherent fertility, and various nutrient deficiencies and imbalances. In addition, Ultisols are highly weathered and acidic, with toxic levels of aluminum and/or manganese whereas Alfisols which have high base saturation present a low structural stability and are thus prone to soil erosion and compaction (Kang and Juo, 1981).

In the past decades, intensive use of industrial fertilizers was advocated to alleviate soil nutrient deficiencies for maximum food crop yields. These inputs require heavy financial investments that are usually beyond the means of the resource-poor farmer in Africa. After few years of application, inorganic fertilizers acidify the soil and create nutrient

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imbalances that are more difficult to correct. The fertility of a soil is often defined as its inherent capacity to supply nutrients and water to plants in adequate amounts and in suitable proportions (e.g. Gilmour and Allen, 1965; Brady, 1974). Nowadays, scientists recognize that physical and particularly biological factors influence soil nutrient status. Soil fertility studies must therefore include biological examinations.

The living phase in tropical soils includes viruses, bacteria, actinomycetes, fungi, algae, protozoa, nematodes, earthworms, arthropods, ants, termites, plant roots, and various enzymes. This soil biomass exhibits diverse types of activities regulated by climatic factors and through the multiple interactions between the organisms and between their effects. Simulation and conceptual models have been developed to facilitate our understanding of the processes. But to date very little information is available to explain the processes in the tropics. The large members of the macrofauna are not considered in the discussion because they have only limited effects in the soil environment.

In this paper, I shall briefly review some biological processes and indicate their role in crop production systems. Much is known about the processes themselves at a descriptive level. My major objective is to point out some aspects of the processes where research is urgently needed as a basis for sustained food production in tropical Africa. Our present

ability to manipulate biological processes is greatly hindered by the difficulties that we have to isolate, identify and enumerate accurately all the organisms in the soil environment where they are not uniformly distributed and where they may be tightly attached to the soil colloids. Our limitations reside also in our inability to assess the substrate and, often, the complexity of substrates that an organism may be consuming at a given time. The interactions between these multiple activities constantly changing in space and time following signals of diverse natures complicate our understanding of the dynamics of the processes such that they could be manipulated. Scientists, however, hope that mathematical modelling will stimulate more useful experimentation.

#### **EFFECTS ON SOIL STRUCTURE**

A well structured soil hold sufficient moisture to prevent water deficits in the root zone; it has sufficient gas-filled pores for gas exchanges with the atmosphere and to reduce the chances of localized anaerobic microsites; it can be properly drained to prevent waterlogging during wet periods (Lynch, 1983). A good soil structure is thus favorable to seed germination and root penetration; it promotes biological activities such as decomposition of organic matter, biological N fixation and nitrification, and it holds to a minimum the processes of anaerobic microorganisms (McCalla, 1945).

The principal mineral portion of the soil consists of sand, silt and clay. These components usually form aggregates held together by physical, chemical and biological forces. Bacteria and clays particles located in the fine pores of the aggregates exert a cementing action. Bacteria interact with clay particles by metal ion bridging or after polarization of their surface net negative charges (Lynch 1983, 1984). This cementing action is accentuated by organic binding agents. Polysaccharides originated essentially from microorganisms have a transient effect; roots and fungal hyphae bind soil particles in a temporary organization whereas resistant aromatic components such as lignin and resins, and strongly sorbed polymers stabilize the aggregates (Tisdall and Oades, 1982). Various monographs (e.g Berkeley et al., 1980; Lynch, 1983) present data and electron microscope photographs demonstrating the determinant role of microorganisms and their products in soil aggregation and stabilization. Microorganisms however can also decompose the soil binding agents. Based on the idea that microorganisms are the major agents in promoting soil structure, cultural practices, such as addition of straw to soil, that will increase soil biomass content will also improve soil structure. The use of inoculant composts containing populations of polysaccharide producers has been recommended as a means to increase soil stability and reduce erodibility (Lynch, 1983). Lignin, resins and other similar molecules, all products of microbial

degradation of organic matter, have been used successfully in limited areas to stabilize the soil and increase its water intake (McCalla, 1945).

Channelling and burrowing by soil animals result in soil redistribution in the profile and in increased soil aeration and porosity. During the process, earthworms produce casts consisting of fine particles, having more water stable aggregates than the underlying soil. Casting is an important activity of many earthworm species. It underestimates, however, their activity and the amount of soil ingested. Earthworm action on soil physical properties has been referred to as "biological tillage". On degraded Alfisols in Southwestern Nigeria, earthworm casting under improved cropping systems can be considered as a barometer of soil fertility improvement (Mulongoy, 1986b). Soil organisms like termites and earthworms are better able to penetrate compacted and poorly structured soils than are plant roots. Scott Russell (1977) found that, in the absence of earthworms, development of plant roots was only restricted to weak planes in compacted soils.

#### **EFFECTS ON SOIL CHEMICAL ASPECTS**

Soil biomass and organic residues constitute the main source of plant nutrients. During decomposition soil animals usually initiate the process with the mechanical breakdown of plant and animal residues in the topsoil. Their action results in improved

conditions for microbial growth. Many litter-feeding animals, however, delay their intervention until the quality of the litter has been modified by fungal action (Swift and Sanchez, 1984).

Decomposition processes are influenced by climatic and edaphic factors. Models have been developed predicting the global distribution of decomposition rates from the prevailing evapotranspiration pattern (Swift and Sanchez, 1984). Climatic factors regulate the system at a relatively coarse level. They set the broad limits of decomposition rates. The actual rate and extent of decomposition are determined essentially by the physico-chemical nature of the organic matter itself. High nutrient status and low contents of lignin and toxic molecules favor decomposition. Other factors affecting the kinetics of organic matter decay in ecosystems include its particle size, whether buried or on the soil surface, the soil type, the intensity and frequency of rainfall, the type of land management (for instance pesticide application, tillage system), and the nature of the decomposer community. Detailed monographs have been published on decomposition in terrestrial ecosystems with chapters on the process in tropical environment (Dickinson and Pugh, 1974a and b; 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  $^{14}\text{CO}_2$  released from

<sup>14</sup>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, and 1986a; IITA, 1983 and 1984; Yamoah et al., 1985.) 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 <sup>14</sup>C and/or <sup>15</sup>N plant materials. Jenkinson and Ayanaba (1977) used rye-grass uniformly labelled with <sup>14</sup>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 on the importance of standardized methods to study decomposition processes, as a

prerequisite to clarify and manipulate biological activities for improved tropical soil fertility (Swift, 1984).

Biochemical decomposition of organic matter consists of a series of enzymatic reactions occurring within and outside microbial or plant cells, living or dead. "The soil is virtually one big digestive system" (Wolf, 1977). Various oxidoreductases, hydrolases and transferases have been found active in soils (Burns, 1978; Lynch, 1983). The disappearance of substrates or the appearance of products is monitored to evaluate the activity of pure enzymes. The study of soil enzymes is complicated by the sorptive influence of soil colloids (Lynch, 1983) and by the interference of microbial growth. Enzymatic degradation of organic matter starts with the breakdown of large polymers such as lignocellulose, chitin and tannins catalyzed by exoenzymes. Both intra and extra-cellular enzymes are operative at a later stage. During decomposition processes, the mineral constituents may be left behind in an available form for plant use. Soil organisms can associate in various ways to perform their decomposing activity. For instance, termites harbour in their guts symbiotic cellulolytic protozoa and bacteria on which they depend for cellulose digestion; some have, in addition, symbiotic N fixing bacteria (J. Roy-Noel 1974).

Microorganisms can change soil pH, and produce organic acids or chelating agents that will solubilize some otherwise



unavailable nutrients. In agricultural soils, however, the plant roots can solubilize nutrients to a much larger extent than any microbiological process (Nye and Tinker, 1977; Tinker, 1984).

Soil microorganisms and extracellular enzymes are also involved in the transformation of man applied pesticides. After an adaptation phase, they either use the pesticide directly as a source of energy for their growth or degrade it via peripheral metabolic processes. Indirectly, soil organisms can cause changes in soil pH that will affect pesticide transformation. They can also produce substances that will interact with pesticides to facilitate or inhibit pesticide action and persistence.

Decomposition processes are intimately coupled to mineralization and immobilization of nutrients. Mineralization 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 fertilizers bypasses the biological pathways. However.

development of low input agriculture for farmers in developing countries cannot rely on expensive inorganic fertilizer inputs (Swift and Sanchez, 1984).

During decomposition and mineralization 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 a fundamental to soil fertility. It acts as a reservoir of mineralizable plant nutrients. Mechanical tillage accelerates its rates of decomposition probably by exposing the molecules to microbial and enzymatic breakdown. A new equilibrium will eventually be reached but its stability can be compromised by further tillage.

In soils, the rates of nutrient mineralization or immobilization are usually determined by N availability. The C:N ratio has been used to draw up some simplified generalizations. When the ratio is relatively high, microbial populations tend to multiply and immobilize nutrients, at least temporarily. When the ratio is relatively small, mineralization becomes prevalent. Manipulation of these two microbial processes can help to minimize nutrient leaching and to maximize the efficiency of

mineralization 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 compartmentalization 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 immobilization 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., 1981a and b) have confirmed these observations unequivocally. Microbial biomass value as a source of plant nutrients is further stressed by Lynch (1983) when he presents data indicating that biomass N can be released during the spring when the crop is most in need of it. Immobilization in winter would prevent leaching during this season. Similarly, soil organisms can immobilize for their own growth nutrients that are released in secretions and excretions, and during decomposition of their dead bodies. Earthworms for instance contain 10%N and 0.7-0.9% P and S (Syers and Springett, 1984). Also their casts contain more N,P, C and CEC than the underlying soil, and they are less prone to erosion as they have more water stable aggregates (e.g. Lal et al. 1982). Sharpley et

al. (1979) found that the amount of dissolved inorganic P and ammonium- and nitrate-N transported in surface runoffs were between four and eight times greater when earthworms were eliminated. Development of practices that can minimize nutrient losses are as important as promoting nutrient gains in farming systems.

If immobilization is a useful process in reducing nutrient losses through leaching, volatilization and erosion, there can be instances whereby soil biomass competes with the plant for nutrients. This biological nutrient 'tie-up' may create and intensify soil nutrient deficiency. 'Microorganisms eat at the first table; they are in contact with almost every particle of soil. Plant roots are not' (Wolf, 1977). Tinker (1984), however, considers biological tie-up of nutrients as being of little significance in natural ecosystems because microbial turnover is rapid.

Mineralized nutrients remain in soil solution. They are prone to losses by leaching, in runoffs and through volatilization. Denitrification is another pathway of N loss. A wide range of microorganisms including beneficial ones like the rhizobia catalyze under anaerobic conditions the reduction of nitrate or nitrite to gaseous N. Colbourn and Dowdell (1984) estimated gaseous losses of inorganic N in England equivalent to 0-20% of the fertilizer N applied to arable soils. Anaerobic conditions favorable to denitrification also stimulate the production of organic acids, hydrogen sulfur and other plant toxicants like ethylene by facultative anaerobes. The undesirable effects of these metabolites has been reviewed by Lynch (1983).

## SOIL BIOMASS MEDIATION IN PLANT NUTRIENT UPTAKE

From seed germination, plant root systems develop in an 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. In 1980, Kloepper et al., and Powell et al. also described siderophores that are bacterial compounds with a strong affinity for iron. Their significance in plant nutrition is uncertain (Tinker, 1984). They probably solubilize 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 profile 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 to 30% in a glasshouse experiment with rye grass 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 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 is reduced to combined N. Only some species of bacteria and blue-green algae possess naturally the nitrogenase enzyme catalyzing this reduction. In the last years, substantial amount of research has been directed

to transfer the nitrogen fixation genes to other microorganisms and to higher plants. Biological N fixation is highly energy demanding. It is therefore restricted to ecologies where the N fixing bacteria can find readily available sources of assimilable C compounds. Of all N 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. The objectives of these studies include the production of an enzymatic process that would rival the Haber-Bosch process for manufacturing N fertilizer, and the induction of dinitrogen fixation in non-legumes by transferring the N fixation (nif) and nodulation (nod) genes to the plant directly or through new microbe-plant combinations. Manipulation of the system has permitted the maximization of N 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 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 source of organic N for the benefit of non-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 fixing bacteria. These microorganisms obtain the needed energy in the form of root exudates. They, in turn, enrich with N the soil in the plant root vicinity. 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  $30 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  (Tinker, 1984). This may be important for natural vegetation but not for intensive agriculture. Nonetheless, associative N fixation expands the scope of biological inputs of N in agricultural systems. However, after a decade of intensive research into biological nitrogen fixation, scientists have failed to bring about substantial reductions in the use of N fertilizers at the farmer's level. Major efforts and funds are still devoted to find ways of maximizing biological N fixation instead of using the existing one in conjunction with N recycling.

Mycorrhizal infection is another symbiotic process that improves plant capacity for nutrient uptake. In this symbiosis,



the infecting fungal hyphae increase the effective absorbing surface of the plant for nutrients like P which is frequently limiting in tropical soils, Zn and some small soluble organic molecules such as amino-acids. Under low nutrient conditions in the lowland tropical forest and savanna areas, plants including food crops have the capacity to associate with appropriate mycorrhizal fungi, particularly the endomycorrhizal type belonging to the Endogone genus. Like the Rhizobium-legume symbiosis, mycorrhizal infections can benefit plant directly by improving their nutrient absorbing capacity and indirectly when mycorrhized plants, particularly perennial trees, are used as source of litter and/or mulch in agroforestry combinations. Positive interactions have been reported between Rhizobium and vesiculo-arbuscular mycorrhizae because nitrogen fixation depends much upon the level of P supply (Munns and Mosse, 1980; Tinker, 1984).

### Conclusions

Low input technology suitable for rural agriculture in the tropics includes legume intercropping, minimum tillage with efficient residue management, and agroforestry combinations. It emphasizes 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 where 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, mineralization potentials, lytic activities, earthworm 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 these interactions on soil fertility parameters. The most sensitive factors would be used to monitor soil fertility in experimental plots where 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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