

management properties
of
ferralsols



FOREWORD

Current projections on increasing population pressure and food production requirements in the next few decades show the urgent need for a world inventory of existing soil resources, and a realistic evaluation of their potential for agricultural production.

Huge areas in the humid tropics of Africa and South America are sparsely populated and offer sizeable possibilities for the expansion of agricultural areas. Climate and topography are highly suitable for vegetal growth but the prevailing soils are strongly weathered and require careful management. These soils formerly known as Latosols or lateritic soils are now classified as Oxisols (USDA, Soil Taxonomy), sols ferralitiques (French classification) or Ferralsols (FAO/Unesco Soil Map of the World).

As a result of their low fertility, shifting cultivation is at present the most widespread type of utilization of these soils. It includes long periods of fallow during which the soil organic matter and nutrient reserves, depleted after a few years of annual cropping, are reconstituted.

Under primitive agriculture and low population density, allowing for long fallow periods, shifting cultivation in humid tropics does not cause any major soil degradation. However, such low intensity type of utilization does not lend itself to accelerated agricultural development and in the areas where the fallow period has been progressively shortened due to population pressure, accelerated soil depletion and degradation are widespread.

It is also a general experience that intensive annual cropping and mechanized agriculture, as practised under temperate climates, may lead in a few years to serious degradation of Ferralsols, unless the cultural practices are carefully adapted to their delicate nutrient balance and the conditions of the tropical environment. With good management practices, however, high yields of both food and industrial crops can be obtained. Such potential for sustained production has been demonstrated in experiment stations, agricultural development projects and industrial plantations.

The purpose of the present Bulletin is to compile the information available on Ferralsols, their properties, the experience accumulated on their management and their production potential for intensive agriculture. It is hoped that this publication will contribute to a better knowledge of one of the most widespread soils on the earth, and to their optimum utilization and conservation.

This is a retyping of the original
bulletin produced in 1974

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INTRODUCTION

Most textbooks on crop technology are object oriented. They have proved to be the most efficient way to convey knowledge from the experimental stations to the farmers. Experience obtained on food crops, oil palm, sugar cane has been condensed in specific publications dealing with a particular plant.

There is no such thing in soil science. Before the advent of a world-wide accepted classification system and precise definitions of soil units, all efforts to compile a reference book on the management properties of a given soil would have been lost.

The FAO legend of the Soil Map of the World has in part filled the gap created by the absence of an internationally accepted classification system. It has provided an adequate basis for gathering information on specific soils, and making it available to farmers.

Ferralsols have been selected as the first soil order for which a reference publication should be made; they occur in tropical regions, where communications and the transfer of knowledge has not kept pace with the rapid development, and the needs of growing populations. Hopefully this bulletin will serve the purpose of bringing technology to the people who most need it.

The present work is certainly incomplete. It is physically impossible to be informed about all the recent advances which have been made on the management of ferralsols. This compilation mainly deals with the management properties which are important for the production of annual crops. Plantation agriculture of tree crops has not been given emphasis, although it is felt that it is an important utilization of the soils under consideration. The principal objective of this review is thus oriented toward food production.

It has not been easy to verify the identity of many soils which are referred to in the literature on soil management of tropical soils. In many instances interesting data could not be used because there was no way to identify the soils; in most cases only those experiments were taken into account where through personal visits to the regions there was a reasonable chance that the experimental fields were located in ferralsols. Due to this restriction the text may seem biased to agronomists working in areas which are incompletely known to the present author.

Grateful acknowledgement is expressed to all scientists who made it possible to accomplish the present work. Even more to all investigators who will send criticism, and in this way contribute in the future to the preparation of a more complete and improved version.

1. FERRALSOLS

1.1 Diagnostic Properties

1.1.1 Differentiating characteristics and definition

The class of ferralsols has been created by soil taxonomists in order to group the soils which are commonly found at low latitudes and present specific properties related to genesis, geographic location, and management practices. These soils occur mainly under tropical climates, and cover extensive areas on flat, generally well drained land. They are considered as being strongly weathered, and to be associated with old geomorphic surfaces.

The criteria which have been selected to define the ferralsols relate to properties that are characteristic of strong weathering in at least one horizon: an almost complete decomposition of primary weatherable minerals and a clay fraction which is dominated by kaolinite and/or sesquioxides. All soils which have a horizon with such properties which is at least 30 cm thick are grouped in the ferralsols. The diagnostic horizon is called the oxic horizon or the oxic B horizon, and is defined by FAO in accordance with the USDA "Soil Taxonomy" (1970) as follows:

"The oxic B horizon is a horizon which is not an argillic 1/ or a natric B 1/ horizon and:

- i. is at least 30 cm thick;
- ii. has a fine earth fraction (less than 2 mm.) that retains 10 meq or less of ammonium ions per 100 g clay from a 1N NH₄Cl solution, as follows:

$$\frac{\text{meq bases retained} \times 100}{\text{percent clay}} \leq 10$$

or has less than 10 meq of bases extractable with NH₄OAc and aluminium extractable with 1N KCl per 100 g clay;

- iii. has an apparent cation exchange capacity of the fine earth of 16 meq or less per 100 g clay by NH₄OAc (pH = 7), unless there is appreciable content of Al interlayered chlorite;

$$\frac{\text{meq CEC} \times 100}{\text{percent clay}} \leq 16$$

- iv. has no more than traces of primary aluminosilicates such as feldspars, micas, glass and ferro-magnezian minerals;
- v. has a texture of sandy loam or finer (in the fine earth fraction of less than 2 mm) and contains more than 15 percent clay;

1/ Argillic and natric horizons are horizons which show significant enrichment in clay which has migrated from overlying horizons. They have usually a blocky structure, a clear upper boundary, and show illuviation cutans (clay skins) on horizontal and vertical ped surfaces. There is a marked increase in clay between the A₁ and B_{2t} horizons over a distance of less than 30 centimeters.

- vi. has mostly gradual or diffuse boundaries between its subhorizons;
- vii. has less than 5 percent by volume that shows rock structure.

The purpose of developing such precise criteria for class definitions is to avoid confusion when soils are compared. More useful recommendations for soil management can be made when the variability of soil properties is restricted to well defined limits. It may nevertheless be helpful to explain the significance of some of the criteria and their pedogenetic and agricultural implications.

Ferralsols are old soils, or are soils that are developed in strongly weathered parent materials. There is usually no evidence of recent deposition in the profile, such as volcanic ash or fresh alluvium. Thin bedding or rock structure is normally absent, since the material has often been reworked by the soil fauna.

The oxic horizon does not release nutrients by weathering of mineral particles. Weathering has acted upon the soil to destroy all primary aluminosilicates (point iv of definition), and soil formation has obliterated the original rock structure (point vii). It is not possible anymore to recognize by the location and arrangement of the individual grains the type of rock from which the horizon was developed, or to detect traces of successive sedimentation by water or wind.

Since kaolinite or oxides are the dominant clay minerals, the capacity of the oxic horizon to retain cations is weak: by definition the cation exchange capacity at pH 7 does not exceed 16 milliequivalents per 100 g of clay. There is no possibility for oxic horizons to contain high amounts of organic matter either, because this would increase the cation exchange capacity above the critical level (see point iii).

Kaolinite has only a low inherent electric charge per unit weight (point ii). In water suspensions, especially in acid conditions, the individual particles cannot absorb a thick cloud of ions which would create repulsive forces and protect them against attraction; most of the clay in oxic horizon is flocculated.

Unless the colloids are protected by organic matter, or when positive charges are present in materials that contain exceptionally high amounts of ironoxides, the typical oxic horizons do not contain water dispersible clay.

Clay which is not dispersed does not move: hence the common absence of clay-enrichment or argillic horizons in ferralsols, and the lack of clear or abrupt textural boundaries between the horizons (point vi). An oxic horizon may therefore not be a horizon which has gained enough clay as to qualify for an argilluvic horizon. Soils with this horizon are usually not ferralsols, unless the illuviation horizon is located under the oxic horizon.

Soil taxonomists have not accepted coarse textured soils within the ferralsols concept. Soils which are rich in sand are not necessarily the product of strong chemical weathering. The dominance of sand particles in the soil material decreases the influence which the clay

fraction may have on the physical and chemical properties. An oxic horizon should always have more than 15 percent clay (point v).

The definition of ferralsols, extracted from the "Key to Soil Units for the Soil Map of the World" which was issued by FAO in September 1970, reads as follows:

Ferralsols are mineral soils (the thickness of the organic horizons does not exceed 40 cm), that have an oxic horizon. The upper boundary of the oxic horizon occurs at less than 125 cm depth. They may not show between 25 and 100 cm of the surface intersecting slickensides ^{1/} or wedged shaped structural aggregates, and cracks which are at least 1 cm wide at a depth of 50 cm. They should not have a spodic horizon.

This definition is a broad one; it covers a wide range of soils and it is centered around the concept of the oxic horizon. Almost all profiles that have an oxic horizon are ferralsols; exceptions occur when the oxic horizon is buried at more than 50 cm depth by materials that are not oxic. This is not a frequent case however, and it does not deserve special attention. By "buried" is meant the actual deposition of material on top of the diagnostic horizon, and not the mere presence of other pedogenetic horizons.

According to the present definition, ferralsols may have sandy textures in some horizons; they may also have an argilluvic horizon below the oxic horizon. They may be influenced by water tables as to form either gley, mottling or plinthite (soft laterite). Such double feature profiles are not uncommon. For this reason it is necessary to subdivide the ferralsols into more homogeneous groups.

1.1.2 Modal concept

The broad definition which was given in the previous section, leaves ample margins for variations. It may therefore be helpful to define and describe the central concept of a ferralsol and try to visualize a modal profile.

Ferralsols are usually deep soils because both the intensity and the duration of weathering have been considerable; the most favourable conditions for the formation of kaolinite are found under free drainage, when silica and bases produced by the weathering of the parent materials can be freely leached out of the profile. These circumstances are conducive to good aeration, under which iron is immobilized in the oxidized stage. It stains the smallest soil particles with yellowish or reddish colours. Most ferralsols are strongly coloured. Ironoxides also contribute to the aggregation of clay and silt which creates porosity and most oxic horizons are friable and have a well aerated structure. Air and water can usually circulate freely through ferralsols; rainfall acceptance by these profiles is usually faster than by most other soils of comparable texture; it also leaches quite rapidly to deeper layers that are beyond the reach of the common rooting of most cultivated crops. Physically, rooting space is abundantly available.

^{1/} Slickensides are polished and grooved surfaces produced on aggregates by one mass sliding past another. They are common in swelling clays that have marked changes in moisture content (U.S.D.A., 1960).

Strong leaching of nutrients and bases is a general property of ferralsols. Downward movement of water is seldom impeded, and the retention of nutrients by the clay fraction which should protect them against losses is not very active. As a result most ferralsols are low in cationic nutrients and the oxic horizons have low pH. The mineral part of a modal profile is considered poor. The amount of available plant nutrients is almost completely dependent on the amount and the quality of the organic matter.

An acid, strongly coloured, deep profile is called typical under most tropical environments. It has usually favourable physical conditions for plant growth, but is deficient in nutrients. This concept of a modal ferralsol may differ from earlier ideas, which related the ultimate stage of tropical weathering to the irreversible induration of friable soil into ironstone upon exposure to sunlight after clearing the forest or during intensive cropping. Such horizons may occasionally occur in ferralsols. However, they are or were previously associated with wetness of the soil and watertables which fluctuate at the depth of the indurating layer. Remnants of such layers, that have hardened, forming ironstone or ironstone gravel, are frequently found. In this context they are not considered an essential part of the modal concept however, but rather as an inactive soil constituent.

1.1.3 Accidental characteristics

As pointed out before, the definition of ferralsols is sufficiently generalized as to accept within its range of variability a considerable number of soils which have striking differences in the composition and the arrangement of horizons and layers.

Stone-lines may interrupt the diffuse transitions from one horizon to another by the sudden appearance of a layer of gravelly material, either rich in quartz or ironstone. If these gravelly layers are closely packed, thick enough and near the surface, root growth may be severely restricted. The soil volume which is accessible to plant roots may also be limited by the groundwater level, and profiles with impeded drainage may present strong mottling due to oxidation reduction reactions of iron compounds.

The organic matter content may be extremely variable and not all ferralsols are poor in organic carbon; in hot equatorial regions, the A₁ horizons are usually thin; even under a dense rainforest, they seldom exceed ten centimeters in thickness. In cool tropical climates, for example at high elevation, the humus content is high, and dark coloured topsoils may cover extensive ferralsolic areas. Other regions where humus tends to be present in considerable quantities are those which at some period have been influenced by basic volcanic ash falls or which contain high percentages of iron oxides.

Other factors, besides climate, may affect soil properties. The nature of the parent rocks may cause marked differences in pedological properties, even in strongly weathered sediments. They are reflected in the particles size distribution, colour and the iron oxide content. Ferralsols from basic rocks have redder hues than those which have developed from acidic rocks, which contain more quartz. The clay content in residual soils depends on the amount of weatherable minerals of the original rock. Geology therefore creates a large variety of subgroups and soil families, that are important to distinguish when evaluating ferralsols for crop

production, or when recommending management practices. Hence the necessity to subdivide the ferralsols into several classes some of which are listed in chapter 1.3.1.

For purposes of fertilization the mineralogy class is particularly important, and special attention should be paid to soils which are either ferritic (more than 40% Fe_2O_3 extractable by citrate dithionite), gibbsitic (more than 40% of gibbsite and boehmite) or oxidic (others which have more than 20% ironoxides plus gibbsite in the clay fraction) (SCS, USDA, 1970). The high amounts of oxides in the exchange complex of these soils may indeed have a marked influence on the nutrient supply in ferralsols. These questions will be discussed with more detail in other parts of this review.

1.2 Related Geographic Distribution

1.2.1 Climatic regimes

Most ferralsols are found at low latitudes lying between the parallels of the tropics ($25^{\circ}27'$). These astronomic lines are not exclusive however and do not set clear boundaries to the distribution of these soils over the world.

The mean annual temperatures may be low and some ferralsolic regions may have as many as ten frost days per year. Precipitation also varies markedly, and the soils may have moisture regimes grading from arid to permanently humid.

Most if not all ferralsols occur under tropical climates and it is worth remembering the unifying characters of the temperature and moisture regimes of the profiles. It is mainly rainfall which determines the cropping period in ferralsols; temperature variations have practically no influence in this respect. The range of monthly temperature changes is narrow, and seasons for plant growth are not defined by a sequence of cold and warm months. The mean annual temperature as it follows changes in elevation ($0.6^{\circ}\text{C}/100 \text{ m}$ or $3.2^{\circ} \text{F}/1000 \text{ feet}$) is only important in the selection of crop and crop varieties.

The primary limiting factor of the duration of the growing season is the amount and the distribution of rainfall during the year. In ferralsols the importance of climatic moisture regimes cannot be over-emphasized. Precipitation reaches its maximum during the astronomic summer, i.e. in each hemisphere the highest rainfall coincides with the summer months in the same hemisphere. At the beginning of the rainy season, there is generally no stored water available to plants in the top layers of well drained ferralsols. This is a contrasting situation as compared to moisture conditions at higher latitudes where the warm growing season starts with the maximum amount of water stored in the soil during the cold winter, when evapotranspiration was low.

Other effects of the tropical climate on management practices are important. In areas with a dry period, the growing season usually starts at the onset of the rains with a high amount of nitrates or nitrifiable residues in the soil. The formation of easily mineralizable organic matter continues during the tropical dry season; nitrification may also go on provided the soil moisture content is not too low. Since there is no leaching and no plant growth, nitrates tend to accumulate in the soil.

This is a contrasting environment compared to conditions in temperate and Mediterranean regions, where the winter temperatures are too low for producing higher amounts of nitrates than can possibly be leached by the percolating rainfall (GREENLAND, 1958).

The climate, more specifically the wet and dry season sequence or the distribution pattern of rainfall during the year, is the key factor for adapting management techniques to local conditions. The duration and the number of dry seasons determine whether one or more cropping cycles will be possible annually, and if irrigation should be considered.

For general purposes it is useful to refer to De Martonne's diagram (fig. 1). Although it is an idealized illustration of the march of rainy periods during the year, it clearly shows the relationship between latitude and rainfall distribution; cloud formation and precipitation reach a maximum in the region of atmospheric convergence which follows the sun's zenithal course between the tropical parallels. This leads to a sequence of wet and dry, or maximum/minimum rainfall periods at given latitudes.

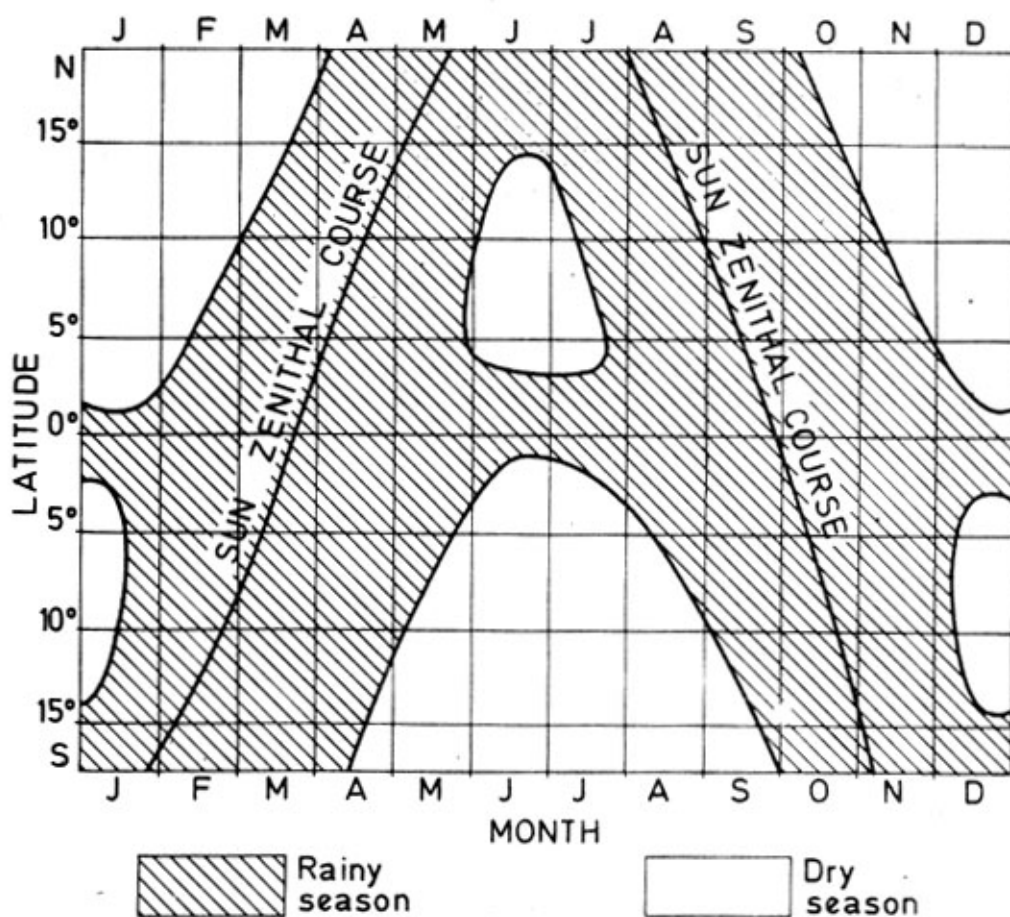


Fig. 1 - Diagram of march of seasons in the intertropical regions (DE MARTONNE, 1958) 1/

In De Martonne's diagram two climatic belts can be recognized; the first one where permanent rain or two long rainy seasons leave room for two crops during the year. The second belt, at higher latitudes, allows only one crop to be grown annually. They are usually referred to as the equatorial and tropical belts.

It may be pointed out that the origin of the rains is largely convectional and that they fall in heavy showers. This dense precipitation at the beginning of the rainy season may cause strong erosion on soils which are not covered by vegetation, as is often the case at the end of the dry period.

1.2.2 Landforms

Ferralsolic regions are typically situated in areas which have not been subjected to intensive folding during recent geological periods, but rather went through long periods of broad and gentle upwarping into swells and downwarping into basins. These minor movements in the earth's crust took place on stable continental platforms, usually with crystalline foundations. In places where the crust broke, tectonic rift valleys were formed, with local, usually basaltic intrusions. The form of these platforms have sometimes been compared with cracked pavements.

Typical examples of ferralsols which occur on these old continental stable shields can be observed in Central Africa, the Brazilian and Guinean shields of South America, and the remnants of old surfaces in the Indian peninsula.

The maps of fig. 2 and 3 show the extent of the regions where ferralsols are dominant in South America and Africa.

Outside the continental platforms the ferralsols are rather rare even under hot humid conditions; Asia and Central America have been subjected to the Alpine orogenesis, and as a rule erosion has constantly removed the weathering products of most parent materials. Only those sediments which weather rapidly such as basic and ultrabasic rocks (for example basalts) or basic volcanic glass, have had time enough to form oxalic horizons.

Generally speaking most ferralsols occur on horizontal uplifted landscape surfaces. These are not necessarily large but they may be scattered like small islands in a steeply sloping topography. They are then remnants of more extensive flat old surfaces which have been dissected by rivers. This is for example the case in the horst region bordering the rift valley in Africa, which was uplifted without much recent folding of the substratum. Good examples of this type of distribution can also be found in Puerto Rico.

The dominant occurrence of ferralsols in flat topography has attracted the attention of many people, because the level plateaus facilitate access, reduce erosion hazards, and offer considerable possibilities for modern mechanized agriculture. When this type of land utilization is envisaged, flat topography is undoubtedly one of the ferralsols' chief assets.

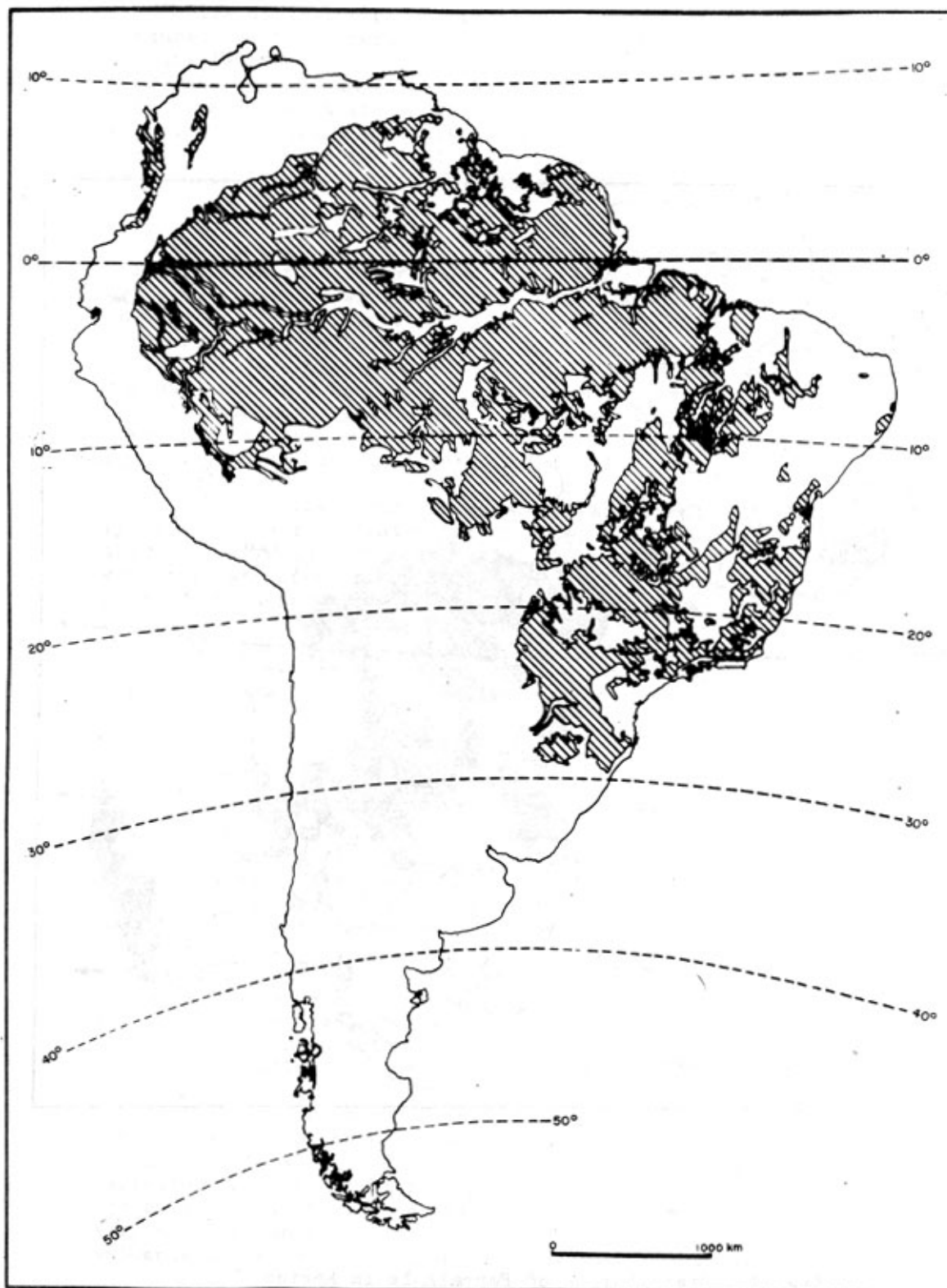


Figure 2 - Distribution of ferralsols in South America

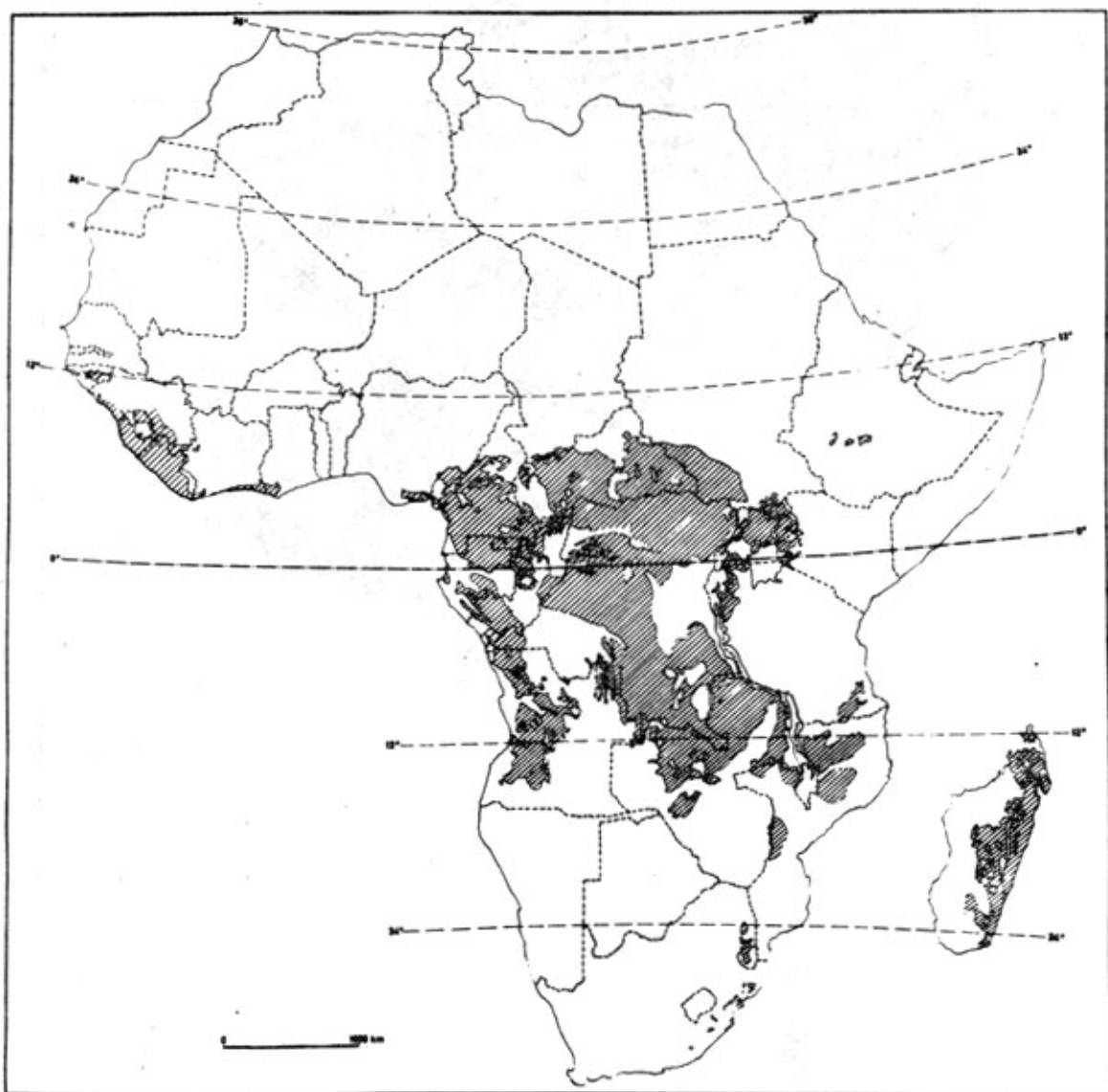


Fig. 3 - Distribution of Ferralsols in Africa

The distribution of ferralsols is related to local landscape features. The topographic factors are the slope gradient, its shape, and its length, which all may correlate with soil properties in many different ways. Huge areas with ferralsols are still open for utilization, and the choice of the best available ferralsols may prove essential in future agricultural planning and determine either failure or success of new agricultural operations. Selection of adequate soils is an essential part of good land management.

Only some principles for guidance in the choice of land will be discussed in this chapter. They have mainly local importance. Relationships between topography and soils are studied first: flat topography protects the soils against runoff and erosion; therefore they are mostly covered by old sediments which are more strongly and deeply weathered than the surrounding valley slopes. Soil water may also be at greater depth on the uplifted plateaus. Less runoff means more water penetration into the soil and more leaching. Consequently the chemically poorest soils occur on the high level areas. This is particularly striking in areas where rivers have cut into rich parent rocks which rapidly develop into productive soils on sloping topography (fig. 4a).

Not all the parts of the slopes in ferralsolic areas are necessarily better from the plant nutrient viewpoint than the land on the flat elevated surfaces. Convex parts, where surface water increases its velocity, are often badly eroded, or highly susceptible to erosion. The profiles in these sites may be truncated, and may contain less organic matter (fig. 4b). Humus is the main supplying power of nitrogen to plants, and is of great value in preventing leaching of nutrients. Erosion may also bring gravelly layers and stone-lines closer to the surface, and may create soils which are too shallow for optimum root development.

In areas that are underlain by poor sedimentary rocks, or are covered by thick sediments in which quartz or oxidic materials dominate, the dissection of the plateaus by shallow river valleys does not modify the nature of the parent materials. Erosion can only take weathered soil materials at the edge of the plateau, and transport it down into the valleys. During this process, soil particles are sorted. Sands remain usually on the slopes, and the clay is partially removed in suspension in the running water. The resulting topographical soil sequence acquires a textural gradient, where the heaviest soil is found on the highest undissected parts of the landscape, and the sandiest soils on lower lying slopes or concave parts of the valleys (fig. 4c). These sandier soils are more permeable to water and dry out more easily. For these reasons they are less suitable for agriculture than the heavier textured associated soils. In such catenas, which present very often parallel colour changes from red to yellow the plateau soils are to be preferred.

The shape of the declivity may also be important. Concave sites tend to receive more water and erosion products than plans or convex gradients. Small differences in these landforms may give considerable variation in land capability, particularly when soil organic matter is redistributed in various parts of hilly topography. Local farmers have very often taken advantage of privileged sites by placing their most valuable crops in hollows, where humus rich colluvium accumulates.

Relief - related distribution of FERRALSOLS

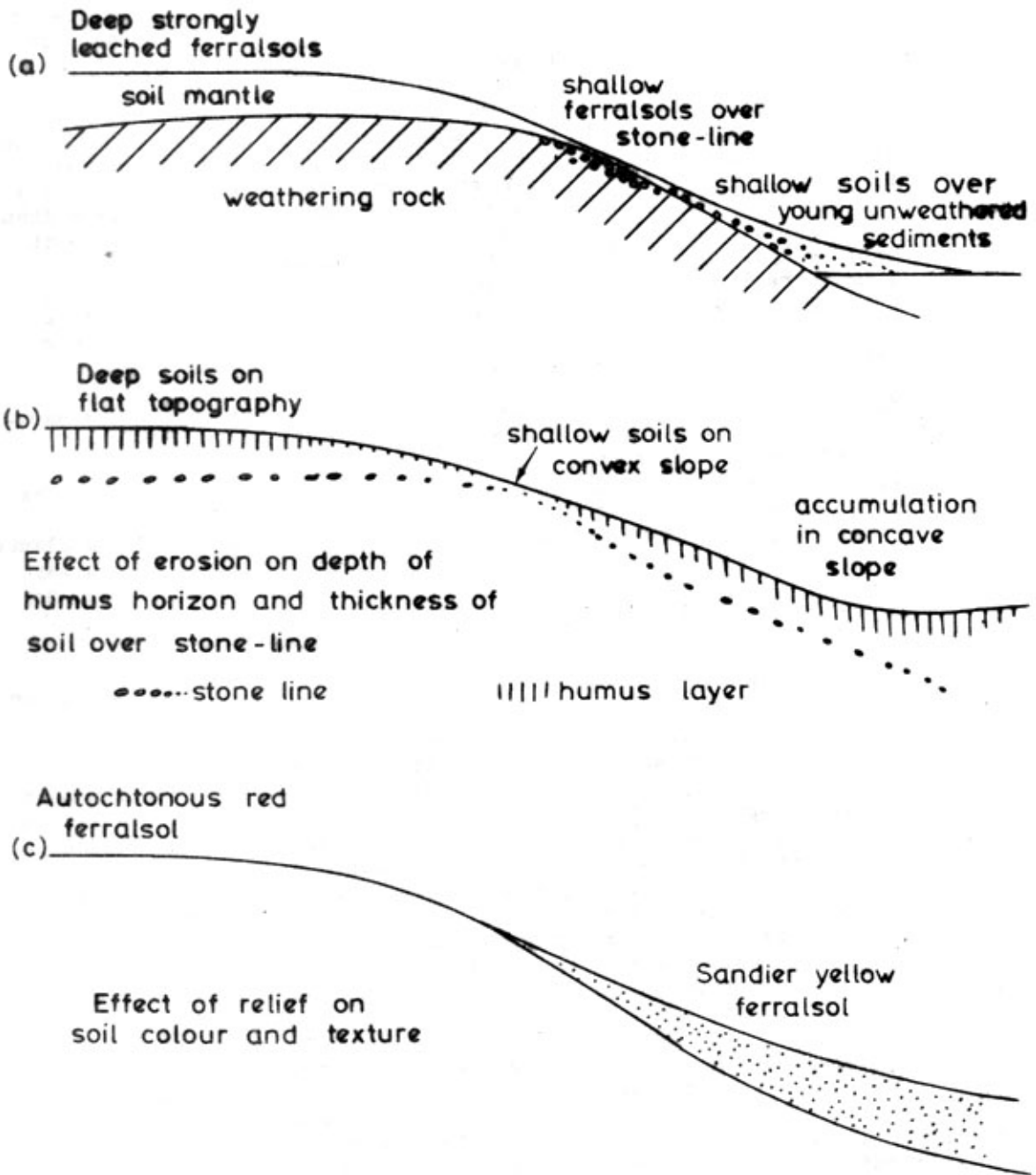


Fig. 4 - Relief related distribution of Ferralsols

There are probably no rigid rules which in all cases would make it possible to delineate on the basis of topography alone the most suitable ferralsols in a given area. Good management of ferralsols starts with the selection of the most productive ones which will be competitive when they are included into a modern market economy. Of course, all soil imperfections may be corrected but never without additional costs. Therefore all agricultural programmes, at whatever level, may greatly benefit from adequate soil selection based on good soil mapping. Local topography and parent material are usually important factors in differentiating soils. At the same time the relief offers reliable external features which help soil mapping and the design of proper erosion control measures.

1.2.3 Vegetation

There are many kinds of vegetation on ferralsols. None of the diagnostic properties of the oxic horizon which are related to the mineral part of the soil, seem to determine the type of vegetation, or exclude the possible development of any particular plant association.

Vegetation patterns rather follow climatic changes and differences in soil drainage classes. Human influence is capable of modifying the distribution of plant communities in the most drastic way.

As present definitions now stand, no cause to effect relationship seems to exist between the ferralsols as a whole and broad vegetation types. Except in the case of a part of the Humic Ferralsols, which will be defined later and which are mainly associated with mountain vegetation of cool tropical climates, all other classes in the FAO system have no climatic nor vegetation implications.

The plant cover seldom reflects the long-term potential and the qualities of the ferralsols, and no conclusions should be drawn regarding their productivity on the basis of the vegetation alone.

This does not mean however that no attention at all should be paid to the kind of vegetation when evaluating the fertility status. Soils are more than mineral bodies, and the type of soil organic matter, which is closely related to the kind of plant cover, is a major although transient production factor. For example, most agronomists in the tropics are aware of the strong differences in potential between land under savanna and under the rainforest. Some types of secondary regrowth may reflect striking differences in temporary fertility levels which can hardly be detected by accurate chemical analyses and sampling techniques. Most local farmers can evaluate tracts of land on the basis of certain plant species or plant associations. In areas covered by ferralsols small differences in vegetation may be closely related to temporary fertility.

The nature of the soil organic matter at a given time depends on the types of vegetation which recently covered or actually covers the soil; its behaviour when soils are put into cultivation is determined by the disequilibrium in ecological conditions which is caused by clearing, plowing, mulching the soil or its exposure to direct sunlight. Management of ferralsols therefore has to consider the position of a given crop in a rotation, the time after clearing, and the types of fallow, more than the actual amount of organic matter in the soil, if maximum use of the natural fertility is intended.

The vegetation itself may be an asset in the nutrition of plants. Considerable amounts of nutrients are stored in the tissues. Table 1 taken from NYE and GREENLAND (1960) sets figures for estimating the importance of this nutrient reserve which may be released either slowly or quickly, depending on the practices that are used for clearing land.

Table 1 IMMOBILIZATION OF NUTRIENTS IN THE VEGETATION (KG/HA)
(NYE AND GREENLAND, 1960)

	N	P	K	Ca	Mg
Rainforest 40 years	1832	125	819	2527	346
Primary rainforest	1236	123	954	2120	325
Secondary forest					
18 years	560	73	405	562	
5 years	391	24	344	293	

Savanna					
grass	27	8	46	35	26
tress	(100)	(15)	(146)	(235)	(63)
Imperata Savanna					
grass	17	6	35	7	13
rhizomes	29	13	71	7	10

1.3 Kinds of Ferralsols

1.3.1 Main subdivisions

The key to soil units of the Soil Map of the World (FAO, 1970), subdivides the ferralsols according to the following criteria:

- i. Ferralsols having a plinthic horizon at less than 125 cm depth.

Plinthic Ferralsols

- ii. Other ferralsols having an organic matter content (weighted average of the fine earth fraction of the soil) of 1.35 percent or more to a depth of 100 cm (exclusive of an O horizon if present); having a base saturation of less than 35 percent (by NH_4OAc at pH 7) at least in some part of the B horizon.

Humic Ferralsols

- iii. Other ferralsols having an exchange capacity (from NH_4Cl) of 1 meq or less per 100 g of clay in at least some part of the B horizon; having no discernable structure in the B horizon or only very weak blocky or prismatic peds.

Acric Ferralsols

- iv. Other ferralsols having a red to dusky red B horizon (rubbed soil has hues redder than 5YR with a moist value of less than 4 and a dry value not more than one unit higher than the moist value).

Rhodic Ferralsols

- v. Other ferralsols having a yellow to pale yellow B horizon (rubbed soil has hues of 7.5YR or yellower with a moist value of 4 or more and a moist chroma of 5 or more).

Xanthic Ferralsols

- vi. Other ferralsols.

Orthic Ferralsols

The purposes of the taxonomists who prepared the key were to separate the ferralsols into groups that are genetically and morphologically homogeneous, and which require similar management practices. The key works by successive elimination of classes.

The first class is set up in order to separate all ferralsols which have a plinthic horizon with its upper boundary at less than 1.25 meter. These soils undoubtedly suffer from impeded drainage during some periods of the year, and are saturated with water during most months in the plinthic part of the profile. The genetical implications for this class are the presence of a fluctuating water table, and the supply of free iron oxides mainly in the low lying parts of the landscape. There are no climatic implications in the concept. From a practical point of view, these adverse conditions call for special care in order to improve aeration of the soil as root development may be restricted periodically by water excess. The agricultural value of the Plinthic Ferralsols will greatly depend on the thickness and the quality of the horizons which lie above the plinthite. If these are too shallow, there is no interest in bringing them into cultivation as there is no point in draining land that hardens into ironstone after removal of the surplus water.

The Humic Ferralsols are soils without plinthic horizons at shallow depth that are rich in organic matter and have a low base saturation. They are typical for the cooler regions that are either situated in mountain areas or at high latitudes. At high elevation the orogenic precipitation increases the leaching intensity and the soils are poor in cations.

The high organic matter content is considered as being the result of slower decomposition; the lower class limit allows a minimum of 0.78% organic carbon as a weighted average of all horizons down to a depth of 100 cm, not including the litter (O horizon). An example of a calculation may help to clarify this diagnostic criterion:

Depth (cm)	Thickness (t) (cm.)	% (c)	t x c	Weighted average
0-10	10	3.4	34	
10-25	16	2.8	42	
25-70	45	1.0	45	$\frac{\Sigma (t \times c)}{100} = 1,43$
70-90	20	0.9	18	
90-120	10	0.4	4	
			SUM = 143	

The profile considered in this example can be classified as a Humic Ferralsol, provided it has a base saturation which is lower than 35%, and that the profile does not present a plinthic horizon at less than 125 cm depth. Although there is no soil temperature restriction in the definition, it is assumed that most of these soils occur in cool climates. However, careful attention should be paid to the question whether the humic ferralsols present acric properties in addition to the humic ones. In this case management decisions should be based on the acric properties rather than on the richness in humus.

The other four remaining subunits of the ferralsols mostly lie in the warm tropical and equatorial regions. The limit with the previous climatic zones lies somewhere around 22°C (72°F) mean annual temperature. The four classes which have been recognized are separated by criteria related to clay mineralogy, cation exchange capacity and base saturation. These differentiating characteristics are to a certain extent defined by the intensity of weathering and the lithological composition of the parent rock. In this respect the iron and aluminum oxides may play an important role in setting the physico-chemical properties of the soil.

The Acric Ferralsols are usually soils that have a high amount of sesquioxides which produces a net positive charge on clay-size particles. Instead of increasing the capacity to retain cations such as Ca, Mg and K, the iron-oxides on the contrary block the existing negative adsorption sites. In extreme cases 100 g soil in the B horizon can only adsorb less than one milliequivalent of bases. These soils are usually clayey, and have normally been subjected to very humid climates during their formation. They are usually very hard to reclaim and to bring into successful types of agriculture. There is not only a strong nutrient shortage, but also a very high capacity of the soil to fix phosphates and to adsorb Ca specifically. Calcium deficiencies are common in these soils. Frequently the pH of the soil measured in normal KCl is higher than the pH measured in water.

The Rhodic Ferralsols, are those ferralsols of the warm tropical regions which have no acric properties, and that are mainly formed on basic rocks, such as basalts, diorites etc. The weathering intensity has not reached the advanced stage of the acric group. Dusky red colours which do not change very much upon wetting and drying are common.

The rhodic soils are preferred in ferralsolic areas, as their potential within this class is certainly the highest. Many examples are known where agriculture has been successful on them, and the nature of the original rock often provides possibilities for an almost continuous nutrient supply from layers below the oxic horizon. Their heavy texture retards the downward movement of water. Their high content of total phosphorus and calcium allows the maintenance of high organic matter levels in the topsoil, at least in the absence of erosion.

The other two remaining groups are the common red and yellow ferralsols, which have been called Orthic and Xanthic in the FAO classification system. Yellow latosols are usually the sandier members of the group, or those that are developed from acidic rocks having a high quartz content. They may also have developed in colluvium on lower slopes. These transported parent materials are currently poorer than the autochthonous soils. It is assumed that they may have lost some of their potential value during the translocation of materials. Red and Yellow Ferralsols often occur in catenary association, the reddish members occupying the higher parts of the relief, and the yellow ones covering the sloping land.

Figure 5 gives an idealized cross-section of the distribution of the different kinds of ferralsols in a hypothetical broad landscape. The next section provides complete description and analysis of typical profiles.

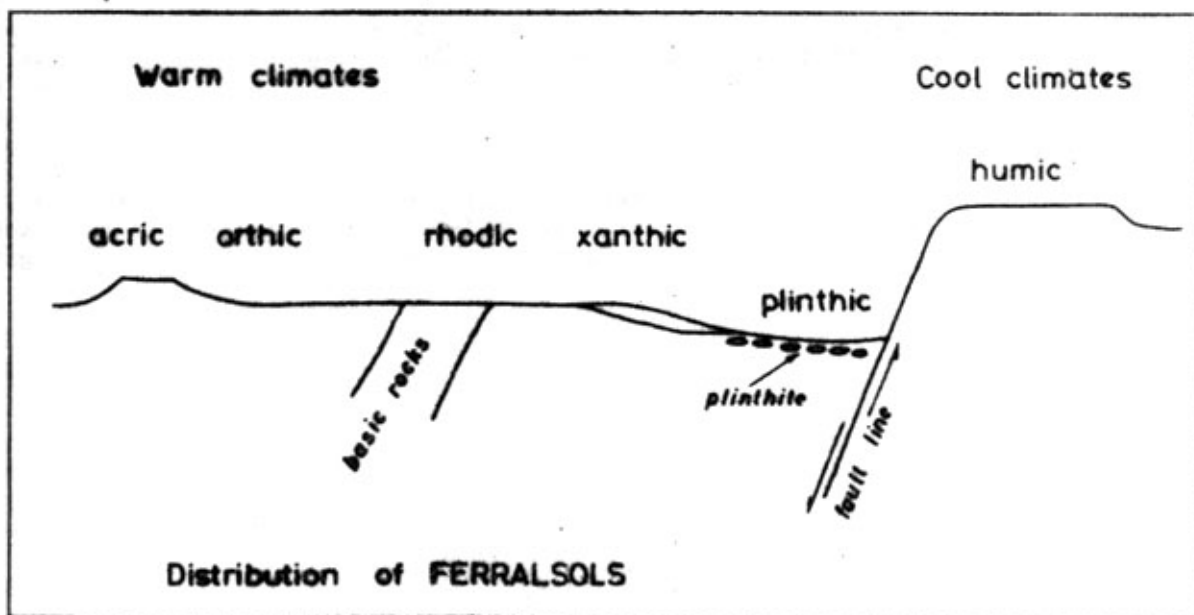


Fig. 5 - Distribution of kinds of ferralsols in the landscape

1.3.2 Correlation with order classifications

The name ferralsols is of recent origin, and much of the earlier literature which deals with their management would become unavailable, if no correlation with other taxonomic system would be made.

The concept of ferralsol of the FAO legend is almost synonymous with the term latosol, as defined in Brazil. One should not extend this identity to the latosols of other regions however. Many Hawaiian latosols, and most latosols which have been described in Central America, do not correspond with the FAO concept of ferralsols; they have generally too high a base exchange capacity (pH 7) which is probably due to contamination by volcanic ash and the presence of allophane.

A very close correlation of ferralsols can be made with the Oxisols of the U.S.D.A. Soil Taxonomy. The only minor discrepancy would be that the oxisol order does not allow profiles with a textural B horizon above the oxic horizon, whilst the FAO system is not specific on that particular point. Such cases are relatively rare however.

The ferralsols can also be compared with the Sols Ferrallitiques Typiques of the French classification. It should be pointed out that the correlation is best achieved with the "typic" groups that are recognized in the "Classe des Sols Ferrallitiques". The other groups, as the "groupes des sols pénévulés, groupes lessivés" do not fall completely within the concept of the ferralsols, and preliminary checking on representative profiles is necessary.

The ferralsols can finally be compared with most Kaolisols of the classification which is used in Zaire. The closest similarity exists with the ferralsols suborder in this national classification system, whilst a certain number of ferrisols, but not all, would fall outside the FAO concept.

At a lower level of generalization the comparisons become more difficult. There are practically no perfect identities between subclasses of different systems. A tentative very loose correlation scheme is given in table 2.

Table 2

BROAD CORRELATION OF SOIL CLASSIFICATION SYSTEMS

F.A.O.	U.S.D.A. Soil Taxonomy	French Classification
Plinthic Ferralsols	Plinthaquex, Plinthic subgroups	Sols à accumulation de fer en carapace ou cuirasse.
Humic Ferralsols	Humex, some Acrorthox and Acrostox	Groupe des sols ferrallitiques moyennement désaturés en (B) - humifères. Groupe des sols ferrallitiques fortement désaturés en (B) - humifères.
Acric Ferralsols	Acrorthox, Acrustox	Groupe des sols ferrallitiques fortement désaturés en (B), typiques, sous-groupe modal.
Rhodic Ferralsols	Orthox and Ustox derived from basic rocks or limestone	Groupe des sols ferrallitiques faiblement ou moyennement désaturés en (B), typiques, dérivés de roches basiques ou de calcaire.
Xanthic Ferralsols	Orthox and Ustox which are yellow in the oxic B	Groupe des sols ferrallitiques faiblement ou moyennement désaturés en (B), typiques, jeunes.
Orthic Ferralsols	Other Orthox and Ustox	Autres sols ferrallitiques faiblement ou moyennement désaturés en (B), typiques.

1.3.3 Description and analysis of typical profiles

i. Acric Ferralsols

Classification: Haplic Acrorthox, clayey, kaolinitic, isohyperthermic.

Location: Amazonas State, along Highway Am-070, 10.5 km from Cacau-Pirêra toward Manacapuru, on the right side 100 m from the road.

Physiographic position: Top of low, gently undulating plateau.

Topography: Level with gradient, 0 to 2 percent.

Drainage: Well drained.

Vegetation: Evergreen tropical forest.

Parent material: Clayey Tertiary sediments of the Barreiras series.

Sampled by: Team of pedologists of IPEAN.

Soil No.: Profile no. 8

Remarks: Very much biological activity in the A1 and A3 horizons, declining to very little in the B22 and B23 horizons. Current earthworm activity has produced pyramidal hills on the surface that are 15 to 20 cm high and 10 to 15 cm in diameter at the base. The forest litter consists of a few partially decomposed leaves and a very few that have not begun to decompose. Many 1 to 2 mm pores throughout. Concretions occur throughout pedon. Charcoal fragments occur in A3.

Colors are for the moist soil.

A1 0-4 cm (0-2 in.). Yellowish brown (10 YR 5/4) sandy loam; moderate fine and medium subangular blocky and weak fine granular structure; friable (moist), slightly sticky and plastic (wet); many fine common, medium, and few coarse roots; clear smooth boundary.

A3 4-19 cm. (2-7 in.). Yellowish brown (10 YR 5/6) light clay; weak fine and medium subangular blocky and weak fine granular structure; friable (moist), sticky and plastic (wet); many fine and common medium roots; diffuse smooth boundary.

B21 19-87 cm. (7-34 in.). Brownish yellow (10 YR 6/6) heavy clay; weak fine and medium subangular blocky structure; friable (moist), very sticky and very plastic (wet); many fine and common medium roots; diffuse smooth boundary.

B22 87-130 cm. (34-51 in.). Brownish yellow (10 YR 6/8) heavy clay; weak fine and medium subangular blocky structure; friable (moist), very sticky and very plastic (wet); few weakly expressed smooth ped faces; many fine and few medium roots, with medium roots located near the zone transitional to the superjacent B21; diffuse smooth boundary.

B23 130-180 cm. (51-71 in.). Strong brown (7.5 YR 5/8) heavy clay; weak fine and medium subangular blocky structure; friable (moist); very sticky and very plastic (wet); common smooth ped faces; common to many fine roots.

Analysis of Acric Ferralsol 1/

Horizon	Depth (cm.)	Size Class and particle diameter (micron)								Extr. Fe %	15 bar water %
		2000	1000	500	250	100	50	20	2		
		1000	500	250	100	50	20	2	0		
A ₁	4	4.7	17.7	15.1	18.6	4.2	1.8	3.2	34.7	1.76	13.1
A ₃	19	2.0	8.9	9.7	13.7	3.8	1.5	4.2	56.2	2.72	19.0
B ₂₁	87	1.9	6.9	7.5	11.1	3.5	1.3	3.6	64.2	2.72	20.8
B ₂₂	130	2.0	4.4	4.6	6.8	2.0	0.8	2.0	77.4	2.77	27.0
B ₂₃	180+	1.7	3.7	3.2	4.8	1.5	0.9	3.4	30.8	2.93	29.9

Horizon	Organ. C. %	Nitrogen %	pH (1:1)		CEC (meq/100 g.)				
			pH (1:1)		Sum of cations	NH ₄ OA (pH 7)	NH ₄ Cl	Sum of cations	NH ₄ OAc
			H ₂ O	KCl					
A ₁	2.76	0.20	4.1	3.5	13.0	6.7	3.2	2	4
A ₃	1.13	0.12	4.4	4.0	8.2	3.4	2.3	2	5
B ₂₁	0.58	0.07	4.7	4.2	6.0	2.8	1.7	1	2
B ₂₂	0.29	0.05	5.4	4.5	5.1	2.4	1.1	1	2
B ₂₃	0.22	0.05	5.6	4.8	4.8	2.1	1.2	1	1

Horizon	Extractable bases (meq/100g.)					Extract. (meq)	
	Ca	Mg	Na	K	Sum	Al.	Acid.
A ₁	0.07	0.09	0.03	0.08	0.27	2.3	12.7
A ₃	0.04	0.05	0.04	0.04	0.17	1.1	8.0
B ₂₁	0.01	0.01	0.02	0.01	0.05	0.6	6.0
B ₂₂	0.01	0.01	0.02	0.01	0.05	0.2	5.1
B ₂₃	0.01	0.01	0.01	0.01	0.03	0.0	4.8

1/ Analysed by the U.S.D.A. Soil Survey Laboratory at Beltsville, Maryland, 1954

ii. Humic Ferralsol

Location: Zaire, Ituri region, Nioka area 2°15' N, 30°32' E.

Climate: Cf (Koeppen): mean annual temperature: 17°C;

annual precipitation: 1450 mm.

Vegetation: Coffee plantation.

Parent material: Weathering products of basic rocks.

Relief: plateau at 2075 m above sea-level.

Drainage class: well drained.

Described by: A. PECROT (1958).

Description

Ap 0-23 cm Clay, 5 YR 3/2, weak medium crumb structure, with some blocks in the lower part of the horizon, very friable, common roots, nonplastic, nonsticky, gradual smooth boundary.

A3 23-40 cm Clay, 5 YR 3/3, moderate fine subangular blocky structure with patchy dark coatings, few roots, friable to firm, slightly plastic, nonsticky, diffuse boundary.

B21 40-70 cm Clay, 5 YR 2.5/2, dark horizon, moderate fine subangular blocky structure with patchy dark coatings on ped surfaces, few roots, friable to firm, slightly plastic, nonsticky, diffuse boundary.

B22 70-100 cm Clay, 5 YR 2/2, dark horizon, moderate fine subangular blocky structure, slightly plastic, nonsticky, diffuse boundary.

B23 100-140 cm Clay, 5 YR 3/2, dark horizon; moderate fine subangular blocky structure with patchy dark coatings on ped surfaces, friable, slightly plastic, few roots, diffuse boundary.

B24 140-170 cm Clay, 2.5 YR 3/4, moderate medium subangular blocky structure with discontinuous clay films on ped surfaces, friable, diffuse boundary.

B25 170-200 cm Clay, 2.5 YR 3/5, moderate structure.

Analytical data: Humic Ferralsol

Horizon	Depth (cm)	Particle size distribution in percent (fractions in microns)							
		0-2	2-20	20-50	50-100	100-250	250-500	500-1000	1000-2000
Ap	0-23	63.4	5.3	5.6	7.7	8.7	5.5	3.2	0.6
A ₃	23-40	65.0	5.0	5.5	6.7	10.0	4.5	2.8	0.5
B ₂₁	40-70	64.1	4.8	5.9	7.7	10.0	5.0	2.2	0.3
B ₂₂	70-100	65.5	4.3	5.7	6.7	11.0	4.5	2.0	0.3
B ₂₃	100-140	66.1	4.0	5.8	7.3	10.0	4.0	2.3	0.5
B ₂₄	140-170	61.4	4.7	6.1	7.3	12.5	4.5	2.5	1.0
B ₂₅	170-200	56.5	5.5	6.5	8.6	13.2	5.0	3.2	1.5

Horizon	C (%)	N (%)	pH (H ₂ O)	Exchange with HCL N/20		C.E.C. pH 7	Fe ₂ O ₃ (%) on clay
				Ca	K		
Ap	3.90	0.040	5.1	4.1	1.05	18.0	8.6
A ₃	1.59	0.013	4.5	1.4	0.30	11.5	7.7
B ₂₁	1.80	0.013	4.5	1.3	0.22	13.0	8.1
B ₂₂	2.02	0.013	4.4	1.3	0.41	14.2	7.9
B ₂₃	1.50	0.012	4.3	1.2	0.23	12.6	9.8
B ₂₄	0.73	0.005	4.3	0.9	0.14	7.9	9.4
B ₂₅	0.54	0.006	4.4	0.9	0.14	6.0	10.4

iii. Orthic Ferralsols (Comissão de Solos, 1960)

Location: Atibaia, São Paulo, Brazil, 780 m above sea level;
5-10% slope.

Parent rock: Gneiss

Vegetation: Melinis minutiflora and Imperata brasiliensis, with trees.

Drainage class: Well drained.

Description

Ap 0-8 cm Sandy clay, 5 YR 3/2, weak crumb structure, very friable, slightly plastic and slightly sticky, clear wavy boundary, abundant roots.

A3 8-28 cm Clay, 5 Yr 4/3, weak very fine subangular blocky structure, very friable, plastic and sticky, gradual wavy boundary, abundant roots.

B1 28-94 cm Clay, 5 YR 4/8, weak medium crumb structure, very friable, plastic and sticky, diffuse smooth boundary, abundant roots.

B21 94-130 cm Clay, 5 YR 5/6, porous massive which breaks into weak very fine crumb, very friable, plastic and sticky, smooth diffuse boundary, abundant roots.

B22 130-220 cm Clay, 5 YR 5/8, same as above, few roots.

B3 220-310 cm Clay, 5 YR 5/8 - 2.5 YR 6/8, weak fine crumb, very friable, plastic and sticky, diffuse smooth boundary, no roots.

C 310 + cm Clay, 2.5 YR 6/8, weak fine crumb, very friable, plastic and sticky.

Analytical data: Orthic Ferralsol

Horizon	Depth (cm)	Gravel %	Particle size distribution (Na OH dispersion)			
			2000 200	200 20	20 2	2 0
Ap	0-8	0	37.8	17.9	7.9	36.4
A ₃	8-28	0.9	30.8	21.4	6.3	41.5
B ₁	28-94	0.7	27.0	14.7	6.4	51.9
B ₂₁	94-130	0.6	25.7	14.4	7.9	52.0
B ₂₂	130-220	1.4	23.7	17.0	7.2	52.1
B ₃	220-310	3.0	21.1	16.7	8.4	53.8
C	310+	4.8	23.6	16.8	15.2	44.4

Horizon	C %	N %	pH		Exchangeable cation (NH ₄ OAc, pH 7) meq / 100 g				Al. (KCl) (extr.) meq	C.E.C. 100 g (pH=7)
			H ₂ O	KCl	Ca	Mg	K	Na		
Ap	1.87	0.17	5.6	4.8	1.97	1.50	0.53	0.06	n.d.	8.83
A ₃	1.25	0.13	4.7	4.1	0.78	0.34	0.19	0.10	0.87	6.56
B ₁	0.75	0.07	4.8	4.2	0.38	0.27	0.05	0.04	0.78	4.83
B ₂₁	0.54	0.05	5.0	4.4	0.28	0.11	0.03	0.05	0.45	3.82
B ₂₂	0.42	0.04	5.4	5.0	0.22	0.13	0.04	0.08	n.d.	3.11
B ₃	0.21	0.04	6.2	6.0	0.30	0.36	0.05	0.10	0.00	1.83
C	0.17	0.02	6.0	5.9	0.27	0.31	0.16	0.10	0.00	1.60

iv. Plinthic Ferralsol (SYS, 1972)

Location: Zaire, 11°40' N, 27°21' E

Climate: C_w (Koeppen); mean annual temperature: 20°C; annual precipitation: 1250 mm.

Vegetation: Tree savanna.

Parent material: Clay weathered from dolomitic limestone.

Topography: Margin of depression in the end tertiary peneplain.

Drainage class: Moderately well drained.

Described by: C. SYS (1972)

Description

A1 0-4 cm Sandy clay loam, 10 YR 5/2, mixed with ash from burning of plant residues; fine crumb structure, friable, many roots, clear boundary.

A3 4-24 cm Clay, 10 YR 6/4, weak medium subangular blocky structure, friable, few roots, gradual boundary.

B21 24-58 cm Clay, 10 YR 5/6, some mottling (7.5 YR 5/6), weak medium subangular blocky structure, friable, diffuse boundary.

B22 58-93 cm Clay, 10 YR 5/6, some mottling, and + 15% soft iron concretions having 1 to 2 cm diameter; moderate fine subangular blocky structure, firm, some tree roots.

B23 93-122 cm Clay, 2.5 YR 6/4, with 5 YR 5/8 mottles.

B24 122-170 cm Clay, 2.5 YR 7/2 with 7.5 YR 5/6 mottles.

Analytical data: Plinthic Ferralsol

Horizon	Depth (cm)	Particle size distribution in percent (fractions in microns)							
		0-2	2-20	20-50	50-100	100-250	250-500	500-1000	1000-2000
A ₁	0-4	24.7	3.9	14.1	8.3	21.3	17.5	10.0	0.2
A ₃	4-24	41.2	4.1	15.9	7.5	13.7	10.3	7.0	0.3
B ₂₁	24-58	56.0	3.7	14.1	5.9	8.7	6.5	4.6	0.5
B ₂₂	58-93	58.9	3.7	13.7	5.7	8.1	5.5	4.0	0.4
B ₂₃	93-122	54.3	4.9	15.6	6.7	8.2	5.7	4.1	0.5
B ₂₄	122-170	53.4	5.0	16.6	7.3	8.5	5.0	3.5	0.7

Horizon	C (%)	N (%)	pH (H ₂ O)	Exchange with HCl N/20		C.E.C. pH 7	Fe ₂ O ₃ %
				Ca	K		
A ₁	0.75	0.058	5.9	2.3	0.21	4.1	0.6
A ₃	0.23	0.024	5.4	1.0	0.17	3.6	0.6
B ₂₁	0.25	0.020	5.7	0.3	0.26	4.7	0.6
B ₂₂	-	-	5.7	0.7	0.21	4.9	0.8
B ₂₃	-	-	5.6	0.3	0.11	4.3	1.0
B ₂₄	-	-	5.5	0.3	0.11	4.8	1.0

v. Rhodic Ferralsol

Latosol roxo Brazil

Rep. FAO-EPTA 2197 Bennema, 1966, p.39, Comissão de Solos, 1960, profile 37, p.287

Location: 15 km N Ituverava, São Paulo State. 20°09'S, 47°47'W

Altitude: 560 m

Physiography: Undulating

Drainage: Well drained

Parent Material: Basalt

Vegetation: Second growth forest

Climate: 1.77, humid tierra templada

Description

A1 0-20 cm Dark greyish brown (2.5 YR 3/3) clay; moderate medium granular structure; slightly hard, friable, slightly plastic, sticky; roots abundant; smooth and gradual boundary.

A3 20-40 cm. Dark reddish brown (2.5 YR 3/4) clay; weak medium granular structure; soft, friable, slightly plastic, sticky; roots abundant smooth and diffuse boundary.

B1 40-60 cm Dark reddish brown (2.5 YR 3/4) clay; weak medium subangular breaking down into weak fine granular structure; friable, slightly plastic, slightly sticky; few roots; smooth and gradual boundary.

B2 60-120 cm. Dark red (2.5 YR 3/5) clay; massive porous breaking down into weak fine granular structure; soft, very friable, slightly plastic, slightly sticky; few roots; clear, undulating boundary.

C 120-130+ Clay loam; horizon comprising rotten rock and material of B₂.

Analytical data: Rhodic Ferralsol

Horizon	Depth cm	pH		Cation Exchange me. %								CaCO ₃ %
		H ₂ O	KCl	CEC	TEB	% BS	Ca	Mg	K	Na	Al	
A ₁	0-20	5.2	5.0	14.2	8.6	61	5.9	2.1	0.6	0.1	5.6	
A ₃	-40	5.7	5.6	10.0	7.6	76	4.7	2.1	0.7	0.1	2.4	
B ₁	-60	6.0	5.9	8.9	7.2	81	4.2	2.6	0.3	0.1	1.7	
B ₂	-120	6.1	6.3	7.4	6.5	88	3.8	2.3	0.2	0.1	0.9	
C	-130+	6.4	6.5	8.2	8.0	98	3.6	3.5	0.8	0.1	0.2	

Horizon	Sol. salts	Organic Matter				Particle size analysis % 1/						Flood index
		%C	%N	C/N	%OM	stones	c. sand	f.s.	silt	clay	texture	
A ₁		1.7	0.15	11		1	3	25	16	56	clay	57
A ₃		1.0	0.08	12		0	2	18	20	60	clay	48
B ₁		0.8	0.06			0	2	16	17	65	clay	96
B ₂		0.6	0.05			2	3	20	19	58	clay	100
C		0.4	0.03			0	9	35	21	35	clay loam	99

Horizon	Solution by H ₂ SO ₄ , d = 1.47, %						SiO ₂	SiO ₂	Al ₂ O ₃	P		
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	MnO	P ₂ O ₅	Al ₂ O ₃	R ₂ O ₃	Fe ₂ O ₃	mg% Truog		
A ₁	18.6	18.9	25.4	5.0	0.2	0.49	1.7	0.9	1.2	1.1		
A ₃	21.5	24.6	23.6	4.4	0.2	0.35	1.5	0.9	1.6	0.7		
B ₁	21.9	26.0	23.2	4.4	0.1	0.33	1.4	0.9	1.8	0.8		
B ₂	20.0	25.3	24.9	5.0	0.1	0.28	1.3	0.8	1.6	0.7		
C	20.6	24.7	24.4	4.5	0.2	0.33	1.4	0.9	1.6	0.7		

Horizon										Moist. Equiv.		
A ₁										29		
A ₃										33		
B ₁										35		
B ₂										34		
C										36		

vi. Xanthic Ferralsol

Kaolinitic yellow latosol, very heavy texture, Brazil
Rep. FAO-EPTA 2197 Bennema, 1966, p.55., Sombroek, 1966
profile 24, p.129.

Location: 247 km S San Miguel do Guamá, Para State, 3°45'S,
47°45'W.

Altitude: 200m.

Physiography: Flat top of high terrace

Drainage: Well drained

Parent Material: Pliocene lacustrine sediments.

Vegetation: Primeval tropical forest, dense undergrowth.

Climate: 1.482, hot tropical

Description

A00 8-5 cm Undecomposed plant residues.

A0 5-0 cm Partly decomposed plant residues with many fine roots.

A1 0-2 cm. Dark yellowish brown (10YR 4/4) heavy clay; moderate medium to fine subangular and weak fine granular structure; many pores; friable, plastic and sticky; locally the horizon is crusty due to the intense activity of insects, especially termites; abundant roots, mostly fine; clear boundary.

A2 2-20 cm Yellowish brown (10YR 5/6) heavy clay; moderate fine subangular blocky and very fine granular structure; many pores; soft, friable, plastic and sticky; abundant roots, gradual boundary.

B2 20-60 cm Strong brown (7.5YR 5/6) heavy clay; weak to moderate, fine to medium subangular and weak very fine granular structure; pores; faint clayskins; slightly hard, friable, plastic, and sticky; many roots; diffuse boundary.

B3 (?) 60-150 cm Strong brown (7.5YR 5/6) heavy clay; weak medium subangular and weak very fine granular structure; pores common; few very weak clayskins; slightly hard, friable to firm, plastic and sticky; many roots; diffuse boundary.

C (?) 150-250+ Yellowish red (5YR 5/8) heavy clay; massive to weak medium subangular structure; few pores; very few roots.

2. MANAGEMENT PROPERTIES OF FERRALSOLS

2.1 Physical Properties

2.1.1 Structure

1. Formation of structure

Virgin ferralsols have excellent physical conditions which favour root penetration and provide ample space for air and water; these advantageous properties are particularly well expressed in the oxic horizons and the overlying humus layers.

When clearing land in ferralsols which were under natural vegetation for long periods, soil management practices do not have to create a suitable soil structure for cultivated plants, but rather to preserve it against deterioration. In most cases the ferralsols, before being brought into cultivation, have already acquired a distinctive pedological arrangement of soil particles as a result of the activity of living organisms, the channelling by roots, and, probably to a less extent, by seasonal wetting and drying.

The concept of soil structure is a complex one, and the understanding of the processes which are responsible for its stability may help to select adequate conservation methods. A preliminary remark may be useful at this point; this discussion does not deal with the cementation of soil constituents into irreversibly indurated concretions as ironstone or ferruginous gravel.^{1/}

The present review only considers those aggregates which slake in water or can be broken by pressure between the fingers or by hand. Their stability depends on the properties of the mineral and the organic parts of the soil and this chapter is divided accordingly.

a. Mineral soil constituents

In order to destroy or to build structure, rearrangement of soil particles is necessary, and this implies movement of some fractions. The more easily clay is dispersed, the more mobile it is and the more rapid the structure is deteriorated under the influence of water.

It has already been said that by definition the dominant clay mineral in ferralsols is kaolinite, combined with various amounts of iron and aluminum oxides. Kaolinite in ferralsols is usually flocculated and the clay micelles tend to stick together. This is due to the low electric charge of this mineral, especially in acid conditions. There are only weak repulsive forces between particles and

^{1/} This induration process may eventually occur in ferralsols with impeded drainage, but it is felt that only limited areas which suffer from this kind of phenomena are considered for agriculture.

they easily cluster into aggregates which do not release much movable clay. The colloidal mineral fraction is not readily mobilized by rainwater as to move into small pores where it may clog available space for water and air.

There are other consequences of the low electric charge of kaolinite clays: only a thin layer of cation is absorbed by this colloid, and there is consequently little swelling or shrinking of the soil upon wetting and drying. In this perspective, swelling is compared with the osmotic uptake of water by the counterion cloud and considered as osmotic swelling. The weak extensibility of the soil material excludes the possibility of building internal pressures and the subsequent closing of pore space; for the same reasons only few cracks develop upon drying.

That there is practically no swelling or shrinking of soil at variable moisture contents in ferralsol was shown by CHANDLER and SILVA (1960), who found that the pore space calculated from bulk density measurements on dry clods was almost equal to the porosity filled by water when the soil was completely saturated (62.3 versus 62.5 percent for a Catalina clay in Puerto Rico, a Humic Ferralsol).

This may be a disadvantage in some subsoil horizons however; one of the mechanisms by which roots penetrate into the soil is based on the shrinking of the soil mass and the concomitant creation of pore space around the root tips by the withdrawal of water during evapotranspiration. This process is probably not contributing actively in the development of rooting systems in oxic horizons.

The clay fraction of well drained ferralsols usually contains besides kaolinite appreciable amounts of ironoxides that are present in various forms of crystallization and hydration. They are usually associated with aluminum hydroxides. Both are thought to have a strong influence on the aggregation of soil particles. It is common experience that the removal of iron and aluminum oxides by chemical methods in the laboratory yields large amounts of clay-size particles, which are released by the Al or Fe cements. The processes involved in this binding of particles are not completely understood, but they may include among other phenomena chemical bonds, hydrogen bridges, or electrical attraction between negatively charged kaolinite crystals and positively charged precipitates of sesquioxides. It is not the purpose of this review to discuss the validity of the hypothesis which have been brought forward on the influence of iron oxides and aluminum in these soils. At any rate, the role of aluminum in precipitating clays is well known and the common acid conditions of ferralsols are favourable for a strong influence of aluminum on the soil suspension.

There have not been many experiments with lime on the stability of structure in ferralsols. As a rule, there is no need for adding calcium ions to the exchange complex in order to prevent the dispersion of clay, as the counterion cloud around the platelets, which is necessary for maintaining

dispersion, is almost non-existent. The primary purpose of liming ferralsols is not to protect the structure: SCHUFFELEN and MIDDELEBURG (1954) have even observed deleterious effects of lime on the stability of the structure in soils with acidic properties. Clays would be peptized at neutral pH conditions by the adsorption of hydroxyl ions, and permeability considerably reduced.

b. Organic matter

There is no doubt that organic matter as a whole contributes substantially in maintaining the soil structure in ferralsols. In the laboratory the removal of organic substances by chemical methods causes the breakdown of aggregates and the release of a considerable amount of clay.

Not all organic soil constituents are equally beneficial for the maintenance of acquired structural features however. Many soil investigators have found that structural stability is primarily dependent on the amount of non-humified organic matter, especially those fractions which are produced by the early decomposition of fresh residues (COMBEAU, 1965).

These compounds are very shortlived and the action on structural stability depends on the biological activity of the soil. COMBEAU (1965) found that the stability decreased with increasing moisture content and air humidity, but improved at high temperature.

The more decomposed forms of humus have either no influence on structural stability, or induce dispersion of clay. It is common experience that the largest proportion of water dispersible clay is found in the surface horizons. The humus which is extractable by pyrophosphate at pH 10, or perhaps the fulvic acid part of it, could be responsible for the degradation of structure after cultivation, especially in light textured ferralsols.

If the stability of aggregates in ferralsols is to be held at its original level, there should be a permanent intensive biological activity in the surface layers, either by the supply of fresh organic matter or by the active decay of roots. This makes soil structure which is conditioned by organic matter rather temporary. Moreover, its stabilization is locally confined to places where fresh organic matter is decaying, or where recent roots are decomposing. RUSSELL's conclusions (1971) may be particularly valid for the management of ferralsols: "the cultivation can rapidly undo an important part of the structure produced by the roots of the previous crop, by breaking up the existing system of stabilized channels. Thus the technique based on minimum tillage should be of particular value for perennial crops, or when pastures or grass leys are to be converted to arable crops".

As far as one can judge from present experience, ferralsols do not suffer from structural imperfections as primary limiting factor. In most cases nutrient shortage, inadequate water supply, or diseases reduce yields before structure deterioration becomes a major problem. This is especially true in extensive agricultural systems, where little fertilizers and pesticides are used.

The same situation may not apply to intensive cropping systems, where the conservation of structure may be as necessary as the supply of nutrients by fertilizers and the protection of crops against pests. Few examples are known however of such undertakings which could support any firmly based management recommendations. It seems that light textured ferralsols suffer more from structure deterioration than clayey soil, which often contain considerable amounts of iron oxides. In sandy ferralsols, experiments in Brazil showed that 4 years cropping reduced significantly the percentage of aggregates of more than 2 mm size, but that the deterioration was the same, regardless of lime and fertilizer treatment (PRATT, 1965). It is assumed that the reduction of structural stability is correlated with the decomposition of organic matter, or with the decrease of microbiological activity.

In ferralsols, high percentages of clay correlate with appreciable amounts of iron oxides, and stronger adherence between particles to form stable aggregates. Sandy topsoils may either fall into single grained loose materials, or become extremely hard and massive upon drying. At present no satisfactory explanation for these phenomena can be given however.

ii. Soil structure data

a. Shape and size of aggregates

aa. Macrostructure

When observed in the field, most oxic horizons present a structure the components of which are fine to very fine crumbs which may combine into weak to very weak subangular blocky peds.

This is particularly noticeable when the study of the structure in the field is done in two ways. The first is to begin with the smallest individual particles and try to determine how they build up the aggregates; the second is to take large fragments out of the soil and see how they break into smaller units. This second method discloses the existence and the forms of surfaces of weakness within the soil mass, which depend essentially on the action of internal pressure induced by swelling and shrinking.

Practically all well drained oxic horizons exhibit, after crushing, a very fine porous crumb structure (less than 1 mm.) the aggregates of which do not display well defined shapes. They consist chiefly of primary aggregates built up of individual

sand particles, and held together by crystallized or amorphous clay-size substances. In the most typical ferralsols these primary aggregates do not build up other aggregates of different shape; they may pile up and form bigger crumbs, which, however, rarely exceed 0.6 cm in size; as a result, the overall appearance of typical oxic horizons is massive.

When the same oxic materials are examined by the second method of appraising soil structure, it is practically impossible to find, within a large fragment, surfaces of weakness having a constant orientation; when a piece of soil is broken into two parts by pulling it apart cautiously with both hands, no preferential surfaces of least resistance can be recognized and it can be fractured along arbitrary planes. Proceeding in this manner it is possible to make fragments of any desired shape, bigger however than the crumbs resulting from crushing. This is especially true for subsoil oxic horizons.

Ferralsols thus have a very open structure: the presence of some blocky aggregates that are usually weakly developed is indicative of younger types of ferralsols, which may have a greater mineral reserve than the typical ones.

In typical oxic horizons, the aggregate surfaces if any appear upon breaking large clods, are not covered by clay skins which may seal inner pore space and make it unaccessible to roots. In younger less weathered layers, few patchy, usually thin, argillans may occur.

Surface horizons, where biological activity is higher, display usually structural aggregates that are formed by the microfauna; coarse pores are evidently more frequent than in the subsoil.

The structures which were described above are undoubtedly favourable for rooting, as far as the mechanisms of root penetration are concerned. They are typical for the oxic horizons and the topsoil of ferralsols. Strictly speaking they do not need to be intensively or deeply plowed, or reworked for the preparation of seed-beds; there is no reasons to dig large planting pits for tree crops either, if the objective of these practices were only to create pore space in virgin ferralsols.

Not all horizons in a ferralsol are typical oxic horizons however. In the lower part of the profile, materials with strongly developed blocky structure or which have kept the original rock structure may be present. The latter are usually mottled by yellow or red streaks on a greyish matrix, and the colour pattern follows more or less the spacial arrangement of grains as it existed in the

parent rock. Such horizons, though potentially better provided by nutrient releasing minerals, are often more closely packed and seldom possess the open structure of the cxic horizons. When planting trees, these horizons should be opened by digging large pits in order to improve root growth; if the weathering rock (saprolite) is overlain by a stone-line, in which the gravel or rock fragments form a barrier, the planting holes should, if possible, at least touch the saprolitic material. The feasibility of such practices depend of course on the thickness of the horizons above the stone-line.

The formation of soil structure may also be influenced by the movement of the water table. Groundwater displaces iron by reducing it into the ferrous stage; air, on the contrary, fixes it as ferric oxides in preferential sites, for example along root channels or in other large pores. The consistence of the soil materials which are impregnated by iron oxides becomes firmer and causes soil structure and consistence to vary; some aggregation occurs which often coincides with colour patterns, commonly known as gley or mottling. Such colour, consistence and structure variations cannot always be clearly distinguished from cementation effects which may be related to plinthite. At any rate, if such structures are present in the main rooting zone of the crops to be grown, the soils should receive special management. Land of this type certainly should be avoided where it is anticipated that plant roots will have to develop into the mottled horizon. It may eventually be used for crops which are produced during the dry season if it is expected that soil moisture will remain close enough to the root zone, or when irrigation and drainage control the depth of the water table. The limiting factor in these cases is not the structure itself however, but poor aeration caused by groundwater. If artificial drainage is envisaged, special attention should be paid to the possible induration of plinthite into ironstone after repeated wetting and drying.

ab. Microstructure

The binding of clay particles to form very small aggregates in ferralsols is particularly pronounced. It can be referred to as microaggregation, which in the earlier literature was known as the formation of pseudo-sand and pseudo-silt. By this process soils with very high clay contents (> 60%) feel loamy in the field, and actually behave mechanically as medium or even light textured soils. The effect of microaggregation is well illustrated by the data listed in table 3 (AHN, 1972), which give the aggregate and particle-size distribution of some ferralsols of Ghana.

The mean size of the micropeds is in the coarse silt and fine sand fraction. As pointed out by AHN, they have considerable stability in the field, as they resist four hours end-over-end shaking in the laboratory. It can also be seen from table 3 that the A horizons have some water dispersable clay, which is not found in the oxic B, thus indicating the action of organic matter on dispersion.

In some cases this strong aggregation makes it necessary to use special analytical procedures when clayey ferralsols which are rich in iron oxides are tested chemically for available nutrients. MOURA (1968) observed that after grinding oxic horizons developed from basic rocks, the usual extractants withdraw more anions and cations than when the unground fine earth is used for the analysis. It is assumed that the interior of the peds is only slowly accessible for the extracting solutions. Some erroneous conclusions regarding fertility levels may be drawn from data obtained by rapid chemical methods which do not take microaggregation into account.

b. Aggregate stability

There are several methods to measure aggregate stability of soils. One of them has been proposed by French pedologists who use an index of structural instability S_1 which is calculated by the following equation (HENIN et al. (1955):

$$S_1 = \frac{L}{A - CS}$$

where L = maximum percentage of clay and silt (0-20 μ) which is released by the soil during wet sieving of the fine earth (passing 2 mm sieve). There are three pre-treatments of the sample: air dried; treated with alcohol, and treated with benzene. L is the largest figure obtained by one of the treatments.

A = arithmetic mean of percentages of aggregates larger than 200 microns that remain on the 200 micron sieve after the standard wet sieving procedure.

CS = 0.9 times the percentage of coarse sand (larger than 200 microns).

For medium textured ferralsols which contain between 13 and 45% 0-20 micron fraction, the percentage of stable aggregates is related to clay and organic matter content, according to the following equation (COMBEAU and MONNIER, 1961):

$$(A-CS)_{\text{alcohol}} = 3.59 + 0.984 (\% \text{ 0-20 } \mu)$$

$$(A-CS)_{\text{benzene}} = 11.43 (\% C) - 16.4$$

Table 3

MECHANICAL ANALYSIS OF FERRALSOLS AFTER DIFFERENT TREATMENTS (AHN, 1972) 1/

Depth cm	Horizon	Organic Carbon %	Treatment	Size (μ) classes in %						
				2000 600	600 200	200 60	60 20	20 6	6 2	<2
0-5	A ₁₁ 2/	2.61	- removal org. C - hexametaphosphate	20.6	36.4	13.9	4.1	3.7	1.6	19.7
			- removal org. C - no dispersing agent	19.6	33.7	22.7	3.0	7.3	3.8	9.9
51-112	B ₂₂ 2/	N.D.	- removal org. C - hexametaphosphate	17.7	15.2	8.4	4.1	1.0	2.1	51.5
			- removal org. C - no dispersing agent	21.2	17.5	17.7	10.8	13.2	3.0	16.6
0-4	A ₁₁ 3/	6.6	- removal org. C - hexametaphosphate	3.5	2.6	2.5	4.6	15.0	6.3	65.4
			- removal org. C - no dispersing agent	6.2	20.1	23.7	9.9	19.3	10.7	10.1
			- no treatment	14.0	30.1	31.0	9.6	7.1	5.2	3.0
38-75	B ₂₂ 3/	0.78	- removal org. C - hexametaphosphate	1.8	1.9	2.1	1.6	tr.	tr.	92.1
			- removal org. C - no dispersing agent	1.9	25.1	41.5	21.6	9.9	tr.	tr.
			- no treatment	3.7	26.8	36.9	23.3	9.3	tr.	tr.

1/ All samples were shaken end-over-end for four hours.

2/ Profile G.1 over granite, Suko series.

3/ Profile LB.2 over phyllites, Yago series.

Structural stability also varies during the year. The lowest stability (highest S_1) is observed during the rainy season; the proportion of stable aggregates is the highest at the end of the dry season. The amplitude of these seasonal variations may be of the order of half the mean annual value (COMBEAU and QUANTIN, 1963; COMBEAU, 1965).

Continuous cropping of ferralsols results in an increase of the instability of soil structure, as shown by COMBEAU and QUANTIN (1963): S_1 was 0.40 under a virgin savanna vegetation; it reached 1.0 after four years cropping and 1.7 after eight years. The soils which were examined contained 15-20% clay. It may be recalled that an index of 1 means that one of the treatments produces almost as much clay plus silt as there are aggregates left on the 200 micron sieve.

Heavy textured ferralsols, that are rich in iron are commonly the most stable. ESCOLAR and LOPEZ (1968) found the following aggregate distribution in the topsoil of a Catalina clay, a Humic Ferralsol of Puerto Rico, (table 4), containing 18% free iron.

Table 4 AGGREGATE DISTRIBUTION IN A CATALINA CLAY (HUMIC FERRALSOL)

Size	>5 mm	5-3 mm	3-2 mm	2-1 mm
Distribution %	43.9	22.5	10.5	12.7
Percent water stable aggregates		90.2	85.3	71.7

The aggregation of this soil was stronger than in comparable horizons of other soil orders of similar texture.

COMBEAU and MONNIER (1961) found the following percentages of water stable aggregates larger than 0.2 mm, after pretreatments of air, alcohol and benzene in subsoil samples from a profile developed on weathering products of basalts: 77.1(alcohol); 73.2(air) and 0.3(benzene). These figures illustrate the high stability of ironoxide rich ferralsols.

As a rule the larger aggregates in the topsoil horizons are more stable than equal-size peds in the subsoil. On the contrary, small aggregates in subsoils are more resistant than their homologues in the surface horizons. Organic matter seems to improve the stability of larger aggregates in the topsoil.

Findings of SMITH and CERNUDA (1951) showed that acric ferralsols are physically among the most stable soils. Subsoil aggregates of 1 g., wetted in partial vacuum to avoid slaking by air-trapping, were only destroyed after the impact of 400 falling water drops (or 400 times 5.6 ergs of energy per milligram of soil), which was about 20 times the energy required for peds isolated from other kinds of soil.

It may be pointed out that burning of forest soils in French Guiana resulted in an increase of the percentage of waterstable aggregates (TURENNE, 1969).

c. Pore size distribution

The porosity of oxic horizons tends to be high. For example, BENNEMA, JONGERIUS and LEMOS (1970) measured the pore volume of subsurface horizons in ferralsols by optical methods and found that it was greater than in argilluvic horizons of similar texture.

The pore-size distribution of a Latosol Roxo of Brazil (Rhodic Ferralsol), is given in table 5, taken from determinations by MOURA (1968). The first site had been cleared two months before sampling, the second had been cultivated for 15 years. The data are illustrated in figure 6a (site I) and 6b (site II).

It is obvious that the non-capillary pores (pores larger than 50 μ) are considerably reduced by cropping: the volume which corresponds to pores of less than 50 microns remains practically unchanged. The cropping of this land which is rich in clay has mainly affected the permeability of the ferralsol, without changing significantly the available water retention characteristics.

MEDINA and GROHMANN (1966) found for medium and light textured soils in the campo cerrado of Brazil the following pore-size distributions (table 6).

The amount of total pores is almost the same in both soils. In the ferralic arenosol (P 854), the proportion of macropores of more than 50 μ diameter is considerably higher however. The sandiest soils are likely to be the most easily leached.

There are practical consequences of the behaviour of ferralsols with respect to pore-size distribution. Medium and fine textured soils may be compacted by trampling by animals, by pressure of heavy machinery, or rolling. As seen in the previous examples, this compaction affects mainly the larger pores. Even after heavy loads of cattle on a Humic Ferralsol in Puerto Rico (Catalina clay) for 18 months, the volume of large pores was not reduced to figures lower than 8.8 volume percent in the first 7.5 cm of soil (CHANDLER and SILVA 1960). The available water holding capacity (between 1/2 and 15 atmospheres) was more than doubled (6.5 to 14%), resulting in an increase of 5.6 mm of water stored in the upper 7.5 cm.

Table 5 PORE SIZE DISTRIBUTION IN VOLUME PERCENTAGE IN A LATOSOL ROXO BRAZIL (MOURA, 1968)

Site	Depth cm	Pores in microns						
		>300 ~	300 100	100 50	50 15	15 3	<3 ~	0- 50
I two months after clearing	4	9.0	7.7	8.1	4.1	1.1	27.9	33.1
	20	13.7	10.6	9.5	4.6	1.4	24.3	30.3
	60	9.3	6.4	11.2	7.3	1.4	24.5	33.2
	86	7.8	7.0	11.2	9.2	1.9	23.8	34.9
	120	10.7	8.6	11.7	8.5	1.9	22.5	32.9
II after 15 year cropping	12	5.2	1.8	3.6	4.8	1.0	26.7	32.5
	24	5.0	1.9	6.1	5.0	1.4	26.5	32.9
	36	7.6	5.5	9.3	6.3	1.7	24.6	32.6
	45	8.9	3.4	8.4	7.1	1.8	24.8	33.7
	85	3.2	2.3	7.8	8.0	1.5	26.6	36.1

Table 6 PORE SIZE DISTRIBUTION OF A FERRALSOL AND A FERRALIC ARENOSOL IN THE CAMPO CERRADO OF BRAZIL (MEDINA AND GROHMANN, 1966)

Profile	Depth cm	Clay % (weight)	Pore-size distribution (volume %)		
			Total	Macropores > 50 ~	Micropores < 50 ~
Ferralsol (p 850)	0-13	24.0	46.4	19.4	27.0
	13-41	25.5	46.5	16.5	30.0
	41-87	27.0	43.4	10.1	33.3
	87-120	32.0	46.8	16.0	30.8
Ferralic Arenosol (p 854)	0-23	13.1	42.3	25.1	17.2
	23-62	14.0	43.1	25.0	18.1
	62-120	15.0	47.3	27.7	19.6

These data are shown in figure 6 (c) and 6 (d).

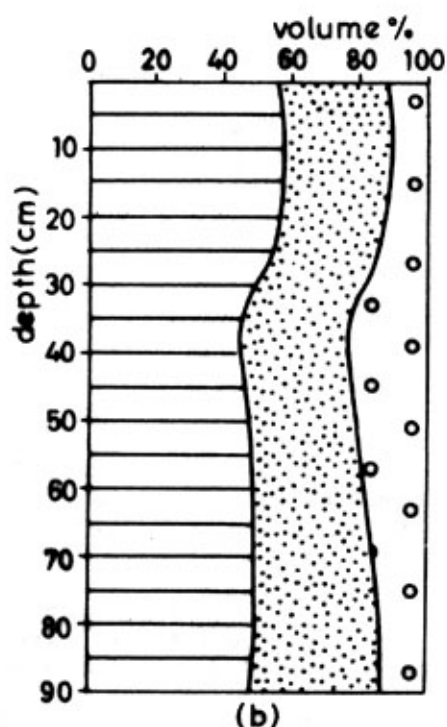
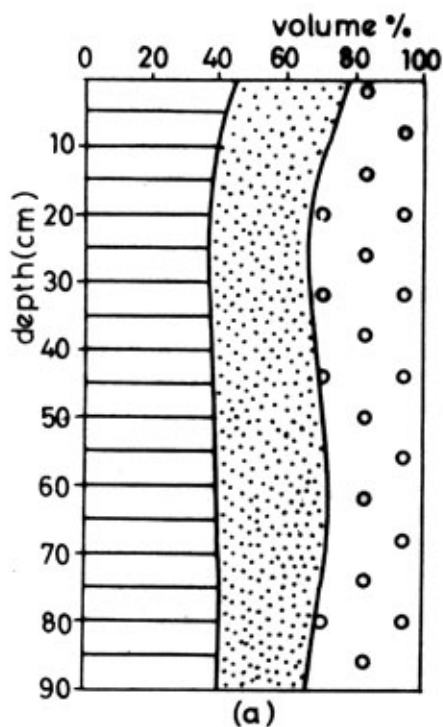
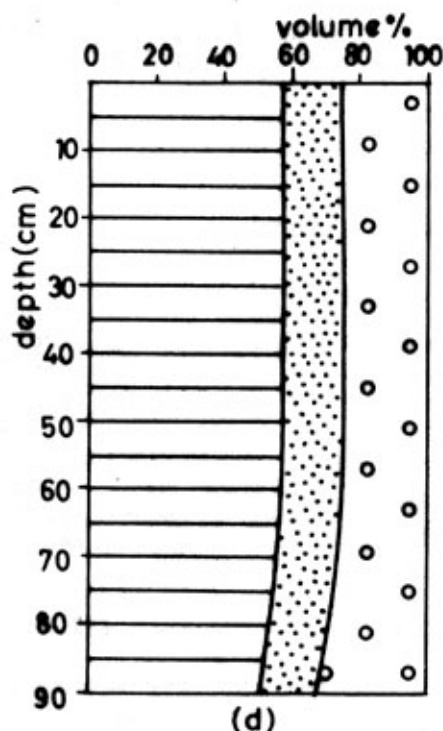
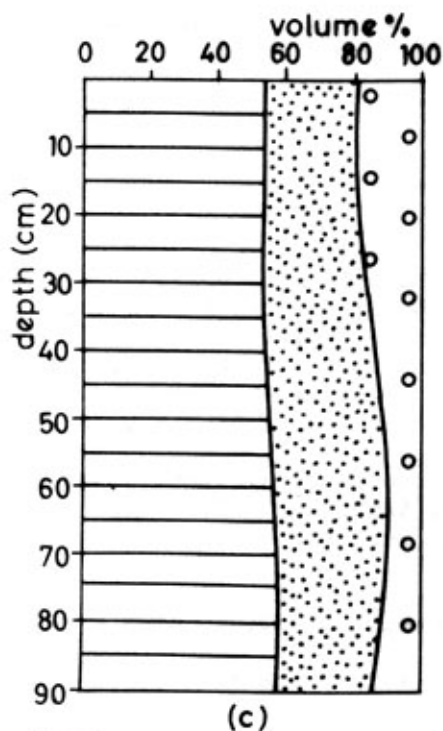


Figure 6

(a) Latosol Roxo,
recently cleared

(b) id., after 15
years cropping



(c) medium textured
ferralsol

(d) Ferralic
Arenosol

solid phase
 pores < 50 μ
 pores > 50 μ

Pore size distribution in ferralsols

d. Bulk densities

Ferralsols which are clayey have low bulk densities in the oxic horizons and in the topsoil. This is partly due to the high microaggregation, and the considerable amount of total pore space.

Light textured and medium textured ferralsols have somewhat higher bulk densities; the lowest values occur in the horizons which contain much organic matter.

The range of bulk densities observed in oxic horizons varies between 1 and 1.5 approximately: the relation between the sand content and the bulk density in oxic horizons is given by the following equation: bulk density (g./cm^3) = $1.03 + 0.004$ percentage sand ($r = 0.727$). In the surface horizons no significant correlation with sand or organic carbon content could be found.

Bulk density is mathematically related to total pore volume. Root development is strongly dependent on pore size distribution, and several authors have studied the influence of bulk density on root elongation.

TROUSE and BAYER (1962) observed a serious reduction of root development in Low Humic Latosols (Ferralsol) at densities of 1.35 g/cm^3 . They observed daily growth of sugar cane roots of 20 mm at bulk densities of 1.04 which was reduced to less than 8 mm. for $d = 1.38$. At this value the roots developed mainly through fracture planes between aggregates.

2.1.2 Soil water relationships

i. Permanent wilting point

The percentage of water held in ferralsols at 15 bars ($pF = 4.2$) is closely related to the clay content. As a rule the correlation between the clay percentage and the moisture held at wilting point is greater in subsoil horizons than in the A horizons. Organic matter seems to interfere with the moisture holding characteristics of the clay, but its influence is not always clear.

Soil compaction and plowing do not change significantly the moisture retention characteristics at high tensions. The water held at 15 bar can be approximated in oxic horizons by the following equation:

$$15\text{-bar water \%} = 10 + 0.234 \text{ clay \% (with } r = 0.645 \text{ at } n = 24);$$

in the horizons overlying the oxic horizon this percentage corresponds to

$$1.3 + 0.375 \text{ clay \% (with } r = 0.867 \text{ at } n = 8).$$

The quadratic regressions for the oxic horizons are:

$$15\text{-bar water} = \text{water} = 15.7 + 0.024 C_1 + 0.0017 C_1^2$$

where C_1 is the clay percentage; in the A_1 horizons this equation is:

$$15\text{-bar water} = -6 + 0.448 C_1 - 0.0065 C_1^2.$$

These equations are shown in figure 7.

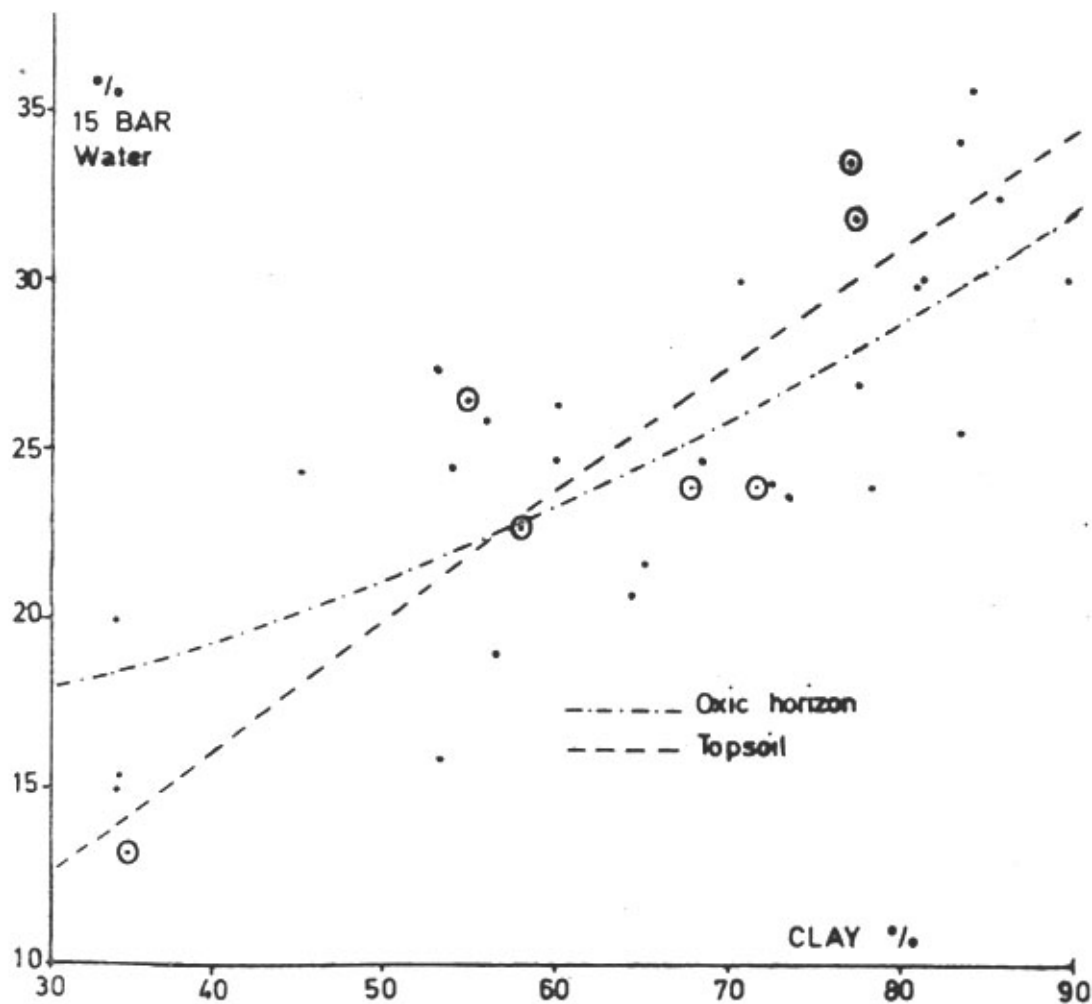


Figure 7 - Water content at 15 bar tension

The organic matter apparently reduces the forces by which the clay holds water at low water contents, particularly in soils that are medium textured. Therefore at equal field capacities, the amount of water available to plants may be greater in horizons which are rich in humus.

ii. Field capacity

There is no good agreement in the literature regarding the tension at which water is held by ferralsols at their field capacity. It is commonly accepted that a ferralsol which has been fully saturated with water reaches a water tension of about $1/3$ atmosphere (pF 2.54) after two days free draining. Some report much lower tensions of $1/15$ and $1/20$ bar in sandy and clayey ferralsols however. Nevertheless $1/3$ atmosphere is usually taken as the conventional limit.

It is assumed that at this point the gravitational movement of water is markedly reduced, leaving only the pores which are smaller than 8.6 microns filled with water. The water which is held at less than $1/3$ atmosphere drains out of the profile in less than two days. As long as it percolates through horizons which are located within the reach of the roots, it is of course still available to plants. Under tropical climates the field capacity has only a reduced practical significance, especially in rainfed agriculture.

The factors which determine the total amount of water held by the ferralsols at $1/3$ atmosphere depends mainly on the pore-size distribution. It is therefore essentially determined by the structure of the soil. Texture may also play a role in as much as fine silt (2-20 μ) tends to increase the field capacity; fine sand, where it contains partly weathered minerals may also substantially raise the water content held at this tension (AHN, 1972).

iii. Available water

Weathering processes in oxic horizons have usually produced maximum amounts of clay. Typical oxisols are moreover exceptionally low in silt (2-20 μ). Silt/clay ratios are often less than 0.15. This causes strong water retention at wilting point, and reduces the storage capacity at field capacity: hence the narrow range of available water which is normally observed in oxic horizons. As a rule of thumb it is commonly accepted that they cannot store more than 10 mm of rain per 10 centimeter of soil depth between the critical tensions of $1/3$ atmosphere (field capacity) and 15 bars (permanent wilting point).

This low figures make ferralsols with deep oxic horizons particularly sensitive to drought especially for crops with shallow rooting habits; drought hazards are also severe in profiles which either contain stone-lines which reduce the soil volume, or where chemical conditions (as Ca deficiencies) are such that they drastically restrict root growth.

In some undep ferralsols the lower parts of the profiles which have not reached extreme weathering may contain more silt and less clay and the available water content may therefore be larger. This important property may partly explain, in addition to the release of nutrients by weathering processes in deeper layers, the higher plant production potential of ferralsols with saprolite at shallow depth, especially for deep rooting crops.

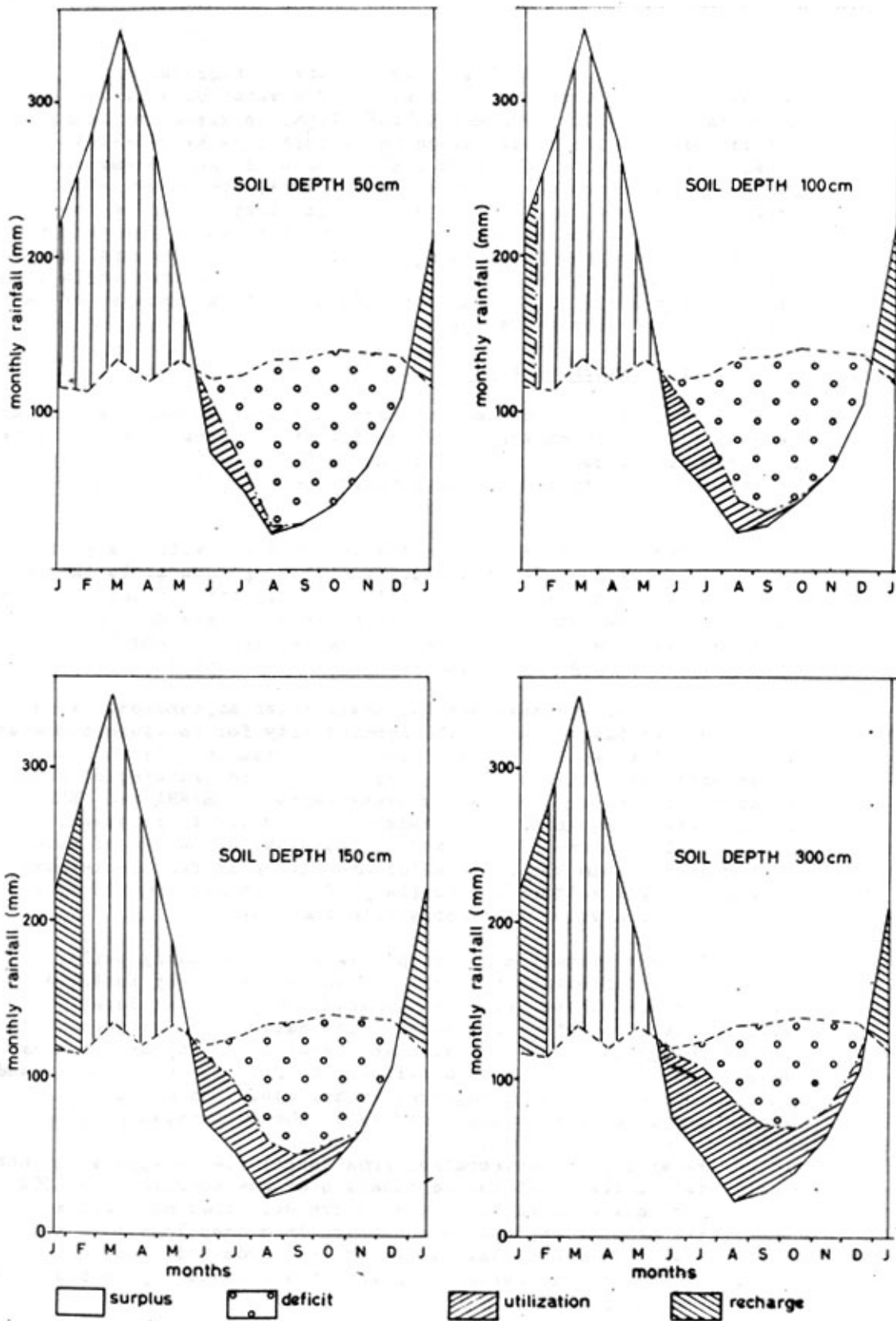


Figure 8 - Soil moisture balance diagrams (Thornthwaite and Mather - 1955)

As pointed out earlier, agriculture on ferralsols is narrowly rain dependent. An example of a water balance diagram according to THORNTHEWAITE and MATHER (1955) is given in figure 8 for different soil depths, based on calculations by BARREIRA PEREIRA and DE SOUZA RODRIGUES (1971) for soils in the Amazon. Taking 10 mm of rainfall per 10 cm of soil, the water deficit for profiles that are 50, 100, 150 and 300 cm deep, would be respectively 482, 432, 382 and 278 mm per year, on the assumption that the plants cannot take water from underlying horizons. Actual evapotranspiration calculated for the whole year in the same soils were respectively 1063, 1113, 1163 and 1267 mm. The advantages of having large rooting volumes are obvious.

iv. Infiltration, water movement

Ferralsols of Puerto Rico have infiltration rates which vary between 8.5 and 15 cm /hour (dry infiltration rates with wet buffer compartment), according to LOPEZ and BONNET (1968); other reports on ferralsols mention 8 cm /hour after one hour of continuous flooding.

Movement of water from moist to dry areas within a profile is as important for adequate water supply to plants as is the amount of available water itself. Usually a distinction is made between water flow at saturation, and movement under stress during dry periods; water may also be translocated as vapour, and transferred from warm to cool areas in the soil by a distillation process.

Ferralsols release most of their water at tensions below 1 bar. When they dewater, the conductivity for moisture decreases abruptly; the capillary conductivity is strongly water content dependent: the drier the soil, the slower the transfer of water towards the roots. Laboratory experiments by SHARMA and UEHARA (1968) have shown that the decrease in conductivity is steep, and that it falls below 10^{-5} cm /sec. at tensions of 60 cm of water. During dry periods the roots which are living in ferralsols have to grow towards moist spots in the profile, rather than to expect any supply from water transfer within the soil.

In this respect most ferralsols behave as sandy soils. There is one difference however for medium and clayey textured oxic horizons: these are physiologically dry at considerably higher water contents than sands. The water which is present in the microaggregates is available as a source for vapour which may move to the rooting zone by distillation effects, and be condensed in cooler areas, which management techniques, such as mulching, should try to create at the vicinity of the cultivated plants.

Water loss by evaporation from ferralsols is apparently not restricted to the first few centimeters of the topsoil. WALTON (1962) contends that in hot climates dry soil does not form a protective barrier and that evaporation from deep layers is not negligible. He found that water was lost from soil horizons between 30 and 60 cm depth, even when the surface layers had dried completely.

2.2 Physico-chemical Properties

2.2.1 Ion exchange reactions

The exchange of cations and anions between the solid and the liquid phase in oxic horizons and in the overlying topsoils is mainly conditioned by the type and amount of clay minerals, oxides and organic matter. Since oxic horizons are generally low in silt, the contribution of this particle-size fraction to exchange reactions is negligible; moreover, the small quantities of micas which might be present do not participate significantly in the possible exchange or fixation of NH_4^+ or K^+ ions.

There are by definition no or only traces of 2 : 1 silicate-clay minerals as montmorillonites, illites, etc. in oxic horizons. The finest soil particles are dominantly composed of kaolinite, goethite, gibbsite and various amounts of other iron and aluminum oxides. The crystals are generally covered by coatings: the cations and anions in the soil solution are said not to be in direct contact with the bare clay minerals, but rather with micelles covered by oxides and organic matter. The presence of organic compounds, which are active ion exchangers makes it convenient to speak of an exchange complex. Its electric charges and the bonding energies for ions result from various processes which have been divided by soil chemists into several classes.

The first one, known as permanent charge, is caused by the isomorphic substitution of Si^{4+} by Al^{3+} , or Al^{3+} by Mg^{++} in the crystal lattice of the clays. There are practically no substitutions in kaolinite however, and consequently, very little permanent negative charge sites in oxic horizons. This permanent charge, however small, is independent of the pH of the soil solution, and the cations which neutralize it can be exchanged at any time, without modification of the permanent cation exchange capacity. Among these exchangeable cations Ca, Mg, K, Na and Al are the most common.

The second kind of bonding energies for ions is due to the dissociation of H^+ from active molecules located at the border of the exchange complex, creating negative sites, or to the protonation into OH_2^+ , giving positive charges. Protons (H^+) may for example be released by acid groups at the broken edges of clay particles, or by carboxyl or phenol groups in the organic matter, or by aluminum and iron hydroxides. The dissociation of H^+ creates vacancies which may be filled by metallic ions. It is strongest at high concentrations of OH^- in the soil solution and is therefore called the pH-dependent part of the cation exchange capacity which increases with raising pH. At low pH values this type of cation exchange capacity may completely disappear.

In some highly weathered soils which are rich in sesquioxides, for example those derived from basalts and ultrabasic rocks, positive charges may develop by protonation of hydroxyl groups. This may eventually produce an anion adsorption capacity. The anion bonding is not exclusively active at low pH values however and the real nature of this positive charges in the exchange complex is still to be more closely investigated. According to ATKINSON et al. (1967) the zero point of charge of goethite is at about pH 7.5, and that of hematite somewhere above 8.5.

Each component of the exchange complex is supposedly associated with a specific part of the soil material. The permanent charge is by definition located in the crystal lattice of silicate clay minerals; the negative pH-dependent component operates from broken edges of clays and oxides, and at sites originating in the organic matter. Positive charges are produced by sesquioxides. Opposed charges can apparently exist simultaneously in the same exchange complex. They do not necessarily neutralize each other neatly, and a rigid framework of specific exchange sites of opposite signs is possible.

The ways by which management practices may act upon the exchange characteristics are illustrated in figure 9 (d). The soil in this example has a moderate permanent charge. There is only little organic matter, and consequently the dissociation of H^+ which produces additional sites for binding metallic cations is very reduced; line (α) indicates this stage. If the humus content were higher (i.e. resulting from erosion control), the pH dependent charge component could be as high as β . The soil contains also considerable amounts of oxides which generate positive charges at pH's lower than 8. Line γ , which quantifies these sites may be moved into position by adding phosphates, silicates, or organic matter which neutralize the positive charges.

The resulting net capacity of the soil to retain ions may be modified by (1) adding organic matter to the soil or (2) applying fertilizers which reduce the quantity of positive charges. By using both methods the dimensions of the net resulting capacity are changed from the lower values shown by the full heavy line to higher ones illustrated by the broken line. Theoretically, if the soil had been maintained at pH 5, it could have passed from acric properties dominated by positive charges to conditions which permit cations to be retained by the exchange complex.

An increase of the CEC could also have been achieved by raising the pH with lime as shown by the dotted line (3). This is only true however if Ca were not specifically absorbed by the oxides, in such a way that it became unavailable, blocked exchange sites, and thus reduced the effective cation exchange capacity. The latter phenomenon is particularly active in soils that have oxidic or ferritic mineralogy. Liming of acric soils, where the ZPC coincides with a high pH, may have adverse effects on soil structure SCHUFFELEN and MIDDELBURG (1954) report that the soil colloids with considerable exchange alkalinity (or substantial positive charges) absorb OH ions at neutral pH conditions, and are thus peptized. The dispersion of clays by liming acric soils may cause a drastic decrease in soil permeability, and depress yields.

Some ion exchange components in ferralsols of Brazil are given in table 7 for surface horizons (0-15 cm).

PRATT and ALVAHYDO (1966) found that the ratio of pH dependent to permanent cation exchange capacity (CEC) was 3.0 to 5.3 for Red Latosols (Orthic Ferralsols), 1.6. to 4.5 for Yellow Latosols (Xanthic Ferralsols). In humic ferralsols, where the organic matter content is high, the ratio may be greater. In ferralsols which intergrade to less weathered materials the permanent charge may become important.

The cation exchange capacity in ferralsols strongly depends on the organic matter content and the pH of the soil. Clay minerals quantitatively contribute very little to the total CEC. In a kaolinitic material at pH 7, 30% clay may only provide sites for absorbing ± 3 meq.

per 100 g /soil, whilst 1% organic carbon in fresh organic matter may bond up to 4.5 meq. Under such pH conditions 60 percent of the CEC originates from the organic matter. Under normal field pH this proportion may be considerably modified however.

Table 7 ION EXCHANGE COMPONENTS IN FERRALSOLS OF BRAZIL (PRATT AND ALVAHYDO, 1966)

Soil	pH paste	clay mineral	meq /100 g			pH-dep. CEC/ perm. CEC ratio
			Permanent CEC (1/)	pH 7	Soil pH	
RYL 1	4.3	Kaolinite	1.3	3.5	2.0	1.7
RYL 2	4.0	Kaolinite, Gibbsite	1.1	4.3	1.5	2.9
RYL 8	5.5	-	2.3	8.0	4.8	2.5
RYL 9	4.6	-	2.8	7.7	2.1	1.6
RYL 11	4.3	Kaolinite, Gibbsite	3.1	7.5	4.5	1.4
TR 16	4.2	Oxides, Gibbsite	1.6	7.5	1.4	3.7
TR 18	4.2	Oxides, Gibbsite	0.9	5.7	0.8	5.3
TR 20	4.1	-	2.2	9.0	2.2	3.0

1/ KCl acidity at zero base saturation

The cation exchange capacity varies after clearing land. Data on virgin forest soils and three months after clearing and burning, gave the following equations for CEC, calculated by TURENNE (1969) from analytical data obtained with NH_4OAc at pH 7:

Virgin Soil CEC = $1.72 C\% + 0.178 (\text{Clay} + \text{fine silt}) - 2.86$

Cleared Burned CEC = $0.358 C\% + 0.203 (\text{Clay} + \text{fine silt}) - 0.585$

This author concludes that the clearing of the land, and the exposure to direct sunlight cause a very rapid decline of the exchange capacity (pH 7) of the organic matter. The factors in TURENNE's equation for the contribution of organic carbon to the CEC of the soil are surprisingly low in the burned soil, and the addition of charcoal to the soil may partly explain the results of his calculations.

GREENLAND (1972) states that the organic matter normally carries about 200 meq. of carboxyl groups per 100 g carbon. Their degree of dissociation, generating sites for cation retention, decreases with pH, the pK_a values ranging from 4 to 6. Thus between pH 4 and 6 half of the carboxyl groups carry negatively charged exchange sites. With these constants, 2% organic carbon would be able to retain 2 meq. per 100 g of soil at pH 5.

The contribution of organic matter to the cation exchange capacity is strongly pH dependent. ABRUÑA and VICENTE (1955) estimated that at pH 7 it would account for approximately 150 meq./100 g organic matter, or 260 meq./100 g C. The titration curves of extracted organic matter indicate a high buffer capacity above pH 7, and an almost four times reduction of the retention capacity at pH 4.5, to \pm 65 meq per 100 g C. The formation of poorly soluble humates was suggested as a possible explanation of the buffering power.

ABRUÑA and VICENTE-CHANDLER (1955) noted strong differences in exchange properties of the various portions of the organic matter in ferralsols. The fraction which can be extracted by flotation has an extremely high capacity (over 700 meq /100 g C); the most easily oxidizable fractions thus appear to be the most active in cation retention. The part of the humus which is difficult to destroy by oxidation has on the contrary no or very little base exchange capacity, and seems to be tightly held by mineral soil colloids.

2.2.2 Base saturation

The net negative charge on the exchange complex is neutralized by cations the most important of which are Ca, Mg, K, Na and Al. Three parameters are commonly used to estimate their quantities and availability, the cation exchange capacity (CEC), the sum of bases (S) and the base saturation (V%). The experience has shown that it is important to distinguish some critical levels with respect to soil fertility in ferralsols, and several class limits with agronomic significance have been proposed.

When the sum of bases (Ca, Mg, K, Na) plus the aluminum extracted by a normal solution of KCl is less than 1 meq /100 g of clay, it is considered that the soil at the field pH has almost no cation exchange capacity. It is then meaningless to calculate base saturation. These soils, Acric Ferralsols, require special practices for fertilization, especially for phosphorus and calcium. There are only few examples however where they have economically been put into crop production and most land of this kind lies idle.

Non-acric soils are usefully subdivided into subtropic and dystrophic groups. Thirty-five percent base saturation (sum of bases x 100/CEC at pH 7) is the limit which is commonly used to separate them.

The depth to which the saturation percentage is to be considered should not be limited to the surface horizons, but should also include the subsoil. Subsoil acidity is detrimental to rootgrowth and it restricts the volume from which plants can extract water. In the dystrophic types it is worthwhile to distinguish aluminum dominated saturations. When

the aluminum occupies more than 50% of the permanent charge, the uptake of nutrients by crops may be severely hindered, and productivity markedly depressed. This is shown in table 8 taken from experiments conducted on ferralsols developed from basic rocks in Paraná (OLMOS et al. 1971). Aluminum saturation is expressed as $(Al \times 100) / (\text{sum of bases} + Al)$.

Table 8 TYPE OF BASE SATURATION IN B HORIZONS OF FERRALSOLS AND YIELDS OF CORN (OLMOS ET AL. 1971)

Type of saturation in B - horizon	Yields of corn Kg./ha	
	without fertilizers	with fertilizers
Dystrophic, Al-dominated	1 004	1 829
Dystrophic, not Al-dominated	1 657	4 205
Eutrophic	2 282	5 198

As the bases are leached from the soil, the adsorption sites that are associated with the permanent charge are gradually occupied by aluminum. In typical ferralsols in which the clay minerals do not possess an appreciable permanent charge, the aluminum saturation is not a major problem. Manganese toxicities instead are more frequent, especially when the organic matter content is low. In ferralsols which are not typical but intergrade to less weathered types, the aluminum saturation on the permanent charge may be important however. Excess aluminum in the soil solution may then hamper the development of plants which are not tolerant to that element.

Chemical Properties

2.3.1 Nitrogen and organic matter levels

The roles of organic matter, nitrogen and living organisms in soils are closely interrelated. Organic matter regulates the nitrogen economy and in this respect it either acts as a source or a sink. It contains bioactive substances which stimulate or retard plant growth; it may favour the development of the microfauna and the microflora and control the activity of pathologic organisms.

i. Nitrogen and organic matter levels

The crop production in ferralsols which do not receive fertilizers is strongly dependent on the natural supplies of nitrogen. These come essentially from the decomposition of soil organic matter. This nitrogen pool has to be replenished, either by fallows, by crop residues, green manures or fertilizers in order to have it operating on a sustained basis.

Although modern agriculture in ferralsols is economically not feasible without high yields, which cannot be obtained permanently from natural sources of nitrogen only, it is useful for good management to understand the mechanisms of soil organic matter changes which provide the nitrogen to the crops in the less intensive agricultural systems.

BARTHOLOMEW (1972), and GREENLAND (1972) have presented excellent reviews on this subject. The concept which they have used are based on a mathematical model which relates the changes in N content of the soil to the algebraic sum of the gains originating from the plant residues and the losses caused by humus decomposition.

The primary differential equation reads as follows:

$$\frac{dN}{dt} = A - kN,$$

where N is the total nitrogen content, t is the time, A is the annual rate of addition, k is a decomposition constant defining the fraction of the total N which is released by the soil organic matter.

When management practices are constant over a long period of time during which k and A remain unchanged, the soil reaches an equilibrium level N_E at the moment that the additions (A) are out-balanced by the losses (kN). Under such conditions N_E equals A/k and the N_E content depends both on the rate of addition and decomposition. At N_E the amount supplied by the soil to the crop cannot exceed the amount of N that is imported into the soil-plant system; if no fertilization is applied, crops have to live on outside natural N sources which are scarce, and would only permit yields of 600-1200 kg/ha of corn, or 400-800 kg/ha of wheat, provided no other limiting factors are restricting plant growth (BARTHOLOMEW, 1972).

It should be pointed out that the equation $N_E = A/k$ is only a rough approximation of the complex processes which take place in the soil organic matter. It is only applicable when A and k are considered over a large number of years at seasonally comparable periods or as annual averages. Obviously A and k change markedly from one season to another in the course of one year and induce fluctuations in the nitrogen content. The larger the amplitude of the seasonal variations, the higher the potential of the soil to supply or to bind nitrogen, provided N_E itself is not too small.

A and k are not identical in all soils, even under similar climatic conditions. The fraction of soil matter which is decomposed per unit time, or k, is related to texture and mineralogy. For example VERDADE (1969) reports that clayey soils in São Paulo have usually double the N content of sandy soils. GREENLAND (1972) states that a large percentage of hydrous oxides leads to lower k values, and consequently to higher N contents. Many tropical soils contain larger amounts of organic matter than soils in temperate regions; this may be due to strong linkage of humus with hydrous aluminum and iron oxides, which protect it against decomposition. The contamination by volcanic ash and the presence of allophane may lead to similar results.

Red soils usually contain more organic matter than yellow soils, even though the latter look darker than the former. SYS (1971) compared a series of soils of Katanga (Zaire) and found the amounts which are given in table 9.

Table 9 ORGANIC CARBON CONTENT (TONS PER HECTARE) IN TOP 50 CM IN RED AND YELLOW SOILS OF KATANGA (ZAIRE)

Parent material	Tons organic carbon per hectare	
	red soils	yellow soils
Clay on limestone	79	65
Clay on slates	71	55
Sandy clay on conglomerate	61	47

Mineralogy and clay content are not the only factors which determine the nitrogen equilibrium levels. Vegetation together with climate, on a broader geographical basis, define the rate of additions. FRANKART (1960) studied the composition of A₁ horizons in comparable soils under savanna and the rainforest in North Eastern Zaire. His conclusions although they cannot be applied without modifications to other transitional areas, are summarized in table 10.

Table 10 C, N CONTENTS AND C/N RATIOS IN SAVANNA AND RAINFOREST SOILS IN ZAIRE (FRANKART, 1960)

	Forest zone			Savanna area		
	Rain forest	Fallow	Crop	Savanna	Fallow	Crop
C/N in A ₁	8.6	9.0	8.6	13.3	13.7	12.4
C/ Tons/ha/ meter	86	88	83	107	121	85
N Tons/ha/ meter	10.1	11.3	10.6	8.9	8.5	7.1

The results obtained by FRANKART show a marked difference between the nature of the humus horizons in the forest and in the savanna soils. Under tropical grassland they tend to be darker. Finely divided coal produced by burning may be partly responsible for it. They also contain less nitrogen than the forest soils and this is attributed to the annual fire in the grassland vegetation which returns much N to the atmosphere. Under forest there is a litter layer; it is absent under savanna. As in other parts of the world, trees tend to concentrate organic matter in the upper parts of the profile, whilst decaying grass roots distribute carbon more evenly in the soil. Roots of grasses however do not pump up nutrients as efficiently, and have less time to protect them against leaching as well as a forest vege-

tation would do. At the beginning of the rainy season, when heavy showers occur, the savanna has not yet developed a suitable root system which could retain the nutrients before they percolate down to deeper layers. Therefore the savanna ferralsols with deep oxid horizon are usually less saturated than their forest counterparts. This is shown in FRANKART's (1960) findings reported in table 11.

Table 11 PH AND BASE SATURATION IN FOREST AND SAVANNA SOILS IN N-E ZAIRE (FRANKART, 1960)

Area	pH in			Base saturation in		
	A ₁	A ₂	C	A ₁	A ₂	C
Forest	6.6	5.6	5.3	91	47	27
Savanna	5.4	5.2	5.3	23	13	19

The rates of addition of organic matter by crops and rotations have seldom been measured in ferralsols. In soils which are rich in bases, or in well fertilized soils, the amounts of plant material which are added (A) will most likely be greater than in poor soils. Modern management therefore is not necessarily responsible for a decline in humus content, but may on the contrary have beneficial effects on the arable topsoil.

SAUNDER and GRANT (1962) contend that organic matter levels can be maintained under cropland for as long as high yields of adapted crops can be obtained by adequate mineral soil fertility and sufficient water supply, and provided plant residues are returned to the soil. Crops with fibrous root systems would be best. Rapid decline in organic matter level will however occur when poor yields contribute little in the way of roots or aerial organic materials.

ii. Organic matter changes and nitrogen supply

The ability of the soil organic matter to undergo changes is more important for crop production than is its absolute amount. This capacity depends on the internal potential of the humus, and on external factors. The latter may be conditioned by plowing, mulching, exposure to sunlight, drought and moisture. The decomposition rates of organic matter and the release of nitrogen may also be modified by the chemical characteristics of the soil environment.

Organic matter in freshly cleared land is reported to behave differently than humus from old croplands in its ability to supply N. This, at least, is what is generally advanced as an explanation for the lack of response to N fertilizers of recently opened fields. Examples of experiments that confirm these views are given below (MASCARENHAS, 1957).

Table 12 YIELDS OF SOYA IN KG/HA, IN LATOSOL ROXO (RHODIC FERRALSOL) OF PH 4.8 AND 5.5, UNDER "CERRADO" SAVANNA (BRAZIL)

Treatment	recently cleared		cultivated land	
	not limed	limed	not limed	limed
O	1.354	1.288	1.497	1.764
PK	2.042	2.653	819	1.563
PK + inoc. <u>1/</u>	1.747	2.424	1.507	2.431
N ₁ PK	2.188	2.344	1.264	2.049
N ₁ PK + inoc.	1.879	2.288	1.118	1.840
N ₂ PK	2.087	2.729	1.257	1.882

1/ inoc. = inoculum

McCLUNG *et al.* (1962) had observed similar reactions on dark red latosols (Orthic Ferralsols), cropped with cotton after cerrado vegetation; he estimated that the supply of N from the soil itself would probably be shortlived, MIKKELSEN *et al.* (1963) even related depressing effect of N fertilization in land which had been opened from natural pastures on latosols (pH 4,9), to stalk breakage and lodging, due to the excessive amounts of N released by fast mineralization.

Although liming generally increased yields in recently opened acid soils, it decreases the response to N (see table 12). An additional example of this can be drawn from an experiment conducted by MASCARENHAS *et al.* (1967) with beans on a Dark Red Latosol (pH 4,0) in São Paulo State of Brazil (table 13).

Table 13 YIELDS OF BEANS (PHASEOLUS VULGARIS) IN KG/HA ON DARK RED LATOSOLS (ORTHIC FERRALSOLS) OF BRAZIL

Nitrogen level	Yields during			
	First year		Second year	
	unlimed	limed	unlimed	limed
N ₀	283	334	445	564
N ₁	269	373	491	751
N ₂	260	378	465	761

SAUNDER and GRANT (1962) found that the rates of mineralization of organic matter depend mainly on clay content. In the field under bare fallow in miniature lysimeters the sands and loamy sands released 4-5% of the total N during one growing season. The rates of decay under similar conditions for sandy loams were 3-4%, for red brown clay-loams and clays 2-3%. Management practices may enhance organic matter decomposition; for example

plowing which causes the breakdown of aggregates may improve aeration and nitrification. Noticeable influence of plowing was observed in the experiments of SAUNDER and GRANT (ibid.).

Not all freshly formed organic matter acts as a nitrogen source for plant nutrition. Smith and ABRUNA (1955) observed that truncated soils, from which the first 90 cm had been removed, could accumulate annually in the top 30 cm under good tropical kudzu and molasses grass (*Pueraria phaseoloides* Benth and *Melinis minutiflora*) 336 kg of N per hectare. This nitrogen however, although it corresponded to approximately 75% of the nitrogen content of normal cropped land, was a poor nutrient supplier, as was indicated by subsequent yields. SMITH and ABRUNA (op. cit.) suggest that most N was tied up in the processes of forming soil organic matter, and they point out that the results of their experiments are consistent with the concept of a stable soil organic matter level, or equilibrium level, towards which a soil has a strong tendency to develop.

a. Gains in nitrogen

The nitrogen pool of the soil has to be replenished periodically in order to balance the losses. There are different natural sources: plant residues, biologic fixation by microorganisms, and the nitrogen contained in rainfall. Obviously, there are no soil-bound limiting factors which are exclusive for ferralsols, although the efficiency of nitrogen fixation is for a great deal dependent on soil properties.

The vegetation itself is a valuable reservoir of nitrogen. Generally applicable data, which give an estimate of the order of magnitude of such possible supplies, have been published by NYE and GREENLAND (1960). BARTHOLOMEW et al. (1953) tabulated the nutrient content of forest fallows, from which figure 10 has been adapted.

The decomposition of litter in a typical forest site at Yangambi rapidly supplies nitrogen and other nutrients. Estimates of the rate of release are illustrated in figure 11.

According to KASS (1970) the annual gains in nitrogen of soil-plant systems in tropical environments may be estimated as follows:

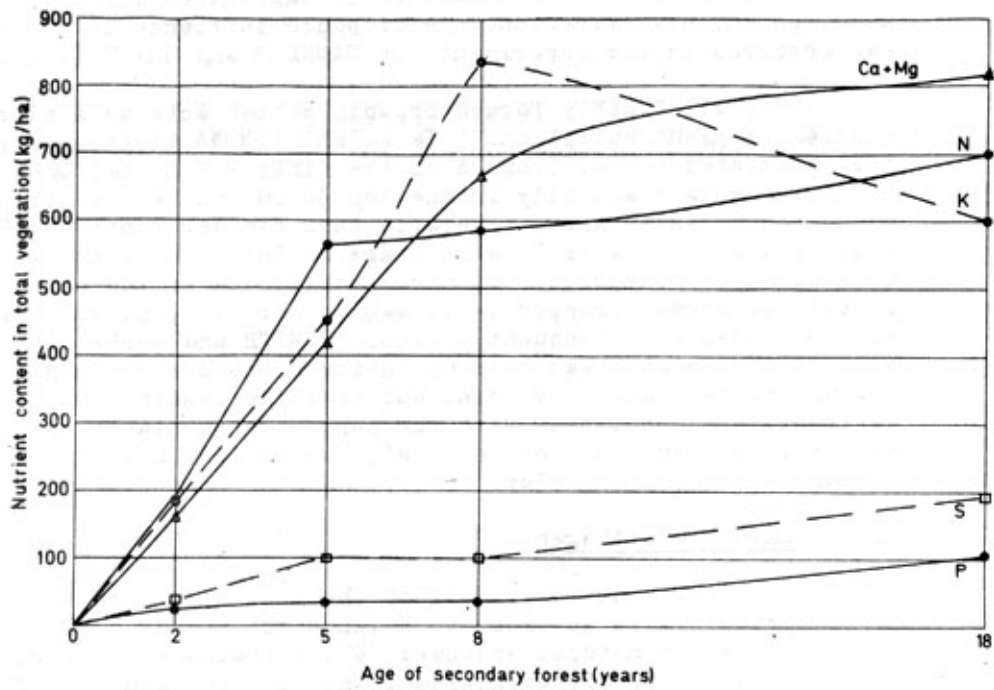


Figure 10 - Nutrient accumulation in a secondary forest in Yangambi (Zaire), according to BARTHOLOMEW et al. (1953), SANCHEZ, 1972

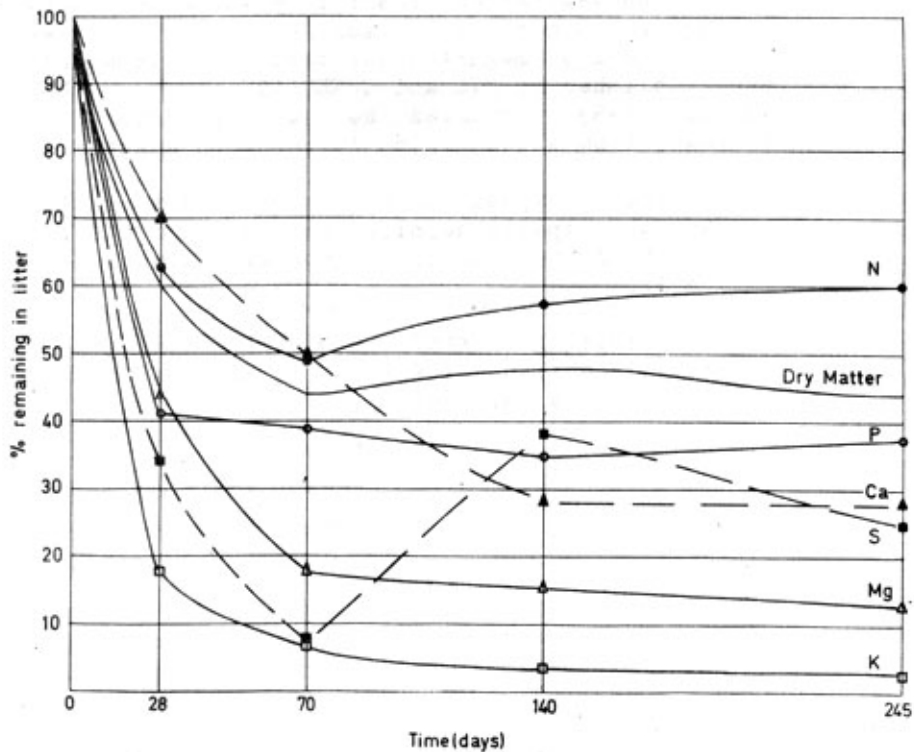


Figure 11 - Litter decomposition rates in Yangambi (Zaire), according to BARTHOLOMEW et al. (1953), SANCHEZ, 1972.

Table 14 GAINS OF NITROGEN IN KG/HA/YEAR IN TROPICAL SOIL-PLANT SYSTEMS
(L = LOW ESTIMATE, H = HIGH ESTIMATE), KASS (1970)

Contribution of	Rainforest		High Savanna Grass		Low Savanna Grass		Sugar Cane		Paspalum notatum	
	L	H	L	H	L	H	L	H	L	H
Legumes	34	68	-	-	0	10	-	-	0	2
Phyllosphere	12	40	0	12	0	4	0	12	0	2
Litter	0	25	0	10	0	6	12.5	50	0	5
Rhizosphere	0	6	0	13	0	6	0	7.5	5	18
Rainfall	0	8	4	8	4	8	4	8		8
Algas				10	0	10	0	10	1	0
Total	46	147	4	53	4	44	16,5	87,5	10	35

Among the processes which are responsible for the addition of nitrogen to the soil-plant system, the fixation by the legume symbiosis, and by free-living bacteria have been studied most thoroughly. These investigations are briefly discussed in the following sections.

Symbiotic fixation

The Rhizobium-legume symbiosis is not the only microbiological process for fixing atmospheric nitrogen. Other plants as Casuarina, Coriaria, Discaria, and Myrica occur in the tropics and produce nodules which fix nitrogen. Podocarpus also is an active nitrogen fixer when living in mycorrhizal association. Blue green alga and other plant species may also contribute in symbiosis to the nitrogen economy, but the applications to soil management are mainly limited to the restoration of soil fertility during long fallows or in forestry programmes. The legumes remain the most frequently used symbiotic host plants in agriculture.

Several general laws regarding the symbiotic fixation of nitrogen that are common to all soils are worth remembering. BARTHOLOMEW (1972) points out that nitrogen fixation processes are growth related: it means that nitrogen is fixed and used only to the extent that it is needed for the development of the bacteria and the host plant. The fixation for example is retarded by the presence of available inorganic nitrogen in the soil: in fact fixation only works when it has to cope with a nitrogen deficit: some bacteria are inactive at some time and nodulation of roots is not always a good guide for estimating the fixation intensity.

Most legumes require optimum soil conditions for sustained high yields, and the symbiosis is only achieved when bacterial strains specifically related to the host plant occur. Phaseolus, Alfalfa, and soybeans are examples of such crops. They cannot achieve efficient nitrogen fixation in most ferral-sols unless the soil chemical characteristics have been thoroughly improved.

In an experiment conducted on Latosol Roxo in São Paulo, a Rhodic Ferralsols, MASCARENHAS (1967) observed that nodulation of soya was increased by liming (3t dolomitic limestone/ha). Applications of nitrogen reduced nodulation especially at high fertilizer rates. In recently cleared land which was included in this experiment, nodulation was more abundant after inoculation, but the yields were not changed. Rhizobium was reported to be inefficient in increasing yields when sufficient N is supplied by the soil itself, as was most likely in a freshly opened field.

In old cropland, spontaneous nodulation often masks the effects of the inoculum on the number of nodules: the yields however respond to inoculation, when no chemical N is added to the soil; this would indicate that good nodulators may be poor nitrogen fixers. MASCARENHAS experiments are summarized in table 12.

Not all Rhizobia are as exacting to calcium supply and host specificity. The Vigna group would have less rigorous requirements. This strain is commonly occurring in most soils of Central Africa (LAUDELOUT, 1961), and it is not necessary to inoculate the cultivated host plants accommodated to the specificity of the bacteria, nor to apply lime even to acid soils. Stylosanthes is also a legume which is particularly well suited for optimum efficiency in soils with a low base saturation. It even seems to be very sensitive to overliming. PRATT (1966) found reduced growth of Stylosanthes after liming a soil (pH: 4,5) high in organic matter, which may have affected the manganese availability. DOBEREINER (1970) states that a soil pH > 5 is detrimental to growth and N fixation in Stylosanthes.

Nodulation of Phaseolus may be improved by green manures. MIYASAKA et al. (1966) report that the incorporation of plant material, especially grasses, into a Latosol Roxo resulted in more abundant nodulation without having significant effects on the yields of beans.

As pointed out earlier the nitrogen fixation is growth related. Therefore the amounts of N which are fixed may vary from a few kilograms to 500 kg N/ha in large yields of soybeans (BARTHLOMEW, 1972). The latter have probably not been obtained in ferralsols.

It is generally accepted that a legume may fix 1 mg of N per 15 mg of carbon assimilated by higher plants (or 67 mg N per G of C). The benefits for the cultivated associated crops, or for the soil depend on the use which is made of the legume.

Fixation by free-living organisms

The extent of nitrogen fixation by non-symbiotic microorganisms is determined by factors that are soil-related. Oxygen supply is of considerable importance: cell-free extracts of organisms fix only nitrogen under anaerobic conditions (STEWART, 1969): Azotobacter, although at is an obligate aerobe, fixes N more efficiently at reduced oxygen pressures (PARKER, 1954); in most laboratory experiments anaerobic fixation is usually four times as important as aerobic fixation.

Most nitrogen fixing bacteria in acid tropical soils are heterotrophs: they need an organic substrate for energy supply and growth. In the case of nitrogen fixation, even though it is an exothermic process, external sources of organic carbon compounds are necessary in order to form the aminoacids. Moreover the Azotobacteriaceae are specific in their requirements, and cannot use complex carbohydrates such as cellulose. They need the association of cellulolytic organisms (JENSEN, 1965). Most experiments on soils have shown that with increasing organic carbon supplies the nitrogen fixation by heterotrophic organisms is stimulated. At any rate, high energy phosphate supply is always needed (STEWART, 1966).

Most organisms have exacting pH requirements. Azotobacter will not fix nitrogen below pH 6.0 (STEWART, 1966). Azotobacter spp. tend to disappear almost completely in soils of pH < 5.0 (CARNEIRO, 1968). Beyerinckia and Derxia, on the other hand, only occur in acid soils. The optimal soil pH for Beyerinckia would be 5.5-5.9; this organism would not survive outside the pH-range of 4.0-7.4 (BECKING, 1961).

Not the overall soil pH has to be taken into account however. In ferralsolic areas with a pronounced dry season, termites may form microenvironments of higher pH by the concentration of bases in

the mounds and nests. BOYER (1971) mentions greater numbers of Beyerinckia and Azotobacter chroococcum in samples from termite mounds built by Bellicositermes than in the surrounding topsoils.

Clostridium, Pseudomonas and Bacillus are found over a wider pH range. It is not established whether the hydrogen ion concentration is directly involved, or if aluminum or manganese activities, or nutrient deficiencies are responsible for the reduced fixation when pH conditions become marginal. At any rate, molybdenum and iron are components of the nitrogenase enzyme complex (BURRIS, 1969). Since fixation is growth-related adequate supplies of K and P are necessary. PRAMANIK and HISRA (1955) found a significant increase of Azotobacter after P fertilization.

It is generally assumed that little N-fixation will occur when sufficient amounts of either ammonium or nitrates are present in the soil. Urea has been reported to retard fixation markedly, and N_2O is a specific competitive inhibitor (STEWART, 1966). It is not possible however to set critical levels only on the basis of the actual amounts of N in the soil. Clearly more complex C:N:P:S ratios are involved in regulating the nitrogen fixation. BREMNER and SHAW (1958), and GREENLAND (1962) found that when the C:N ratio in the soil is less than 5, no fixation of nitrogen may be expected.

Among the climatic factors, the soil moisture content which may be seasonally deficient may reduce cell growth and nitrogen fixation may. Beyerinckia is particularly sensitive to drought.

Under normal field conditions temperature is seldom a limiting factor. Optimums for growth are 26-33° C for Beyerinckia fluminensis, 25-37° C for Derxia gummosa, 29-37° C for Azotobacter paspali (DOBEREINER, 1969).

There are some special environments in tropical agriculture which influence microbiological activity that are worth mentioning: in paddy soils algae may be the major contributors to N fixation. Blue green algae only fix nitrogen at pH's between 6 and 9, although some have been found to operate at pH4.

Another specific ecosystem is the litter, and other plant residues which may form substrates for nitrogen fixation by heterotrophs. Not all residues are adequate however. The efficiency of mulches for tropical crops depends much on their C/N ratio. Data of BARTHOLOMEW et al. (1953) show that no gains

from fixation should be expected with ratios of less than 20; where forest mulches produce gains for the ecosystem, they are of the order of 1-2 mg N per Kg of plant material (1-2 ppm) in 35 weeks.

Some tropical crops such as sugarcane produce huge amounts of organic matter; the high frequency of Beyerinckia in such fields, may enhance nitrogen fixation KASS and DROSDOFF (1970) calculated however that the gains would not be more than one ppm of N per year, or 2-3 kg/ha/year. The Azotobacteriaceae in addition have to live in association with celluloses decomposers, or with photosynthetic organisms in order to obtain the simple carbohydrates which they need for N-fixation.

The rhizosphere is a suitable environment for the development of microorganisms, by the exudates and the presence of decaying plant tissues. This area however is not particularly abundant in nitrogen fixing species, except for the rhizoplan of sugar cane, rice and some tropical grasses described by Brazilian investigators. The number of microcolonies never exceed 10^5 per gram soil however. Such low populations may increase the yields of associated crops, but it is not demonstrated yet if these increments are due to better nitrogen supplies, or to production of growth stimulating agents (BROWN et al. 1964, MISHUTIN, 1967). Whether Azotobacter may control pathogenic organisms is still under discussion.

Stimulating effects of higher plants on asymbiotic N fixation appear to be specific. Azotobacter paspali only develop faster when they are associated with tetraploid forms of Paspalum notatum (DOBEREINER, 1970). Some plants on the other hand, reduce the bacterial development: Melinis Minutiflora depresses Beyerinckia occurrence (DOBEREINER, *ibid.*).

KASS, DROSDOFF and ALEXANDER (1971) observed that the association of Azotobacter paspali only increases the N content of the roots, and not the areal parts of the grass. Since all fixation ceased when soils were incubated in the dark, the activity of a photosynthetic microorganism may be involved. The authors estimated on the basis of the greenhouse experiments that the nitrogen gains by Paspalum notatum are probably between 10 and 20 kg/N/ha/year.

To summarize, N fixation by free living organisms is a process which needs considerable amounts of organic matter to be efficient. According to DOBEREINER (1969) free living organisms would be able to fix between 12 and 30 mg. N per g of carbon source. In the absence of nitrogen in the soil, for ten kilograms of N fixed per hectare, the bacteria would have used between 330 and 830 kg of carbon, all other conditions being optimized.

Non symbiotic fixation in the field is a process by which nitrogen is brought into the soil-plant system mainly in order to restore equilibria between C and N as determined by prevailing ecological conditions. The estimates by KASS and DROSDOFF (1970) of the amounts that are gained are rather low. They are only effective when environmental conditions are such that organic matter and living organisms act as nitrogen fixers, and not as immediate sources of nutritional nitrogen to plants which are cultivated simultaneously.

In the field there are seldom situations whereby the soil organic system releases N to plants, and at the same time operates as a nitrogen fixer. Both processes seem to be mutually exclusive. Therefore they are interesting for management operations which use fallows, or long resting periods during which high equilibrium N_E levels can be achieved.

In intensive agriculture where such long resting periods are not economic, they are not considered as primary sources of N for crop production. This is particularly true for cropland. Pastures and livestock production in extensive system may be partly supported by biological nitrogen fixation; in intensive management its role is rather minor.

b. Release of nitrogen

Ammonification and nitrification

Successive wetting and drying produces increased mineralization of organic matter in practically all soils. Ferralsols exhibit the same phenomena. In areas which are subject to repeated drying and which are exposed to high temperatures in the surface horizons, the stimulation of organic matter decomposition may bring about a nitrate flush at the beginning of the rainy season. Clearing forest land often produces the same effects.

The amount of N released depends on the temperature, the length of the dry period, the organic carbon content, the C/N ratio of the organic matter, and the kind of soil (AGARWAL, SINGH and KANCHIRO, 1971). The process may in part be purely physical and chemical as far as the production of ammonium is concerned, but nitrification is essentially biological.

Ammonification is not narrowly controlled by ecological conditions, and occurs in a wide range of temperatures and pH environments. Even between

50°-70° C it produces high amounts of NH_4^+ , provided sufficient moisture is present. Ammonification continues up to moisture tensions of pF 5.6 (DOMMERMUES, 1962).

Nitrification from ammonium is achieved by two autotrophic obligate-aerobe microorganisms: Nitrosomonas, which produces nitrites (NO_2^-) and Nitrobacter which finalizes the oxydation into nitrates (NO_3^-). Their activity is highest between pH 7 and 9. The minimum pH is flexible and varies between 7 and 5 (DOMMERMUES, 1970).

Nitrobacter is sensitive to temperature and is not active at more than 40° C; its efficiency is lowered by excessive concentrations of NH_3 in the soil. As a rule nitrification is diminished by impeded drainage and lack of oxygen due to water-logging. At the dry end of the soil moisture range, nitrification is stopped at pF 4.5-4.2. Therefore high temperatures, above 40° C and low water contents seem to favour the accumulation of ammonium or nitrites.

Grassland soils contain usually less nitrifying bacteria than forest soils. MEIKLEJOHN (1962) found that nitrite oxidizers were almost absent in savanna soils even after the start of the rainy season. The lack of available N is often due to the absence of bacteria able to oxidize nitrite to nitrate. The growth of the nitrifying bacteria may be suppressed by toxins secreted by some tropical grasses (BOUGHEY et al. 1964); grassroots are more capable to absorb N as ammonium directly and may therefore become more competitive to other plants for obtaining nitrogen nutrients.

Volatilization of nitrogen

Denitrification is probably not a major cause of nitrogen losses in well drained ferralsols, since it requires dominant anaerobic conditions, pH's well above 5, sufficient nitrates, and a good supply of organic matter. The optimal pH for denitrification is between 7 and 8.6, which reflects neutral to alkaline conditions which seldom occur in ferralsols. In some special habitats as irrigated rice paddies high pH's may exist and special management practices should then be selected in order to avoid N-losses. Some of these are the non-utilization of nitrate fertilizers or the use of denitrification-inhibitors.

GREENLAND (1962) conducted incubation experiments in the laboratory with samples taken from freely drained upper slope soils of Ghana at pH's ranging from 6 to 7. For water contents of 160% of the waterholding capacity the tests showed that very rapid losses of N could occur; most took place within

three days of incubation. Under field conditions however it is unlikely that denitrification would cause appreciable nitrogen losses, except when soils are flooded and oxygen pressures are reduced within the soil mass. Soils may eventually be saturated with water after heavy rainstorms; but this condition in well drained ferralsols would not last much more than one day.

The amounts of nitrogen which are lost from tropical soils by ammonium volatilization are the highest from soils with a low cation exchange capacity. The release is the slowest in acid soils (CORNFORTH and DAVIS, 1968); sandy soils which warm up more quickly may suffer heavier ammonium losses than clayey soils. When large amounts of readily decomposable organic matter are added, the production of ammonium and its accumulation in the topsoil may inhibit the nitrification of nitrites. Possible losses of N_2 which are formed by the decomposition of ammoniumnitrites have been suggested as a possible explanation (ibid.). The soil mixtures which were used for the laboratory and greenhouse tests contained 0.225 and 0.45% N; this high percentage was reached by adding plant materials having a C/N ratio of 9. Such amounts of organic material in cultivated soils are rather unfrequent.

Leaching of nitrogen

Most nitrogen losses in ferralsols have been attributed to leaching.

Lysimeter experiments conducted by KUPPER et al. (1953) showed that nitrates, applied on the soil surface at a rate of 30 kg N/ha, are completely leached after six months (or 962 mm of rain) at more than 45 cm depth in clayey soils; the same effect is obtained after two months in sandy soils. The columns used in these tests did not carry any vegetation.

Normally ammonium does not percolate through the soil fast enough so that it can escape nitrification. In KUPPER's experiments it was completed after two months in the light textured soils, and after four months in the clayey materials.

In most soils which are not covered by vegetation all applied nitrogen will be leached from the first 50 cm after 1 000 mm of rain; in light textured ferralsols it is estimated that about 750 mm would be sufficient.

The vegetation offers the most efficient way for reducing nitrogen losses due to leaching. At any rate in humid climates they will always remain

considerable. VICENTE-CHANDLER et al. (1964) found that intensively managed forage crops only recovered 55, 54, 48 and 30% of the nitrogen applied to Humic Ferralsols, at rates of respectively 200, 400, 600 and 800 kg N/ha as ammoniumsulphate.

2.3.2 Phosphorus

i. Forms of phosphorus

It is generally accepted that with increasing weathering the percentage of total P in the soil decreases. Moreover, an important part of the phosphorus which remains in the profile is occluded by sesquioxides during the weathering process, and becomes practically unavailable for plant nutrition.

There is also a gradual decline in the proportion of the "active" mineral phosphorus, as slowly available aluminum, iron and calcium phosphates. The rest of P, which occurs as organic compounds and in solution, is present in greatly varying amounts among the ferralsols.

The distribution of the various soil phosphorus components in an Orthic Ferralsol, under tropical savanna, is illustrated in fig. 12. The profile in this example is an intergrade to younger less weathered soils, and it contains more KCl extractable aluminum than the modal concept would normally accept. Some chlorite is present in the clay fraction. It can be seen that below 40 cm depth the amount of inorganic P is constant; only the organic P varies. In the top layers, approximately 75% of the total P is organic. It is assumed that the plants have in part extracted P from the mineral pool, and preserved it from further losses by tying it up in the organic matter. The original data for figure 12 are given in table 15.

Not all ferralsols show a distribution of phosphorus similar to the given example however. The topsoil of rhodic ferralsols may contain as much as 1000 ppm of total P; the orthic and xanthic types normally have not more than 400 ppm, as was reported by JORGE and VALADARES (1969) in Brazil. In these investigations it was found that only 5-15% is in the organic form.

WESTIN and DE BRITO (1969) determined between 18 and 284 ppm of total P, with values of 20-40 for the percentages of organic-P on the total P content in ferralsols of Venezuela.

Low percentages of total phosphorus in parent materials of ferralsols are often responsible for poor soil fertility. The original P content places a ceiling on the soil potential, not only for crop production, but also for organic matter accumulation and nitrogen fixation. Since there are only few external sources of phosphorus, the amounts of total P in soils parallel those of the parent rocks. Acid igneous rocks contain usually less than 800 ppm, whereas basic rocks may have as much as 2700. Sedimentary rocks range between 250 and 750 ppm. Basic rocks are therefore in a better position for maintaining soil fertility, by the more intensive organic matter turnover which reciprocally keeps phosphates for longer time in more available forms.

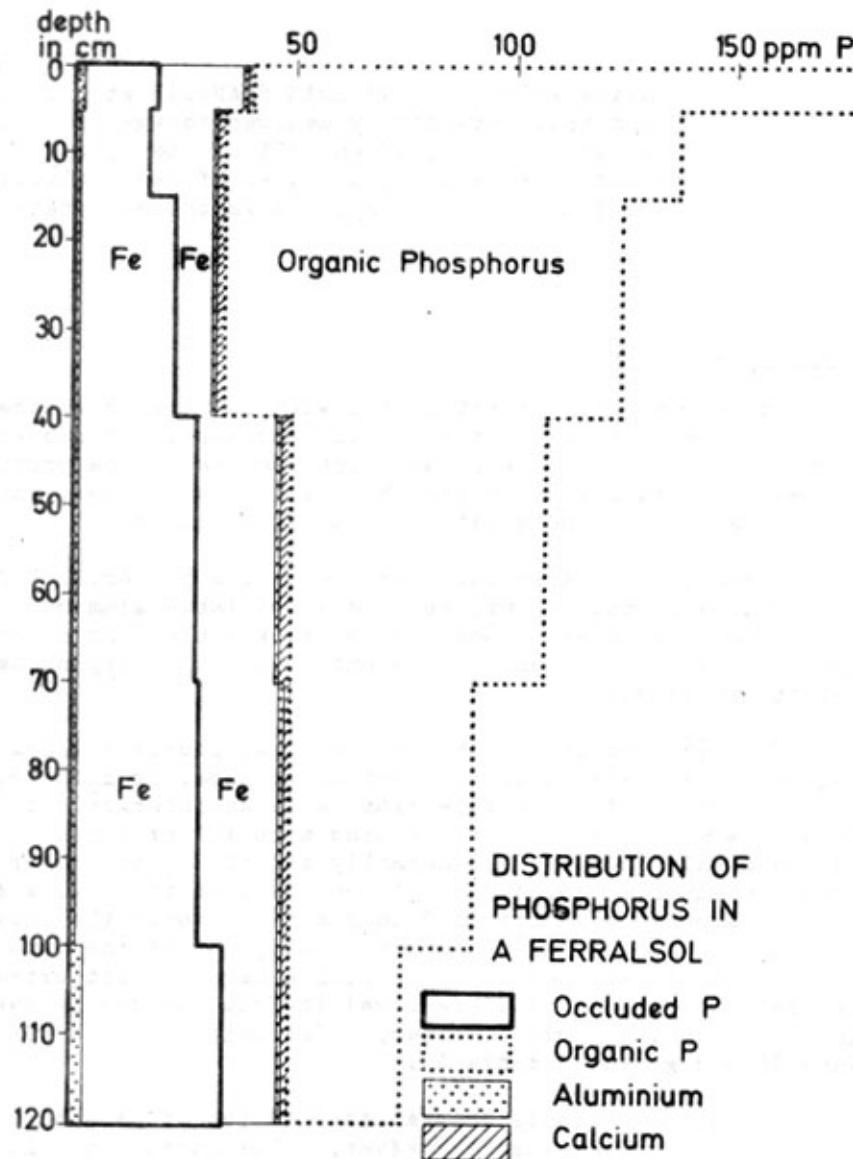


Fig. 12 - Distribution of phosphorus in a ferralsols (BENAVIDES, 1963)

Table 15 FORMS OF PHOSPHORUS IN A FERRALSOL IN PARTS PER MILLION (BENAVIDES, 1963)

Depth (cm.)	Total P	Organic P	Inorganic P				
			Active			Ocluded	
			Ca	Al	Fe	Fe	Al
0-5	185	138	1.6	1.4	18.9	16.5	2.3
5-15	151	104	0.8	1.3	15.1	15.7	1.5
15-40	126	92	0.9	1.5	8.4	21.5	1.7
40-70	114	60	0.9	1.4	7.7	36.9	1.6
70-100	90	43	0.5	0.9	8.1	38.0	1.0
100-150	84	27	0.5	0.9	3.3	41.0	3.3

Low Al-P amounts are indicative of strong weathering under well drained conditions: the tie-up of phosphorus in occluded form would be the most intensive in climatic regimes having a dry season. Impeded drainage would somewhat raise the aluminum phosphorous level (WESTIN and DE BRITO, 1969).

ENWEZOR and ALBOORE (1966) found in the surface horizons in Nigeria organic/total P percentages between 17 and 29% in savanna areas and 72% for forest soils. The total phosphorus content in the upper horizons in forest soils was almost twice as much as under savanna. The natural grassland vegetation has apparently only a low efficiency in recycling phosphorus. The forest is more active in absorbing P by roots in the subsoil and, unless time is a limiting factor, is more capable to restore P levels in the surface layers.

Since a substantial part of the phosphorus components in ferralsols are organic, the agricultural practices which favour the decomposition of humus result in an accelerated release of P to the soil solution. Liming may have such effects. When they are combined with the neutralization of exchangeable aluminum, lime significantly increases the amount of available phosphorus, provided the organic P-pool is sufficiently large. In highly weathered soils of the tropics, and where the economic resources of the farmers cannot support the expenditures for purchasing chemical fertilizers, the phosphorus management is largely a soil organic matter management.

C:N:P ratios in ferralsols have not yielded significant correlation with the mineralization of P from organic sources, and further research on this subject is needed.

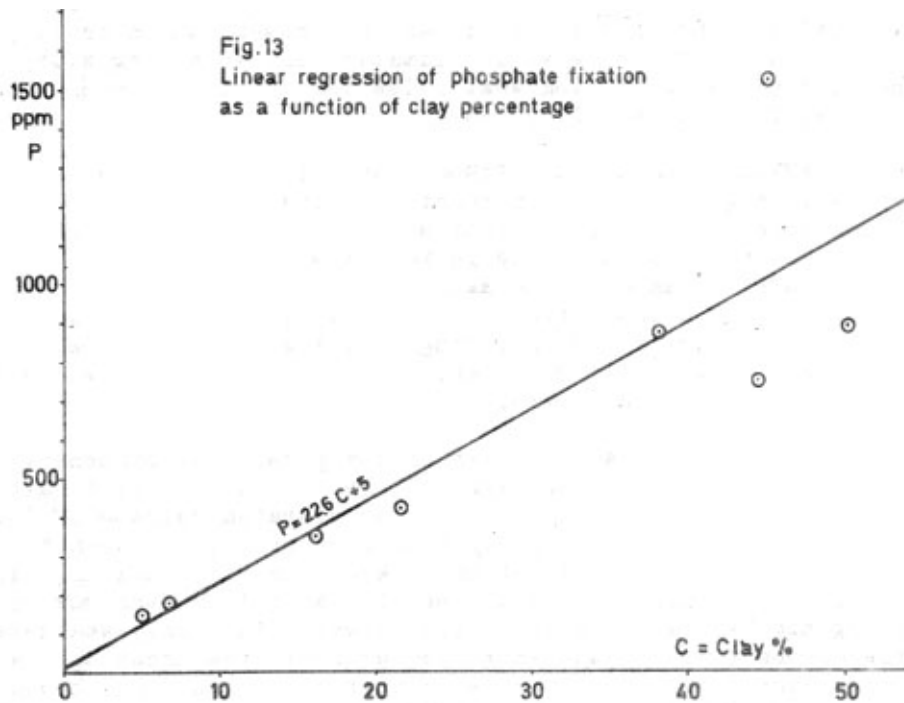
Phosphorus adsorption, fixation and residual effects

The capacity of soils to fix phosphorus was estimated by CATANI and GLORIA (1964) using p^{32} . As in many other investigations it was found that there is a close relationship with texture (figure 13).

Other factors are also important. Within soils of equal mineralogy the amount of P retained by soil samples is correlated with the free-iron content, with the clay percentage and with the extractable aluminum. As a rule, the more crystalline the exchange complex, the smaller the fixation capacity; in ferralsols of comparable pH, the strongest fixation will be found in soils intergrading to rejuvenated profiles, in which the KCl extractable aluminum content and the permanent charge are higher than modal. Contamination with volcanic ash may also raise the P-fixation power of ferralsols.

FOX et al. (1968) ranked the fixation capacities of the most common components of clays as follows: amorphous hydrated oxides > gibbsite > kaolin > goethite > montmerillonite.

The fixation intensity due to the action of oxides may be lowered by blocking the bonding sites with organic matter, as explained in the chapter dealing with the charge characteristics of the exchange complex; conversely, application of phosphates



may increase the net cation exchange capacity. Significant response to such treatments will only be obtained in soils that are particularly rich in iron oxides, especially of oxidic or ferritic mineralogy.

The concept of fixation is not well defined. Much fixed phosphorus remains slowly available for plant nutrition, and residual effects of fertilizers applications are common in ferralsols. It is seldom known how long they last however. LAUDELOUT (1959) observed that freshly precipitated iron and aluminum phosphates are as available to plants as the phosphorus from the fertilizer itself.

Evidences of residual effects of phosphates in humic ferralsols with acric properties in Brasilia were obtained by IRI Research Institute (1967), from which report figure 14 has been reproduced. The soybean yields obtained one year after the application of superphosphate significantly correlated with the amounts of P_2O_5 .

According to FOX (1973), phosphate adsorption values can be converted into phosphate fertilizer requirements. Adsorption isotherms describe the equilibria between adsorbed P and the activity of P in the soil solution. Examples of such curves, given by FOX (ibid.) are illustrated in figure 15 ^{1/}. Assuming that corn requires 0.06 ppm P in the soil solution the orthic ferralsol would need approximately 200 ppm P adsorbed on the exchange complex. Ferralsols are not the strongest phosphate fixers.

^{1/} see page 80

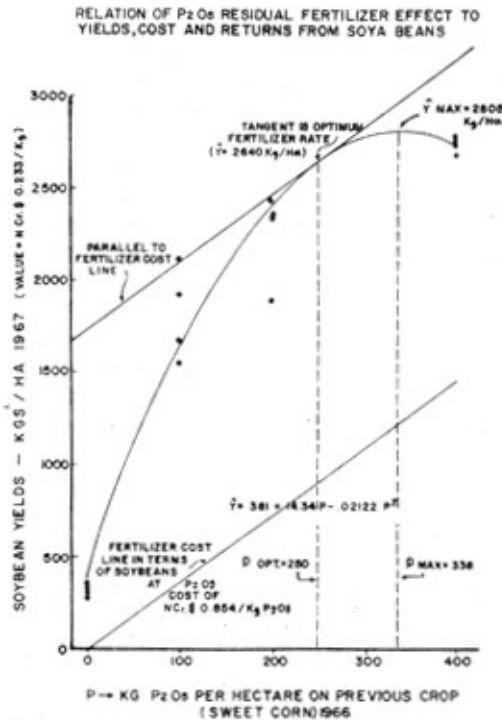


Fig. 14 - Residual effect of phosphorus on yields, costs and returns from soya on Eumic Ferralsol at Brasilia (IRI Research Institute, 1967)

Phosphate adsorption by plants is conditioned by other nutrients. Transport in the plant depends on the availability of magnesium, and is important especially for the production of seeds which are rich in oil. Magnesium deficient ferralsols will often not respond to phosphate fertilization, if the unbalanced cationic nutrition is not corrected simultaneously.

2.3.3 Potassium

Oxic horizons by definition contain only traces of weatherable minerals. Consequently they are poor in potassium included in the crystal lattice of soil particles. The bulk of potassium is essentially present in solution or it is adsorbed on the exchange complex.

Another kind of K-reservoir exists in the soil organic matter and the vegetation. The order of magnitude of the latter can be estimated from that data in table 1, page 14.

Since there are only limited amounts of 2:1 minerals in the clay fraction, little K-fixation is normally occurring in oxic horizons. However the horizon which contain an appreciable quantity of chloritized expansible layer silicates or which have a sizeable amount of amorphous materials may not release potassium with chemical extractants as readily as may be expected from exchange reactions. In such cases the potassium removed by crops frequently exceeds the quantities which are determined by chemical laboratory analysis as soluble or in exchangeable form (OLIVEIRA et al. 1971).

The activity of potassium in the soil solution depends on the percentage K saturation and the nature of the exchange complex. Adsorption isotherms which express the relation between adsorbed K and K in solution at given ionic concentrations, have been presented by FOX (1973). They indicate that in ferralsols only low K saturations on the exchange complex are necessary in order to achieve adequate potassium intensities in the soil water for uptake by plant roots, and that at this level the capacity of the mineral soil to maintain continuous replenishment of K in the soil solution from exchange sites is rather limited.

They also imply that potassium ions are not tightly held by ferralsols and that K is subject to leaching. As compared to Ca and Mg, losses by lixiviation are not so severe however. The behaviour of potassium is somewhat similar to the leaching of nitrogen, although N shortage usually appears earlier in crop rotations than the potassium deficiency.

Potassium supply to the soil solution is not biologically controlled as it is the case for nitrogen. After a period of dryness, the heavy rain does not produce a potassium "flush", comparable to the surge in nitrates due to accelerated nitrification. Therefore losses are less important. The most effective way to prevent potassium leaching in ferralsols, is to have crop roots developing as early as possible in the growing season into the deeper layers, from which it may be adsorbed and recycled in the vegetation. This recovery of potassium by plant roots is probably more efficient in tropical climates, where periods of rainfall and plant growth coincide, than in temperate or mediterranean climates, where the highest precipitation occurs in the cropless winter season.

According to MIDDELBURG (1950) and SCHUFFELEN and MIDDELBURG (1953), the leaching of cations in soils with low base exchange capacity, results in an increase of the ratio of monovalent to divalent cations adsorbed on the exchange sites. The leaching in acid ferralsols is therefore achieved mostly at the expense of calcium and magnesium. This may explain why potassium deficiencies are rather late in becoming limiting in the sequence of nutritional disorders which affect crop production in ferralsols. Potassium furthermore seldom appears as a single factor in causing reduction of yields, and equilibrium levels between Ca:Mg:K in the soil solution determine cationic uptake by plants. Mg and K antagonism are well known. The optimum ratios in exchangeable bases will be discussed in later chapters on diagnostic techniques for fertilizer requirements.

2.3.4 Calcium, aluminum, pH and liming

i. Calcium deficiencies

With increasing leaching many ferralsols become depleted of available calcium. At low base exchange capacities, the strong dilution progresses at the expense of bivalent rather than monovalent cations. It is mainly under savanna vegetation, which has only a weak capacity to recycle nutrients into the surface horizons, that calcium deficiencies are most likely to occur.

There may be other reasons for having calcium deficient crops in acidic, iron rich ferralsols. Specific adsorption may take place, and calcium may be fixed and made only slowly available to plants. In such cases the tie-up of calcium also causes a reduction of the cation exchange capacity, due to blocking of available sites.

Examples of calcium shortage in soils are known from Latin America. Many soils of Central Brazil which occur under savanna vegetation (cerrado) have only traces of exchangeable calcium (de FREITAS, McCLUNG and LOTT, 1960). The roots of most crops do not penetrate into layers which lack or are extremely poor in calcium (PEARSON, 1966). The soil volume which can be explored by the rooting system is consequently reduced.

Due to the low mobility of calcium in soils and plants, increased efficiency of liming can be achieved by the incorporation of the amendment into the subsoil. MIKKELSEN et al. (1963) at Orlandia reports that plowing down half of the lime (2 tons of 27% CaO and 19% MgO) to 25 cm depth produced 80% more seed cotton than disking in the entire two tons at 10 cm depth only. In the same experiment it was noted that two tons of lime applied half by plowing to 25 cm and half by disking at 10 cm depth produced 95% of the yield obtained by four tons of lime disked into the surface ten centimeters only.

ii. Exchangeable aluminum, aluminum in solution

As leaching becomes more intensive the amounts of Ca, Mg and K in the exchange complex and in the soil solution decrease. The soil may adjust to the new concentrations of cations by changing the activities of H^+ and Al.

In ferralsols which have a permanent charge (by definition not higher than 10 meq /100 g of clay in the oxic horizon) it is commonly assumed that the permanent exchange sites which become available are readily occupied by exchangeable aluminum, which produces acidity by hydrolysis. If aluminum occupies more than 60 percent of the exchange complex (which is active at the pH of the soil), large quantities of Al occur in the soil solution (NYE et al. 1961).

In ferralsols which have a low permanent charge, or a high ratio pH-dependent to permanent charge, as it is the case in most typical profiles, the leaching of cations and the dilution of the soil water causes the effective exchange capacity to decline. The soil acts as a weak acid and, since both the CEC and the exchangeable bases decrease simultaneously, there is practically no modification of the base saturation. There are no exchange sites to be occupied by aluminum. The pH of the soil is then primarily defined by the ionization constants of the acidic groups: as a rule, organic compounds develop more acid conditions than sesquioxides and kaolinite. Since aluminum does not participate

significantly in the exchange reactions, toxicities originating from this cation are not frequently encountered; high acidity rather causes manganese concentrations to become increasingly detrimental to plant growth, especially in soil layers which are low in organic matter.

The critical pH below which aluminum begins to play a role in exchange reactions is usually 5.2 in ferralsols. Changes in pH therefore control the effects of aluminum ions in the soil solution. These may be achieved by liming or other chemical amendments. Flooding of ferralsols, and reduction of iron, also causes the pH to raise, and subsequently reduces the activity of aluminum (CIAT, 1972).

iii. pH and Liming

As the cation exchange capacity of ferralsols is predominantly pH-dependent, there is no consistent relationship between the saturation percentage calculated on the basis of the cation exchange capacity determined at pH 7, and the pH of the soil suspension. A low soil pH either indicates a weak base saturation in soils having a permanent charge, or a small amount of exchangeable cations in a horizon which is rich in organic matter. In both cases it denotes soils which are chemically poor. The opposite is not always true. A pH close to six may be obtained in poor soils having a very small or no CEC, especially in sub-surface horizons.

The purposes of liming may vary considerably from one case to another; one may apply calcium only as a nutrient, in order to correct deficiency symptoms in crops. The objective of applying lime may be to neutralize the aluminum which is present in ferralsols having a permanent charge, and depress its detrimental effects on plant development. In other instances, manganese toxicities may be controlled by lime applications.

One of the purposes may be to raise the pH of the soil to optimum levels for cultivated plant species, or reach values which are adequate for phosphorus availability. The efficiency of nitrogen fixation is also strongly influenced by soil pH, aluminum and manganese activities in the soil solution. In soils that are not oxidic or ferritic, liming may increase the capacity of the soil to retain cations. On the other hand calcium contents usually enhance mineralization of soil organic matter, and indirectly act on the nitrogen supplying power of the surface horizons.

2.3.5 Sulphur and minor elements

i. Sulphur

OLSON and ENGELSTAD (1972) estimate that the highly weathered soils of the tropics only contain 100 ppm of S. In surface horizons most of it would be in the organic form. Sulphur deficiencies have most frequently been observed in savanna soils. McCLUNG

et al. (1959) reports that 75% of the sulphur contained in gramineae may be volatilized by burning. Severe nutritional disorders occur when less than 3 ppm of S is extracted by neutral NH_4OAc , or if the organic sulphur content does not reach 35 ppm.

Lack of sulphur becomes only evident during intensive farming. MIKKELSEN et al. (1963) estimate that 30 kg S/ha may satisfy the needs of most crops, and that usually 40 kg of gypsum/ha, or superphosphates which contain this sulphate are sufficient to correct the sulphur shortage.

McCLUNG and QUINN (1959) assume that sulphur deficiencies are often induced by the formation of organic matter after substantial nitrogen fertilization. Any practice which increases the nitrogen in the soil, and contributes to organic matter accumulation would at the same time sequester sulphur, and make it temporarily unavailable to plants. Normal C:N:S ratios in the soil would be about 10:8:1.

Grasses are stronger competitors for sulphur than legumes. In pastures the latter suffer more from lack of S than the former, and may completely disappear. Without augmented sulfur supply to grass/legume associations, the grass may become completely dominant (McCLUNG and QUINN, 1959).

ii. Minor elements

Minor elements are seldom limiting factors in crop production under extensive systems of agriculture in tropical areas where traditional yields are low (DROSDOFF, 1972). With more intensive management, the demand for micronutrients by plants increases beyond the supply levels of virgin soils however. This is especially true of acid soils which are under continuous cultivation and receive large amounts of nitrogen and phosphorus fertilizers. Boron, zinc and molybdenum are usually the most deficient, particularly when liming and high pH's may have reduced the availability of boron and zinc in the soil.

Excessive amounts of oligoelements in acid soils of the tropics are related to the desaturation of the exchange complex which may either be due to leaching, the utilization of acidifying fertilizers, or to the lack of organic matter which may control their solubility. Manganese, aluminum and iron are the most common cations which are discussed in toxicity cases.

a. Boron

Highly leached acid soils are generally low in available boron, and most of it is in organic form, which can be supplied to plants after the decomposition of humus.

MARTIN (1969) found boron deficiency symptoms in oil palm on soils which contained less than 0.2 ppm of B; they are easily corrected by applications of borates at a rate of 50 g per tree (or 7-8 kg/ha).

Fertilized and limed humic ferralsols with acric properties at Brasilia responded not significantly to applications of boron with corn, cotton and soya as test crops (BRITTO et al. 1971) Borax at a rate of 10 kg/ha was used in this experiment.

b. Iron (CIAT, 1972)

The iron content in the soil solution of flooded ferralsols increases considerably when reducing conditions are maintained for considerable time during irrigation. CIAT (1972) in rice experiments on ferralsols found that the Fe concentration remains low for several weeks before rising sharply to a maximum of 300-350 ppm. After the peak the high pH depresses the solubility of about 150-200 ppm, the Eh decreases at about 90 mV and the pH equilibrates at a value of 6.5

Rice may suffer from Fe toxicity when the soil solution concentration is above 300 ppm; at lower levels the deposition of iron oxides as coatings on roots is reported to prevent the uptake of nutrients, especially P, in flooded previously well drained ferralsols, and to cause orange and early senescence of lower leaves.

The excessive amounts of iron in the flooded rice paddies can be avoided by intermittent or rotational irrigation. The correction may also be achieved by improving the internal drainage, often at the expense however of stronger leaching of nutrients. Preflooding which has the advantage of passing the Fe peak before the early stages of the growth of the rice, has the disadvantage of more important P fixation by the soil.

c. Manganese

The uptake of manganese by plants in well drained ferralsols is dependent on the pH conditions of the soil, its calcium and iron content, and the amount of organic matter. Crop species are also important.

Most ferralsols develop excessive manganese contents at low pH and weak base saturation. ABRUNA et al. (1970) found that ferralsols in Puerto Rico with a base saturation of 32-40% gave: 2380 ppm Mn in tobacco, leaves; levels of 3000 are considered toxic; at a saturation of 95%, this amount was reduced to 580 ppm. The soils had an initial pH of 4.4, contained 200 ppm of exchangeable, and 2000 ppm of easily reducible manganese. PRATT (1966) found that a pH of 6 is completely effective in eliminating toxicity levels in ferralsols of Brazil.

The critical pH depends on the soil organic matter content. MCALF (1956) found that mulching has a depressive effect on the uptake of Mn by coffee.

BOYER (1956) reported manganese deficiencies in groundnuts on light textured ferralsols in the République Centrafricaine, when the total manganese content was below 60 ppm.

d. Molybdenum

Molybdenum is present in soils as molybdate anions, which are nearly immobile and in this respect are very similar to PO_4 . In acid soils it occurs adsorbed or included in crystals of hydrous iron and aluminum oxides; when adsorbed it is able to react with other anions; it may also be fixed as insoluble salts. A part of it is present in the organic matter (SAUCHELLI, 1969).

The availability of Mo increases with pH, even above neutrality; in soils which only contain marginal amounts of micronutrients the addition of lime may correct the deficiency of molybdenum, but also reduce the availability of manganese and zinc below critical levels (DROSDOFF, 1972).

Molybdenum is essential in nitrogen fixation reaction.

NEWTON and SAID (1957) mention molybdenum deficiencies in ferralsols of Java. Applications of 1 kg/ha of sodium molybdate increased yields of groundnuts.

DE FREITAS, McCLUNG and LOTT (1960) observed response to applications of molybdenum on recently cleared ferralsols after savanna vegetation with soybeans only in the absence of liming. Increased yields were then obtained by 0.3 kg sodium molybdate per hectare. MASCARENHAS *et al.* (1967) did not detect minor element deficiencies in newly opened fields which were limed and fertilized on Latosol Roxo after cerrado vegetation. The test crop was also soya.

IRI (1968) considers that molybdenum is probably needed for obtaining adequate production of *Stylosanthes gracilis* on savanna soils of Brasilia. CHACON (1968) found better response of soya and groundnuts to molybdenum when soils were not limed in the Eastern plains of Venezuela.

e. Zinc

The solubility of zinc in the soil decreases with rising pH; at pH above 6.5, only small amounts of available zinc are present in weakly buffered ferralsols. The critical pH level is difficult to define however. DROSDOFF (1972) mentions zinc deficiency symptoms both in light textured ferralsols at pH below 5, and in clayey ferralsols with a pH above 6. Both the total and the available zinc are important in evaluating optimum conditions for plant uptake of this element.

Some zinc deficiencies in ferralsols would be due to overliming. MOITY (1954) reports a soil pH above 6.5 as inducing zinc deficiencies in bananas.

The solubility of zinc nitrate is very high, and would be mainly responsible for leaching losses in most ferralsols, which could cause depletion of exchangeable zinc under acid conditions.

According to STANTON and BURGER (1967) well crystallized iron oxides, for example goethite, could fix zinc under slowly available forms.

IRI (1969) observed that corn develops extreme foliar chlorosis and fails to develop normally when zinc is not applied to sweet corn on fertilized and limed ferralsols at Brasilia, in fields which were newly opened after savanna vegetation.

In light textured soils the application of five kg/ha of $Zn SO_4$ banded adjacent to the row with other fertilizers was the most efficient way to correct the nutrient deficiency. 25 kg broadcast was also effective (IGUE and GALLO, 1960).

Humic ferralsols with acidic conditions at Brasilia, when fertilized and limed, respond strongly to applications of zinc both with corn, cotton and soya as test crops (BRITTO et al. 1971). Micronutrients alone, nor macronutrients alone had any effect on corn. Ten kilos zinc sulphate per hectare was enough to correct the deficiency.

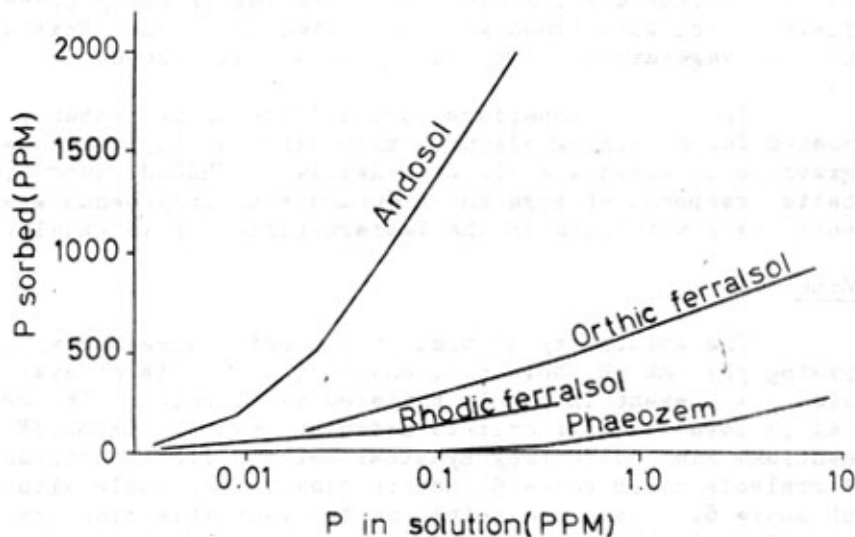


Fig. 15 - Phosphate sorption by ferralsols of tropical America (adapted from FOX, 1973)

3. SOIL MANAGEMENT

3.1 Tillage Practices for Seedbed-rootbed Preparation

In order to obtain good tilth several operations, including plowing, disking, rolling and harrowing may be necessary. They are all discussed in this chapter under the common name of tillage practices. Their most current objectives are to create optimum conditions for germination and for the development of a root system.

It is normally accepted that maximum yields are obtained from soil materials in which the aggregates that are close to the seeds are 3-12 mm. in size. Larger lumps may be present but should not be in contact with the seeds. WILSON and WINKELBLECH (1969) recognize two aspects in soil tillage, the seed zone and the root zone. In order to obtain uniform stands, the seeds should be surrounded by uniformly sized, closely packed crumbs particularly during the early stages of germination. The root zone, which operates once the root system is developed, requires less initial pulverization because it is exposed during much more time to the action of weather on the breakdown of soil clods.

Tillage operations as a rule should therefore aim at producing the highest proportion of suitable crumb (3-12 mm.) firmly packed at the depth where the seeds are placed. According to what has been said before, it is not required to have the same degree of granulation achieved over the entire soil surface, but only at the vicinity of the seed. A rougher surface between the zones may increase the rainfall acceptance of the field, reduce erosion hazards, and prevent soil crusting.

Suitable tilth is obtained by correcting adverse soil properties. There may be other purposes besides structure for working the soil. The most important objectives are listed below without suggesting any rank of priorities or making them mutually exclusive:

- i. change the pore size distribution in case it were inadequate for root penetration;
- ii. increase the water intake capacity of the soil in order to take maximum advantage of rainfall, reduce runoff and control erosion;
- iii. improve soil aeration and thus stimulate the decomposition of organic matter, and enhance nitrification;
- iv. mix fertilizers, green manures or other amendments with the soil, in order to incorporate them at suitable depth in the soil profile;
- v. control weeds by turning them under at a depth which restricts their growth.
 - a. There is usually no possibility to carry out intensive plowing on virgin ferralsols which are recently cleared from the rainforest. Too many thick roots and stumps hamper the normal operations of tillage implements. It is moreover doubtful whether intensive plowing of forest ferralsols is needed, let alone whether it is desirable. Soil pores of suitable size in freshly cleared land are presumably present in sufficient amount.

Unfortunately there are only few data on the minimum pore size requirements for roots. RUSSELL (1971) reports that small seeded crops will only send their roots into pores that are larger than 100 microns (some grasses) or 200 microns (wheat). Virgin ferralsols in the tropical rainforest areas will certainly have enough pores of this size, and probably enough channels of this diameter, and therefore no deep plowing would be needed, in order to increase their porosity, when such plants are cultivated directly after clearing.

The bulk density of the plow layer, which is related to total porosity, has more often been referred to with relation to the effects of tillage operations. TROUSE and BAVER (1962) found that root elongation in low humic latosols (ferralsols) was reduced at a bulk density approaching 1.35 g./cm^3 . LE BUANEC (1970) reports that in savanna the sols ferrallitiques of Ivory Coast the root development of cotton was stronger in surface layers having a total porosity of 55% (bulk density of 1.15), than in horizons having only 40% (bulk density of 1.50).

Penetration of the root tip in pores and channels is followed by expansion. Not all plants have similar requirements however. Trees and shrubs for example have roots which expand appreciable with age. Soil strength is one of the main factors which reduce the possibilities of root development in soils of critical bulk density. It is also known that soil materials are more rigid when dry and that mechanical impedance starts to restrict root development in soils of high bulk density (> 1.55), before the water stress begins to retard plant growth. The main purpose of tillage operations in surface layers of high bulk density is to create large pores, channels and void planes in the rooting zone, resulting in a lower bulk density, and achieve a better distribution of air and water in the vicinity of the growing root tips.

LE BUANEC (1970) has found that the sols ferrallitiques at Bouaké (25% clay) do not give satisfactory yields of igname, unless the soil has been loosened by deep plowing. Root crops need undoubtedly more plowing than small grains or grasses. BAVER et al. (1972) state that in low humic latosols (ferralsols) of Hawaii the rooting depth of sugarcane is generally restricted to the depth of tillage, and that deep plowing on these soils is therefore essential for optimum cane growth. In this case the soils had been cultivated over long periods of years, and the aeration effects of the preceding natural vegetation had probably disappeared.

Most investigators concur that tillage of ferralsols results in higher yields (JURION and HENRY, 1969, page 130). It is not always clear however whether the benefits are due to improved pore size distribution and root penetration or whether other factors are involved.

It has become a matter of routine to insist on proper soil moisture content for plowing, but no accurate measurements on the optimum humidity have been found in the literature on ferralsols. The moisture content should be low enough so that the soil cohesion within the aggregates is sufficiently strong as to resist compaction and puddling. On the other hand, soil moisture should permit the

breakdown of clods into pieces of suitable size. Deterioration of structure is more likely to occur in light textured ferralsols than in clayey ones, in the case that plowing had been done in too wet conditions. The high ironoxide content in the finer soils are usually a favourable factor for structure stability. Most problems have been encountered in coarse topsoils; for example surprisingly severe hardening of sandy red loams (72% sand) was observed in East Africa as a result of plowing under wet conditions. This hardening effect extended to a depth of 2-3 inches. (PEREIRA et al. 1958).

- b. The second objective of tillage operations is to promote the water intake capacity of the soil. Oxidic horizons and topsoils do not easily form surface crusts which are the main cause of limiting water acceptance; low fine silt contents and high percentages of free iron oxides do not seem to be conducive to crust formation, except in very fine sandy topsoils. The light textured surface horizons either become hard and massive when dry, or fall apart into single grained structures. In the case of hardening, plowing in too dry conditions will result in a cloddy surface condition, which may be adequate for rainfall intake, but not necessarily for germination, and require many post plowing treatments, or strip preparation of seedbeds.

There are no soils which can resist the high rainfall intensity of tropical regions, and adsorb water fast enough at any time as to avoid runoff; cultivation on the contour should always be the rule. BERTONI (1966) measured the effects of contour plowing and sowing versus downslope operations in ferralsols of Sao Paulo (Brazil), on 6% slopes under 1300 annual rainfall, and found that soil losses were reduced from 21,4 tons/ha/year to 4.1 tons. Water losses by runoff decreased from 64 mm /year to 36 mm /year. In this experiment it was shown that contour sowing is even more important for soil and water conservation than contour plowing. Conservation of the topsoil is particularly important in ferralsols, because the fertility is often exclusively present in the surface horizons.

In areas that are under the climatic stresses of erratic rainfalls, it is imperative to increase the water acceptance by the soil surface. A system of tied ridges, which consists of furrows tied at intervals to form basins, has been tested on lateritic soils in Kenya (PEREIRA, HOSEGOOD, and DAGG, 1967). It is essentially a system to make sure that maximum benefit shall be obtained from precipitation. In some years it increased the yield by 40% relative to those from the fields which had been cultivated on the flat (DAGG and MACARTNEY, 1968).

Ridging of ferralsols which are not exposed to erosion is not without presenting drought hazards however, especially in climates with strongly contrasting seasons (WALTON, 1962). It has been found that in the beginning of the growing period the moisture available in the topsoil is less under ridged than under land on the flat. The difference is attributed to the larger surface area exposed by ridging (ibid.) and to more important losses by evaporation. When plants have been sown on the ridge, they may suffer

from drought at the initial stages of their development before their roots have reached deeper layers where the moisture content does not closely follow temporary dry spells. For early planting flat cultivation on land with less than 1% slope will most frequently produce the highest yields. The danger of the water strain may be lessened by planting on the side of the ridge, or by ridging after the establishment of the crop (WALTON, op. cit.).

The choice of the most suitable tillage practice will be governed by the slope gradient and its shape, and the characteristics of the rainfall. Tillage practices which build ridges along the contour, without closing the furrows at regular intervals, do not remove the risks of accelerated erosion caused by large masses of water which collect in the long furrows during heavy storms. Therefore PEREIRA, HOSEGOOD and DAGG (ibid.) emphasize the need of ridging and tying in one and the same operation.

Most experiments on ferralsols have shown the remarkable stability of slopes under intensive cultivation along the contour; there is usually only a slow downhill creep causing accumulation of soil materials and the formation of benches above terraces. If full conservation precautions are taken, the stability of the soils is adequate for arable cultivation on slopes up to 10%. The erosion hazards do not come as much from the plowed fields themselves as from running water collected by road drainage systems, housing, etc. which cannot be kept under control during intensive rainfall.

Soil tillage practices improve aeration; if they are applied after clearing, and coincide with a marked change in ecological conditions towards warmer temperature regimes, they will favour the nitrification of the organic matter, and increase nitrogen losses due to leaching. The rate of decomposition of organic matter can for example be measured by CO₂ release from the plowlayer. MEYER et al. (1959) report for ferralsols at Yangambi (Zaire) a period of about twenty days immediately after the first tillage operations, during which CO₂ and N are released at a rapid rate. It is therefore important to accomplish the tillage operations as shortly as possible before the time of planting in order that the crops benefit from the available nitrogen; by this practice the losses due to leaching of nutrients are reduced to a minimum. It may be questioned whether such a flash release should be stimulated by aeration in the presence of a considerable labile organic nitrogen pool and under conditions of high temperatures. MEYER (1959) noted that turning the organic matter layer under a subsoil material during plowing, reduced the mineral N content of the soil markedly (from 60 ppm to 8 ppm, 8 days after tillage, in a soil with 0.196 % total N). It should however be avoided that seeds are located in materials which fix phosphorus at higher intensity than the topsoil.

The time of plowing with respect to clearing and sowing also depends on the kinds of tillage operations. Pre-plowing cultivation can help to reduce the time of exposure to direct sunlight. It avoids the formation of large clods or continuous soil slices held together by roots or by compaction, and shortens the weathering period needed after plowing for clod breakdown; it permits

the operations for building tilth to be carried out immediately following one another. According to BOSHOFF and HILL (1969) it also reduces the cost of seedbed preparation by some 25% over the conventional technique where plowing is done first.

In deciding on the type of tillage to be carried out, the climate is important. In clayey ferralsols with high nitrifiable organic matter in the hot tropics, minimum tillage or burying of the humus horizon may be recommendable.

In cool climates, in humic ferralsols, or soils under grassland, where C/N ratios are higher, more intensive plowing may be justified, depending on specific purposes, and other management practices that are accomplished simultaneously; the same holds true when incorporating plant residues of high C/N ratios, depending on whether mineral fertilizers are used at the same time, and whether any immediate release of N is expected or if, on the contrary, biologic N fixation is one of the main objectives.

BOUCHARD and RAKOTOARIMANANA (1970) recommend plowing of the soil at the end of the cropping cycle as a means of increasing the structural stability in arable land which has suffered deterioration during clean weeding. They attribute the effect to aeration and drying during the rainless season.

- d. The fourth purpose of the preparation of a rootbed is related to the mixing of amendments into the soil, especially in the case of nutrients that are slowly soluble, and do not migrate into deeper layers. Lime is more efficient in soils which lack calcium when it is incorporated at great depth, thus enabling roots to grow into horizons which received calcium carbonate. The crops can then benefit from a greater soil volume and water supply. Results of experiments conducted in ferralsols were discussed in chapter 2.3.4 (i), page 74.
- e. Ploughing reduces the need for weeding, and permits to save labour and to keep more strictly to an agricultural timetable. JURION and HENRY (op. cit. page 130) report to have obtained a reduction by + 60 mandays per hectare by plowing fields where the invasion by *Imperata cylindrica* was to be controlled. With the advent of pesticides, the economics of such practices are to be reinvestigated.

3.2 Fallows

Fallows are convenient management practices for restoring the productivity of the soil in countries where the price of new land and the cost of clearing the vegetation are cheaper than the overcharge due for the conservation of soil fertility in permanent cropland.

Under other circumstances the occupation of arable land by the fallow makes the rest period economically unsound, especially when it has been proved that the productivity can be increased either by fertilizers, irrigation, or pest control. In the case that modern technology cannot be applied, fallows are often the only alternative which is left after that continuous cropping has depressed the yields below acceptable standards.

The purposes which can be achieved by fallows are listed below:

- i. replenish the surface horizon with fresh organic matter, in order to increase its nutrient supplying power, particularly of nitrogen, and improve the cation exchange properties. In addition, transform nutrients into more available compounds.
- ii. develop a root system which draws Ca, Mg, K and other nutrients from lower layers, and concentrates them either in the vegetation, or in the topsoil.
- iii. improve the structure of the soil, both by the development of a root system and by the addition of fresh organic matter.
- iv. refill the soil with available moisture in order to use it during the growing season.

Not all fallows are equally efficient in restoring the soil productivity. The time needed to rebuild an agricultural soil may vary from one season to several decades. There are even huge areas which never recovered from deforestation and where the original vegetation was never able to reoccupy the land.

3.2.1 Restoration of chemical fertility

i. Fallows in rainforest regions

Among the different types of fallows in the hot humid tropics, the secondary forest is the most capable of bringing the soil productivity potential close to its original level. The trees operate by deep rooting and pick up cationic nutrients from the subsoil. Unlike savannas, they restore the readily decomposable organic matter pool without severe losses of N by annual burning. The forest may be very difficult to establish however and its development may be slow.

The efficiency of a forest fallow depends essentially on its ability to create in a short time a vegetation which protects the soil against high temperatures and erosion. The sooner the ecological conditions of a forest are reinstated, the faster the increase in organic matter of the soil. It is obvious that the control of soil losses due to erosion contributes to a better conservation of the gains.

The early stages of forest fallows are the most efficient in rebuilding the soil organic matter. LAUDELOUT (1960) considers that a duration of minimum ten years, and maximum fifteen is adequate for reaching nearly the original organic matter level of the rainforest. At later stages, the older regrowths immobilize the nutrients almost exclusively in the woody parts. In order to obtain a closed plant canopy right from the start of the fallow period, it is usually recommended not to end the cropping cycle with a clean weeded plant. Cassava or bananas, which tolerate mixing with pioneer forest species, are for example suitable transitions from crop to fallow. At the same time, plant residues that are rich in starch enhance N fixation and may accelerate the restoration process.

The importance of the type of crop which comes last in the rotation and the ecologic conditions of the surroundings has been stressed by JURION and HENRY (1969). They contend that a weeded crop such as groundnuts at the end of the cropping cycle on medium textured orthic ferralsols in the center of a forest region, does not retard the recolonization by trees, provided that forest strips border the fields, that isolated trees act as seed bearers and perches for birds, and that stumps left in the fields give a quick start to the regrowth by sending up shoots. They obtained rates of spontaneous recolonization which made it unnecessary to try to plant forest species for the only sake of accelerating the establishment of a suitable fallow.

Such favourable circumstances may not prevail at the edges of the rainforest regions, and competition between savanna and tree species may become very harsh. Winds and fires are effective allies of savanna communities for taking advantage of ill-disposed soil properties.

Among the most difficult ferralsols for recolonization by trees are the acric ferralsols, followed by the dystrophic groups which are dominated in the effective base exchange capacity by aluminum. If the oxic horizons are thick (i.e. more than two meter), and when the profiles are freely drained, a short dry period, aided by fire, may favour the establishment of grasses and allow them to impede or to retard drastically the return of the rainforest.

Undeep ferralsols, in which the oxic horizon is underlain by weathering rock which may supply nutrients to penetrating roots, and contain more available water, are among the most suitable for the restoration of surface layers by forest fallows. They are approached in this capacity by the deep xanthic and orthic ferralsols, and only surpassed by the rhodic suborder. The eutrophic phases are usually the most favourable.

There are other soil properties which may retard or completely hold up the reclamation process of surface layers by forest fallows. Erosion causes most damage on convex slopes; sandy topsoils make ferralsols particularly sensitive to drought; strong declivities reduce water intake. These are conditions which should imperatively exclude agricultural uses, which involve clean-weeded crops, in acric, orthic and xanthic dystrophic ferralsols from areas which have no other resources than fallows for the rehabilitation of the arable topsoil, and where a dry season, however short, aided by fire may hamper the establishment of the forest pioneer plants. Even under better circumstances should it be recommended to apply management practices which stimulate the prompt establishment of a secondary forest; i.e. by leaving forest vegetation strips between fields, protection against intensive fires, wind breaks, and erosion control.

The importance of a rapid re-establishment of the vegetation for the efficiency of the restoration process has also been stressed by GREENLAND and NYE (1959). They estimated that a crop to fallow ratio of about 1:3 could maintain the humus level in forest soils at 75% of the equilibrium level.

The length of the fallow period in forest regions will depend on the quality of the soil, and the status which the fertility has reached at the moment the field was abandoned. In xanthic ferralsols which were dystrophic and medium textured, JURION and HENRY (1969) have described systems which allow for three to four years of cultivation followed by twelve to fourteen years of fallow; the crop to fallow ratio in this case was 3:12. How often such a sequence can be repeated could not be determined experimentally. The intermixed crops included bananas, cassava, rice and corn.

In areas which mainly consisted of eutrophic orthic ferralsols the best observed crop to fallow ratios were 6:15, 5:12 and 5:15. Some more demanding crops as cotton could be included in the rotation. Eutrophic ferralsols in the rainforest belt that are protected against fire allow about 30% of the arable land to be occupied by crops; dystrophic ferralsols in the same area would only support approximately 20% cropland. This means that farm holdings which are planned for forest fallow rotations, or shifting cultivation, should have five times as much arable land than the area which is actually cultivated, when the soils are predominantly dystrophic. In the case of eutrophic ferralsols the factor would be 3 or 4. The importance of land prices and soil properties in estimating the feasibility of management systems based on long fallows is obvious. Not only direct agrotechnical considerations come into play, but also the costs of building a suitable socio-economic infrastructure. The latter may be prohibitive in the case that the area of the rural community has to be extended five-fold particularly in the case the project has to be integrated into a modern market economy the objectives of which reach beyond traditional subsistence levels.

In order to cope with these problems, efforts have been made to shorten the fallow periods, or to increase the crop/fallow ratio. In the forest zone grasses have been used to replace the tree species. JURION and HENRY (1969) conclude that on the whole Pennisetum purpureum is not capable of maintaining soil fertility, except on eutrophic Rhodic Ferralsols. Other plants, such as Chloris gayana, Desmodium intortum, Canavalia ensiformis, and Stylosanthes gracilis, did not offer any improvement compared to natural fallows. They advocate the use of fertilizers in order to correct the deficiencies caused by continuous cropping, claiming that the effect of chemical amendments is relatively greater than that of organic dressings (JURION and HENRY, op. cit.).

Fallows in savanna regions

Natural savannas on deep ferralsols only slowly succeed in creating suitable environments for restoring the soil productivity. Compared to forest regrowth, they poorly protect the soils against erosion, particularly when long dry seasons and fires reduce the plant cover to a minimum. The phosphorus and N levels under savanna are usually less than in the rainforest areas. The production of organic matter by grasses is strongly dependent on seasonal rain distribution; it may be high in perhumid climates, but low in regions with a dry season. AHN (1970) estimates that in West Africa

the amounts of plant material added annually to the soil would in practice not exceed 2,5 Tons/ha which compares very unfavourably with the 15 to 20 Tons/ha produced by an established forest fallow.

The inefficiency of savanna fallows on ferralsols is often demonstrated by the need to scrape surface soil into individual mounds on which crops are grown, or to concentrate on spots where heaps of fallow vegetation have been burned.

There have been many attempts to improve the efficiency of savanna. Most include the control of fires. JURION and HENRY (1969) report that protecting spontaneous three years old grass fallows from fire on eutrophic orthic ferralsols increases the yields of seed cotton by about 170 kg/ha and of corn by 350 kg/ha dry grain in a subsequent two years rotation ending with groundnuts which did not show any response. Other investigations aim at replacing the natural grasses by herbaceous plants selected for their ability to regenerate the soil, control weeds, and possibly produce forage.

JURION and HENRY (op. cit.) mention Sotaria sphacelata and Brachiaria ruziziensis among the grasses which are adequate in controlling Imperata cylindrica. The legume Stylosanthes gracilis has a high feed value, and is capable of dominating the same weed. The experiments which lead to these conclusions were carried out on eutrophic ferralsols, or soils with a favourable base status. It is not certain, whether similar results could be obtained on dystrophic or allic soils, without the aid of chemical fertilizers. Weed pollution is indeed particularly severe in desaturated soils which are either poor in calcium or rich in exchangeable aluminum, or both.

In the hot tropics, under primitive management, which does not include the use of fertilizers, without effective erosion control, and without limitation or fires, etc. there has been no experience where the spontaneous regrowth of savanna on dystrophic orthic, xanthic or acric deep ferralsols improves the chemical fertility of the topsoil. There is not much evidence either that improved pastures would do any better, as they are usually invaded by weeds and require prohibitive inputs of labour or capital in order to keep the grassland clean.

The same limitations exist for grassland which is sown directly after clearing rainforest, or after a first crop, as it is traditionally practised in South America. Under extensive management systems, the intended pastures can neither resist the pressure of spreading poor savanna species in places where drought and fire impede the return of a forest, nor withheld the establishment of a secondary forest under wetter conditions. The action of the tree fallow is thus substantially retarded. The alternate use of grassland as fallows on dystrophic or acric ferralsols is only justified when it is complemented by fertilizers which take care of the mineral nutrient supply to the plants. The role of the fallow in the latter case is then essentially related to physical problems occurring in the soils after long periods of cultivation, and to the maintenance of organic matter levels.

Grazing of grass leys which are included in a crop-fallow rotation in savanna areas may have beneficial effects upon the subsequent arable crop. The action is particularly noticeable just at the opening of the arable cycle. STOBBS (1969) assumes that most benefits result from the greater quantity of nitrogen which accumulates in the grazed land. There may be some transference and concentration of fertility by moving animals from surrounding permanent grassland into the fallow area. Nutrients may be transformed into more available compounds; defoliation is thought to stimulate plant growth, and increase the efficiency of bringing up cations from lower layers into the surface horizons. Possible reduction of weed growth under heavy grazing is also mentioned as a possible reason for increased yields. The experiments reported by STOBBS had a 3/3 crop fallow year ratio, and production figures correspond to a 20% increase for night grazing, and a 10% increase for day grazing. The description of the experiment carried out by STOBBS does not give detailed information on soils, and it is not known whether the results are applicable to ferralsols with low content of bases. To be efficient there must be some mineral reserve in deeper layers, or suitable nutritional conditions in the topsoil, or transference of fertility from the outside.

iii. Fallows in cool tropical regions

There have been no basic investigations on the effects of natural fallows in humic ferralsols of the cool tropical climates. They have usually high organic matter contents with wide C/N ratios and are poorly saturated with bases. The dark humus rich horizons are thick enough, and the only possible benefit from fallows would be to supply the topsoil with bases or with readily decomposable organic matter.

These purposes are not easily achieved in soils with thick oxie horizons. JURION and HENRY (1969) estimate that approximately ten to twenty years of natural grass fallow would be needed in order to restore the soil after a one or two years crop rotation. The crop/fallow ratio would thus be 1/10, the lowest mentioned in primitive agricultural systems.

Most of the attempts of increasing the efficiency of fallow in the cool tropical savanna of Zaire aimed at controlling the invasion of couch grass (Digitaria Vestita), by introducing plant species which would hasten the restoration process. No promising results were obtained neither with Cassia didymobotria nor Setaria sphacelata (JURION and HENRY, op. cit. page 142), whether grazed or not. Setaria sphacelata moreover has the disadvantage that it cannot be ploughed into the soils with the implements which are available to local farmers.

3.2.2 Restoration of physical properties

Cropping necessarily leads to the deterioration of soil structure. MOREL and QUANTIN (1964) found in virgin savanna soil instability indexes of 0.4. Sandy topsoils degraded after two years, medium textured soils after four years, reaching indexes of about 1.5. Longer cropping periods lead to indexes of 2 or higher.

Fallows of running grasses, or with superficial rooting were able to restore the index to 1-1.3; crest grasses with deep rooting habits could achieve better results and bring the structural index back to 0.8-0.4. Cover crops, such as Stylosanthes and Pueraria were rather poor in improving soil structure, except for Gajanus indicus which accomplished a better task in the amelioration of physical conditions.

If the structural instability has not reached extreme values, such as 2, it is suggested that 3 to 4 years of a natural grass fallow will be sufficient to correct structural deterioration.

The present experience thus seems to indicate that natural fallow communities including deeply rooted erect grasses are the most suitable for restoring soil structure. They improve the ability of the soil to accept rainfall and to transmit water, primarily by increasing the volume of freely draining very large pores and channels, (20 cm water tension, PEREIRA et al. 1954). In ferralsols they do not affect the distribution of the finer pores, for example those which are filled at field capacity. The influence of grasses on structure is mainly one of improving on soil aeration; according to PEREIRA et al. (1954) they do not confer continuing advantages, and the soil returns to its unfavourable state after the first year of cultivation. This is probably due to the fact that the better physical conditions are essentially the result of an increase in the amount of the large pores which are necessarily the most fragile.

Natural grass fallows however are very demanding on soil moisture and a dry season may deplete a 3 meter deep profile of all available water. PEREIRA et al. report that soils kept bare during the same time still contained 230 mm of available water. Such severe water deficits have deleterious effects on the following crops, especially if the rainfall distribution at the beginning of the growing season is erratic.

Grass species differ markedly in their ability to protecting the soil against erosion. The bunch grass, like Panicum Maximum are less suitable to reduce run off and soil losses than stoloniferous or sod types. SMITH and ABRUNA (1955) indicate that Melinis minutiflora, once it is established, provides excellent soil protection. Generally the losses during seedbed preparation and the early seedling stages of the grasses are higher than the total for several years after grass establishment (op. cit.).

3.2.3 Soil and water conservation by fallows

The most difficult task for fallows is to restore the available water content of the profile. Only bare fallows may achieve such purposes in tropical regions. The difficulties to control soil erosion on a bare surface render this type of fallowing a dangerous technique however. PEREIRA et al. (1958) showed that volunteer covers may remove all available water in regions with a single rainy season where precipitations amount to approximately 500 mm, and where open water evaporation from a 120 cm diameter sunken pan averages 2108 mm per annum.

Natural fallows which are composed of indigenous plant species have usually deep rooting systems which exhaustively extract water from the entire profile. Introduced grasses with shallow rooting habits, when properly sown may suppress volunteer regrowth and afford some protection against erosion, without depleting the available water in deeper horizons.

3.3 Fertilizer and Lime Requirements

3.3.1 Nitrogen fertilization (BARTHOLOMEW, 1972)

The quantity of fertilizer nitrogen (N_F) which should be added to a soil depends on:

- i. the amount of N_M required by the crop in order to achieve a possible maximum yield. The maximum crop production is usually determined by limiting factors other than nutrients, such as environment, diseases, genetic plant characters, etc. (N_M)
- ii. the nitrogen which is supplied from natural sources and absorbed by the crop during the growing season (N_S).
- iii. the efficiency of the soil-plant system in using the added fertilizers (f = fraction of fertilizer N added which is adsorbed by the plants).
- iv. the cost/benefit relationship between the expenditures for the added fertilizers and the profits related to the increase in production.

Taking into account the first three factors, the following equation expresses the foregoing statements:

$$N_F = \frac{N_M - N_S}{f}$$

A brief review of the present knowledge regarding the adequate techniques for evaluating N_M , N_S and f is given below. Current management practices act on all three components.

a. Crop use requirements (N_M)

The average crop use requirements for corn, rice and wheat have been estimated by BARTHOLOMEW (1972), using experimental data obtained both in tropical and temperate regions. They are illustrated in fig. 16. The slope of the curves was defined by the following regressions:

$$\Delta N = 30 + 1.3 I \quad \text{for corn}$$

$$\Delta N = 58.1 + 0.005 I \quad \text{for wheat}$$

where ΔN = kg N needed to obtain a one ton increase in yield

I = the check yield in tons/ha from which the increase was measured

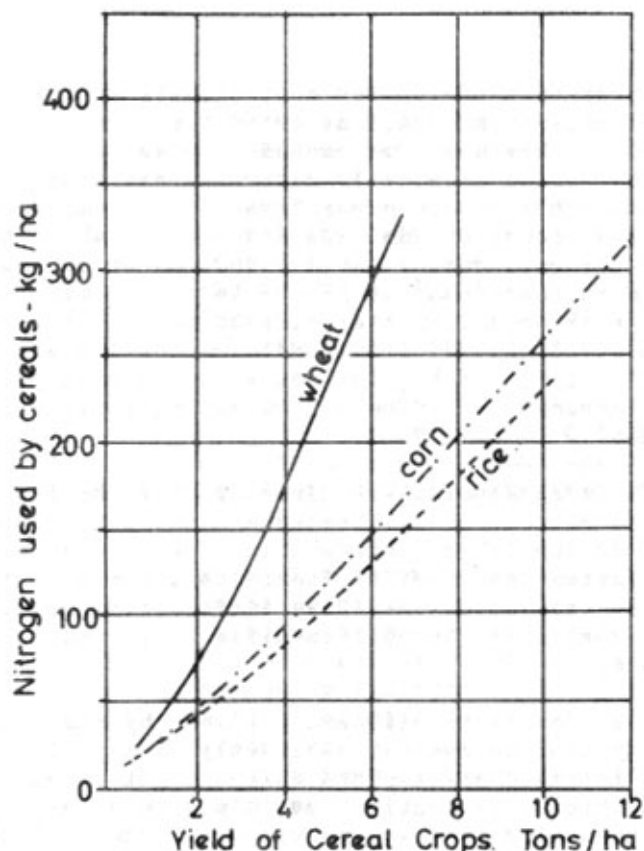


Fig. 16 - Nitrogen requirements of cereal crops (BARTEOLOMEW, 1972)

The equations fit curves which indicate the trend toward greater nitrogen requirements per unit yield increment at high production levels. For rice it was estimated that 43 kg N were necessary to produce a one ton increment in brown rice.

Crop use requirement curves for other crops have not been computed; it should be noted that the equations consider the nitrogen needs of the entire plant, and not just the export of the harvested product. It is also worth mentioning that in BARTHOLOMEW's approach it is assumed that the N fertilizer response is essentially rectilinear up to a maximum yield level beyond which the response to fertilizers is either zero or negative. This maximum obtainable yield defines a ceiling of response. Its position may be modified by acting on other nutrient levels, or it is determined by climatic conditions, water supply, etc.

b. Natural supply of nitrogen (N_s)

It is very difficult, if not impossible, to predict the amount of N which will be supplied to the crop by the soil environment during a forthcoming season. The former history of the land, the weather conditions and the management practices cause considerable modifications in the rate of nitrogen release by the soil. They cannot be taken into full account by whatever laboratory methods.

Incubation procedures most closely approach the potential rate of mineralization of the organic matter in the field. They are time consuming however. Less reliable methods which chemically determine extracted fractions of inorganic N are more expeditive; for example the measurement of the amount of ammonium and nitrate which has accumulated in the soil during the dry season, or during a rest period, have been found to relate to actual mineralization rates of soil organic matter, including the crop residues. LATHWELL et al. (1972) found that the total N extracted by a 0.01 M CaCl_2 and K_2SO_4 boiling solution highly correlated with the amounts of N mineralized during varying periods of incubation.

It is an absolute requirement that the laboratory diagnostic methods be calibrated against crop response measured in the field; since this experimental work has only a limited domain of applicability, the soil testing procedures themselves only give satisfactory results when they are restricted to well specified soil and cropping conditions.

The amounts of nitrogen supplied by the soil-plant system may also be evaluated directly from yields that are obtained in field check plots which do not receive fertilizer N. Traditional production levels may be a basis for assessing the natural N_g supply, provided no other nutrients are limiting.

BARTHOLOMEW (1972) proposes such a system. For example the amounts of nitrogen used by corn which produces two tons would be approximately 50 kg per hectare (see figure 16). In the absence of fertilizers, this quantity would be a reasonable estimate of the quantity of natural nitrogen which is absorbed by the crop during the growing season. Tables which are established locally by observation on given crops and sites could become satisfactory guides for assessing the importance of the natural supply processes. They could also be used as standards for calibrating soil test procedures when a great variety of field conditions occur. More detailed discussions of the method can be found in BARTHOLOMEW's publication (1972).

c. Use efficiency of fertilizers

It can be estimated from figure 16 that corn uses 140 kg more N per hectare to produce 8 tons than to produce the traditional amount of two tons per hectare. This supplement should be given as fertilizers to the soil. Only a part of it (f) is taken up by the crop however.

The importance of nitrogen losses by leaching in ferralsols has been discussed on page 68.

The efficiency of nitrogen fertilizers can be increased by adapting the time of application to the growth pattern of the crop and to the periods of nitrogen supply by the soil. After a dry season there is usually an increased nitrogen release by the organic matter at the moment the rains start. No nitrogen fertilization is needed at that time. Later on split applications will therefore usually result in a better utilization of the fertilizer. The kinds of nitrogen carriers are also important, and slow release fertilizers may give good results. Placement should be such that the N reaches the active root zone when it is most needed by the plant. The moisture regime largely determines the time and the placement techniques. Band applications are only necessary when it is expected to have favourable interactions with phosphorus.

Since nitrogen uptake by the plant occurs mainly by mass flow through the transpiration stream, and because under tropical conditions the soil water movement in ferralsols is essentially rain dependent, split applications and slow release fertilizers should normally achieve the highest efficiency. AHN (1970) reports that split applications of nitrates to annual crops at one month and at two months after planting were more efficient than single applications either at planting or at two months after planting.

Nitrogen fertilization should not be in excess of phosphorus availability. The N:P ratios which have been proposed by DABIN (1967) are given in the following chapter.

3.3.2 Phosphorus fertilization

Phosphorus moves to the roots mainly by diffusion through the soil water. It is the concentration of P in the soil solution which defines the rate of movement of phosphates to the root, by establishing a concentration gradient. This concentration is therefore called the intensity factor in phosphorus nutrition.

The solid phase must be able to provide sufficient phosphorus to the soil solution in order to avoid its depletion by the uptake of P by the crops. The quantity of P which is available for replenishing the soil solution is called the capacity factor.

There are several chemical reactions and adsorption processes which govern the equilibria between P in solution and the active P in the solid phase. Adsorption isotherms have been proposed to describe quantitatively these phenomena. The curves which have been obtained by FOX (1973) have been reproduced in figure 15, page 80.

In order to maintain a concentration of 0.2 ppm, which would be adequate for most crops, the Orthic Ferralsol (fig. 15) should have 380 ppm of sorbed P. This corresponds in a 20 cm thick surface layer of 1.3 bulk density to 988 kg per hectare of sorbed P, or 2261 kg P₂O₅.

How much of this is present in the soil, and to what extent it can provide phosphorus to the soil solution which is in contact with the roots, is a problem which has locally been solved by quick chemical extraction methods coupled to field experiments. There are no soil test procedures which have general applicability however.

CATE and NELSON (1965) mention tentative critical levels of P extracted from soils by different methods. The amounts of P below which the probability of response to fertilization is high, were:

- 6 ppm : Bray N^o1 method (0.1N HCl + 0.03N NH₄F)
- 30 ppm : Bray N^o2 method (0.025N HCl + 0.03N NH₄F)
- 18 ppm : North Carolina method (0.05N HCl + 0.025N H₂SO₄)
- 10 ppm : 0.1N HCl
- 22 ppm : 0.7N HCl
- 1.2 ppm : H₂O extract.

BOYER (1970) reports that research on Sols Ferrallitiques indicated a close relationship between total phosphorus and crop yields. MOULINIER (1962) found that production of cacao varied between 100 kg per hectare at 65 ppm of total P, to 800 kg at 200 ppm. Cotton seemed to be more demanding for phosphorus, and soils were considered poor when their total P content was less than 300 ppm, and rich when it exceeded 400. Only if a large part of the soil phosphorus is in the organic form, the determination of total P may produce a satisfactory correlation with crop production.

The management of P nutrition in ferralsols is closely related to organic matter content and to the nitrogen supply. BOYER (1970) mentions that for soils with a pH higher than 5.5, the total N to total P ratio should be between 9.1 and 4.6 DABIN (1967) indicates that a ratio of $r = \text{total N/available P}$ of more than 22.9 would correspond to a shortage of nitrogen; a ratio of less than 45.7 would produce phosphorus deficiencies and consequently a poor utilization of nitrogen.

It is seldom possible to satisfy in one operation the phosphorus sorption capacity of the arable layer in order to achieve an adequate P concentration in the soil solution. The investment is financially too high to be borne completely in one growing season. Therefore management tends either to concentrate the fertilizer by placing it close to the seeds or the roots, or to granulate it as to reduce the contact area with the soil, or to block by other chemicals the fixation capacity of the soil.

Lime used in such amounts as to neutralize the exchangeable aluminium also increases the effectiveness of P fertilizers; it may also accelerate the decomposition of organic matter, and in this way contribute to the phosphorus supply from soil sources; where aluminium is dominant in the exchange complex, as in the younger members of the ferralsols, phosphorus fertilizers which contain both silica and calcium are usually most efficient. Basic slag and Rhenania phosphates give usually very satisfactory results in such soils.

Single superphosphates are most commonly used in typical ferralsols for immediate crop response. Less soluble forms are more convenient for soil fertilization than for crop fertilization.

3.3.3 Potassium fertilization

Nutrient deficiency symptoms become noticeable in most crops when the amount of exchangeable potassium is less than 0.10 meq per hundred gram soil. This critical level constitutes an absolute minimum which is valid for many soils, including the ferralsols. Only a few plants as cassava may be productive at lower contents (0.06 meq K per 100 g, ROCHE et al. 1959).

Sandy topsoil ferralsols are the most deficient in potassium. BOYE (1962) only found 0.02 meq K in oil palm plantations, where the trees responded to applications of 1 kg KCl per tree, raising the yields from 250 kg to 2000 kg oil per hectare.

Many crops present potassium deficiencies at higher percentages however. This may be due to a lack of sufficient soil volume for the roots to explore; soil chemists have rather stressed the importance of the balance of potassium with other nutrients, particularly magnesium and calcium.

Although only small quantities of exchangeable potassium are necessary to maintain suitable concentrations in the soil solution of ferralsols, it is usually recommended to have more than two percent of the sum of the exchangeable bases as potassium.

Comparable requirements for robusta coffee on ferralsols have been formulated by FORESTIER (1964), who parallels the cation exchange capacity with the clay plus silt content. He recommends critical exchangeable potassium levels of 0.12 meq K per 100 g soil, when there is 20% clay plus silt, but 0.50 meq K for ferralsols containing 65% particles smaller than 20 microns.

BOYER (1972) in his review of potassium in tropical soils states that a magnesium to potassium ratio of 3:1 seems to be favourable to the majority of crops. Ferralsols planted with oil palm should have Mg:K ratios greater than two, and Ca/K ratios of more than five (JULIA, 1962); disequilibria resulting in excessive potassium uptake occur frequently when the exchangeable K content exceeds 1 meq per 100 g soil (FRANKART and CROEGAERT, 1959).

Fallow vegetation forms an appreciable reservoir of potassium. LAUDELOUT (1961) found that a thirty years secondary rainforest releases upon burning approximately 130 kg K per hectare; in the Yangambi ferralsols the exchangeable K was raised from 0.067 to 0.325 meq K per 100 g soil after clearing operations which included fire.

Leaching of potassium fertilizers increases in the following order: potassium metaphosphate, potassium chloride, and potassium nitrate (AHMAD and DAVIS, 1970).

Losses of potassium can be reduced by adjusting the time of application to the needs of the plants, for example by split applications. ROOSE et al. (1970) nevertheless estimate leaching losses to 50%. Well developed rooting systems are the best barriers to potassium lixiviation.

3.3.4 Lime requirements

DE FREITAS, PRATT and VETTORI (1968) compared different rapid laboratory methods for the determination of the lime requirement of soil by calibrating the tests against the amount of CaCO_3 needed to raise the pH of a soil sample during incubation. The time to reach the equilibrium pH was approximately six weeks.

The results of their experimental work on samples of ferralsols are given in tables 16 and 17.

It can be seen that the $\text{Ca}(\text{OAc})_2$ method (VETTORI, 1948), would bring the pH between 6.1 and 6.5; the WOODRUFF (1948) procedure would achieve the same results; adding calcium as to reach a base saturation of 86% (CATANI and GALLO, 1955) most frequently raises the pH to values between 5.6 and 6.0. The KCl method or the neutralization of exchangeable aluminium has no consistent influence on pH.

The authors stress the importance of the pH with relation to phosphorus availability which would be optimum near 6.0. Molybdenum uptake increases at high pH, and organic matter decomposition would be the fastest at pH 6.0. Aluminum is neutralized completely at pH 5.5, and there would be no toxic effects of manganese at pH close to 6.0.

The tables also indicate that the lowest amounts of calcium are those which only aim at neutralizing the exchangeable aluminium. Under many circumstances the minimum amount of lime is the only economically feasible for many farmers, and according to present experience it permits to obtain satisfactory yields with most crops.

The time of reaction to reach an equilibrium pH in the field left under natural vegetation takes at least six months in dystrophic heavy textured Latosol Roxo of Brazil (MUZILLI et al., 1969). The residual effect of lime, especially when it is only added in order to reduce the aluminium activity, is not well known. It would probably not exceed one year, and repeated applications are probably necessary in soils having more than the modal amounts of exchangeable aluminium.

Liming requirements do not depend only on inherent soil properties. The acidifying effects of fertilizers must also be neutralized. It is for example usually recommended to use one ton of lime per ton of ammonium-sulphate. Equivalent acidities of most common fertilizers, which indicate the amount of calcium carbonate required to neutralize the hydrogen ions released by 100 kg of fertilizers have been published elsewhere. Data from AHN (1970) are given in table 18.

The importance of incorporating lime into deeper layers has been discussed in chapter 2.3.4 (i), page 74; deleterious effects on the structure of ferralsols having a net positive charge has been mentioned in chapter 2.2.1, page 49. Specific adsorption of calcium and blocking of exchange sites and a subsequent decrease of the CEC have been studied in Hawaii (UEHARA, SWINDALE and JONES, 1972).

Table 16 LIME REQUIREMENT (meq per 100 g) OF FERRALSOLS ACCORDING TO VARIOUS LABORATORY AND INCUBATION METHODS (DE FREITAS et al. 1968)

Soil No	pH after incubation			Ca - (OAc) ₂	Woodruff	Base saturation	KCl
	5.5	6.0	6.5				
1	1.6	2.1	2.7	2.4	2.2	2.0	2.7
2	1.9	2.8	3.6	3.0	3.2	2.4	2.8
7	2.3	4.8	7.2	6.2	5.0	3.6	0.0
8	0.0	1.0	2.0	3.2	2.8	1.1	0.0
9	3.7	5.8	8.0	8.2	7.2	7.0	2.8
10	1.2	3.0	4.1	4.4	4.4	3.8	2.6
16	3.7	5.4	8.0	6.4	5.6	5.6	2.8
18	2.4	4.2	6.0	5.8	5.2	5.0	2.9
19	3.2	5.1	6.6	5.2	4.8	4.4	1.7
20	4.8	7.5	11.0	8.6	7.0	7.2	2.8

Table 17 FREQUENCY DISTRIBUTION OF PH REACHED BY FERRALSOLS AFTER LIMING ACCORDING TO LIME REQUIREMENT TEST (DE FREITAS et al. 1968)

pH	Ca(OAc) ₂	Woodruff	Base saturation	KCl
6.6-7.0	1	1	1	0
6.1-6.5	8	5	3	1
5.6-6.0	1	4	7	3
5.1-5.5	0	0	0	4
4.5-5.0	0	0	0	2

Table 18 EQUIVALENT ACIDITY AND BASICITY ^{1/} OF FERTILIZERS (AHN, 1970)

Fertilizer and Formula	Equivalent Acidity	Equivalent Basicity
NITROGEN		
Sodium nitrate (NaNO ₃)		29
Ammonium sulphate (NH ₄) ₂ SO ₄	110	
Ammonium nitrate (NH ₄ NO ₃)	60	
Calcium nitrate (Ca(NO ₃) ₂)		21
Urea (CO(NH ₂) ₂)	80	
Calcium cyanamide (CaCN ₂)		63
Ammonium chloride (NH ₄ Cl)	120	
PHOSPHATE		
Di-calcium phosphate (Ca(HPO ₄))		25
Rock phosphate		variable
Basic slag		variable
POTASSIUM		
Potassium nitrate (KNO ₃)		23

^{1/} The equivalent acidity is the number of kg of calcium carbonate required to neutralize 100 kg of the fertilizer; the equivalent basicity shows the neutralizing capacity, expressed as kg of CaCO₃ of 100 kg of the fertilizer.

3.4 Irrigation of Ferralsols

The topographic location of most ferralsols seldom allows irrigation; they frequently occur on elevated plateaus with deep water tables where the cost of bringing water are prohibitive.

There are a few examples however where well drained red ferralsols have been used for irrigation agriculture. CIAT (Centro Internacional de Agricultura Tropical, 1972) has reported its experience on acid highly leached ferralsols of the Llanos Orientales of Colombia, which were cropped with flooded rice. Their findings are briefly summarized below.

Irrigated rice production faced the problem of the appearance of a physiological disease called "anaranjamiento" or orange leaf disease. The symptoms are described as follows, (CIAT, 1972):

"Flooded rice grown in the llanos normally appears rather healthy and green during the first month of growth. During the second month, however, the plants become stunted, have insufficient tillering and the leaves start turning yellow to orange. Typical "anaranjamiento" begins with yellowing at the tip of the lower leaves, progressing down the leaf, especially along the margins, and moving up the plant to the higher leaves. The lower leaves eventually dry up and die"

"The roots of affected plants are generally short with few rootlets and are covered with a red iron oxide deposit. Sometimes the root tips are slightly enlarged and dark red. Most roots seem inactive."

It is postulated that the disease is due to the toxicity of a product formed by the reduction of the well drained ferralsol which is rich in free iron oxides.

The effects of flooding on Eh and the Fe concentration were measured. With irrigation the Eh decreased from 545 mV to a constant value of about 90 mV in 10-15 weeks. It was assumed that the free iron content buffered the soil solution at relative high Eh, and no potentials low enough to reduce sulphates were ever reached.

After several weeks the concentration of Fe in solution rises to a maximum of 300-350 ppm, but drops to a constant level of 150-200 ppm because of the influence of increasing pH during flooding. The Mn concentration was never higher than 2 ppm. No direct Fe or Mn toxicities seemed to be involved.

The conclusions of the CIAT investigations regarding the origin of the disease and the soil management problems related to irrigation of well drained iron rich ferralsols included the following points:

- a. "Orange leaf disease is not a direct Fe toxicity since it may occur at relatively low Fe concentrations in soil solution, resulting in relatively low Fe levels in the plant. However it seems to be caused by damage of the root system by a reduction product, most likely Fe. The deposition of Fe oxide on the outside of the root not only limits root growth but also prevents the uptake of nutrients, especially P. In a soil already low in plant nutrients

this limited uptake ability of the plants leads to an imbalance between supply and demand. In a large plant with a large demand, a small increase in Fe concentration in the soil solution and subsequent coating of the roots leads to a shortage of nutrients. The plant compensates for that by translocation of nutrients from the lower to the higher leaves resulting in orangings and early senescence of the lower leaves.

For that reason, healthy plants, grown under conditions of high P and N or low Fe, are always first and most severely attacked by "anaranjamiento", once the Fe concentration in solution starts to build up. Similar conditions of restricted root growth in plants grown in too small a pot, plants grown on compacted soil, or plants from which the roots have been cut, will lead to the same "anaranjamiento" symptoms in other than the llanos soils. Since "anaranjamiento" is a root problem, and primarily a result of extreme P deficiency, foliar applications of P eliminate the symptoms."

- b. "In soils with a rapid build-up of soluble Fe, the plant remains stunted from the beginning and there is no need to balance the top growth with the limited nutrient supply. In this case no typical "anaranjamiento" develops, but the plant may suffer from direct Fe toxicity."
- c. "A slow reduction results in good initial plant growth, but the subsequent late occurrence of the Fe peak results in severe "anaranjamiento" and a considerable reduction of grain yields."
- d. "The severity of "anaranjamiento" can be reduced by a combination of water management and fertilization practices designed to maintain a low level of Fe and a constant supply of soluble nutrients in the soil solution."
- e. "A build-up of soluble Fe can be prevented by intermittent or rotational irrigation. A low Fe concentration during flowering, obtained by mid-season drainage, is advantageous for grain formation. Constant flooding with internal drainage maintains a low Fe level, but the loss of nutrients in the drainage water makes it counterproductive. Preflooding for three weeks has the advantage of passing the Fe peak before seeding or in the early stages of growth, but has the disadvantage that P applied at seeding is more rapidly fixed. For that reason preflooding for more than three weeks is not beneficial." (CIAT, 1972).

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