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9. ABSTRACT

Analyses of 518 topsoil samples collected from a 600,000-sq.-kilometer area in central Brazil were conducted to establish their pH, Al, nutrient, organic matter, cation exchange capacity (CEC), texture, and color. The soils typically have a pH of 4.8 to 5.2, percentage of organic matter of 1.5 to 3.0, and extremely low values of effective CEC and extractable calcium, magnesium, phosphorus, zinc, and copper. They had a high degree of aluminum saturation, iron, and manganese, and a broad range of textures. The productivity of the soils was estimated from the natural vegetation at the sample sites. A positive correlation was found between the amount of vegetation, and in order of importance, the following: zinc, magnesium, effective CEC, calcium, pH, phosphorus, potassium, copper, chroma, and level of organic matter. Results showed three groups of variables to be important: (1) chemical variables (phosphorus, zinc, and magnesium); (2) texture variables (silt/clay and sand ratio); and (3) color variables (hue and chroma). The ratio of silt to clay was not positively related to the amount of vegetation.

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A SURVEY OF THE FERTILITY STATUS OF SOILS UNDER "CERRADO" VEGETATION IN BRAZIL

By

Alfredo Scheid Lopes

A thesis submitted to the Graduate Faculty of
North Carolina State University at Raleigh
in partial fulfillment of the
requirements for the Degree of
Master of Science

DEPARTMENT OF SOIL SCIENCE

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ABSTRACT

LOPES, ALFREDO SCHEID. A Survey of the Fertility Status of Soils Under "Cerrado" Vegetation in Brazil. (Under the direction of FREDERICK RUSSELL COX).

Soils under natural "cerrado" vegetation were surveyed for their fertility status. A total of 518 topsoil samples were collected from a 600,000-square kilometer area in central Brazil. The samples were characterized for soil pH, Al, nutrient (including micronutrient), and organic matter levels, effective cation exchange capacity (CEC), texture, and color (hue, value, and chroma). The range, median, and relative frequency distribution were calculated for each soil property. These soils typically have a pH of 4.8 to 5.2 and an organic matter level of 1.5 to 3.0%. They have extremely low values of effective CEC and extractable calcium, magnesium, phosphorus, zinc, and probably copper. The degree of aluminum saturation in the samples, however, was high, as were the levels of extractable iron and manganese. There was a broad range in the texture of these soils.

The natural vegetation was also classified at the site each soil sample was taken, and this was used to estimate productivity. Correlation and regression procedures were conducted to determine the relation between vegetation and the various soil properties. The correlation procedure indicated a positive relation between the amount of vegetation and the following (in order of degree of importance); zinc, magnesium, effective CEC, calcium, pH, phosphorus, potassium, copper, chroma, and organic matter level. There was a negative relation between the amount

of vegetation and hue, value, percent aluminum saturation, silt/clay ratio, silt, and iron level.

Multiple regression analyses were conducted to further elucidate the relation between amount of vegetation and soil properties. The results indicated that three groups of variables were important. They were (1) chemical variables (phosphorus, zinc, and magnesium), (2) texture variables (silt/clay ratio and sand), and (3) color variables (hue and chroma). The amount of vegetation was positively related to each of these properties except silt/clay ratio.

Additional insight regarding each important chemical variable was obtained by relating the phosphorus, zinc, and magnesium levels to other soil properties. Numerous variables and interactions among variables appeared related to the native phosphorus status of these soils. Manganese level, color variables, and their interactions seemed somewhat more important than other variables in this case. The zinc status of these soils was largely related to cation exchange capacity and factors associated with it, such as organic matter and soil pH. Zinc level was also generally higher if the manganese level in the soil was high. This may be an indication of differences in parent material. The magnesium status of these soils was found to be very closely related to the cation exchange capacity, calcium level, and percent aluminum saturation.

BIOGRAPHY

Alfredo Scheid Lopes was born on December 19, 1937 in Minduri, Minas Gerais, Brazil. He received his elementary and secondary education in Lavras, Minas Gerais, graduating from Instituto Gammon in 1957. He obtained his Degree of Engenheiro Agrônomo from the Escola Superior de Agricultura de Lavras in December 1961.

From 1961 to 1963 he worked as an Assistant Professor of Geology and Mineralogy in the Department of Chemistry and Technology of the Escola Superior de Agricultura de Lavras. From 1963 to 1972 he worked as an Associate Professor of Soil Science in the same college. From 1969 to 1972 he was also Head of the Department of Chemistry and Technology of the Escola Superior de Agricultura de Lavras. In 1972 he came to North Carolina State University to pursue the Master of Science Degree in Soil Science.

The author is married to Selma Lopes and they have two children, Claudia Mara and Luis Henrique.

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Finally, the author wishes to dedicate this dissertation to the memory of his parents, Mr. and Mrs. Antonio de Araujo Lopes, whose guidance, encouragement, and sacrifice made his education possible.

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INTRODUCTION

About 20% of Brazil is occupied by savanna vegetation that in a broad sense is called "cerrado." This "cerrado" vegetation can have specific designations according to changes in the ground layer material and the density and height of woody plants.

Most of this area has been used for extensive cattle production on unimproved natural pastures. The soils under "cerrado" vegetation generally have low levels of available nutrients, high phosphorus fixation, and clays of low activity. They have good structure throughout the profile and occur on gentle slopes. These factors indicate a potential for intensive agriculture.

Brazil is involved in major efforts to develop this area. Improved paved roads, railroads, loan facilities for agricultural purposes at low interest rates, subsidized lime, and technical assistance have been provided as an incentive for people to move into these areas. There has been rather marked progress in several regions under "cerrado" vegetation in Brazil; in many small localized areas of São Paulo, in the Triangle of Minas Gerais, and in a section of southern Goiás. Annual crops like upland rice, soybeans, corn, sorghum, cotton, beans, and pineapple all have been grown with some degree of success. Pasture improvement and reforestation with eucalyptus and pines are also being tried.

One of the main limitations to the most efficient use of these soils is the lack of information needed to provide an adequate base of technology and management. Data are needed on the nature of these soils

and on responses, fixation, and evaluation of critical levels for the various nutrients in these soils.

Soil survey maps of most of the area under "cerrado" vegetation in Brazil are exploratory on a scale of 1:5,000,000. These do not have adequate detail for interpretation at the farm level. Although experiments involving macro- and micronutrients have been conducted with many crops, most are from São Paulo State which has only about 10% of its land under "cerrado" vegetation. Relatively little information is available from the bulk of the area under "cerrado" vegetation.

Additional information is needed on the properties of soils under "cerrado" vegetation. Problems and potentials shown by these properties must be evaluated. Therefore, a survey was planned with the following objectives: (1) characterize the topsoils under "cerrado" vegetation in central Brazil chemically and physically, (2) compare these results with some of the critical levels suggested for soil fertility interpretation, (3) study the relationship between type of vegetation and other soil and location variables, and (4) study the relation between important soil chemical variables and other soil properties.

LITERATURE REVIEW

Geographic Location

The area under "cerrado" vegetation in Brazil continuously comprises almost all of the state of Goiás, the western part of Bahia and Minas Gerais, and all of eastern Mato Grosso (from north to south, but wider in the center and south). It also extends as great peninsulas of "cerrado" north into southern Maranhão and southern Piauí, west into central and southwest into Mato Grosso and adjacent Paraguay. Small outlying disjunct areas of "cerrado" occur in several places in north and northeastern Brazil, in São Paulo State, and in a few tiny atypical areas in northern Paraná. A tentative map of the native vegetation in Brazil is shown in Figure 1, but the limits for the "cerrado" area are still questionable.[1]

The particular area under study is located in between 10°17' and 21°41' latitude south, and between 44°02' and 52°43' longitude west of Greenwich. It is triangular in shape going from Belo Horizonte in Minas Gerais to Pôrto Nacional in the north of Goiás and to Mineiros, on the border between Goiás and Mato Grosso (Figure 2).

Climate

Camargo (1963) compared the distribution of "cerrado" vegetation in Brazil prepared by Azevedo (1959) with a climatic classification of the same area according to Koeppen and presented by Bernarde (1959).

---

[1]Appreciation is expressed to Mr. Marcelo Camargo, EMBRAPA, Brazil, for his help in delineating some of the "cerrado" areas in this map.

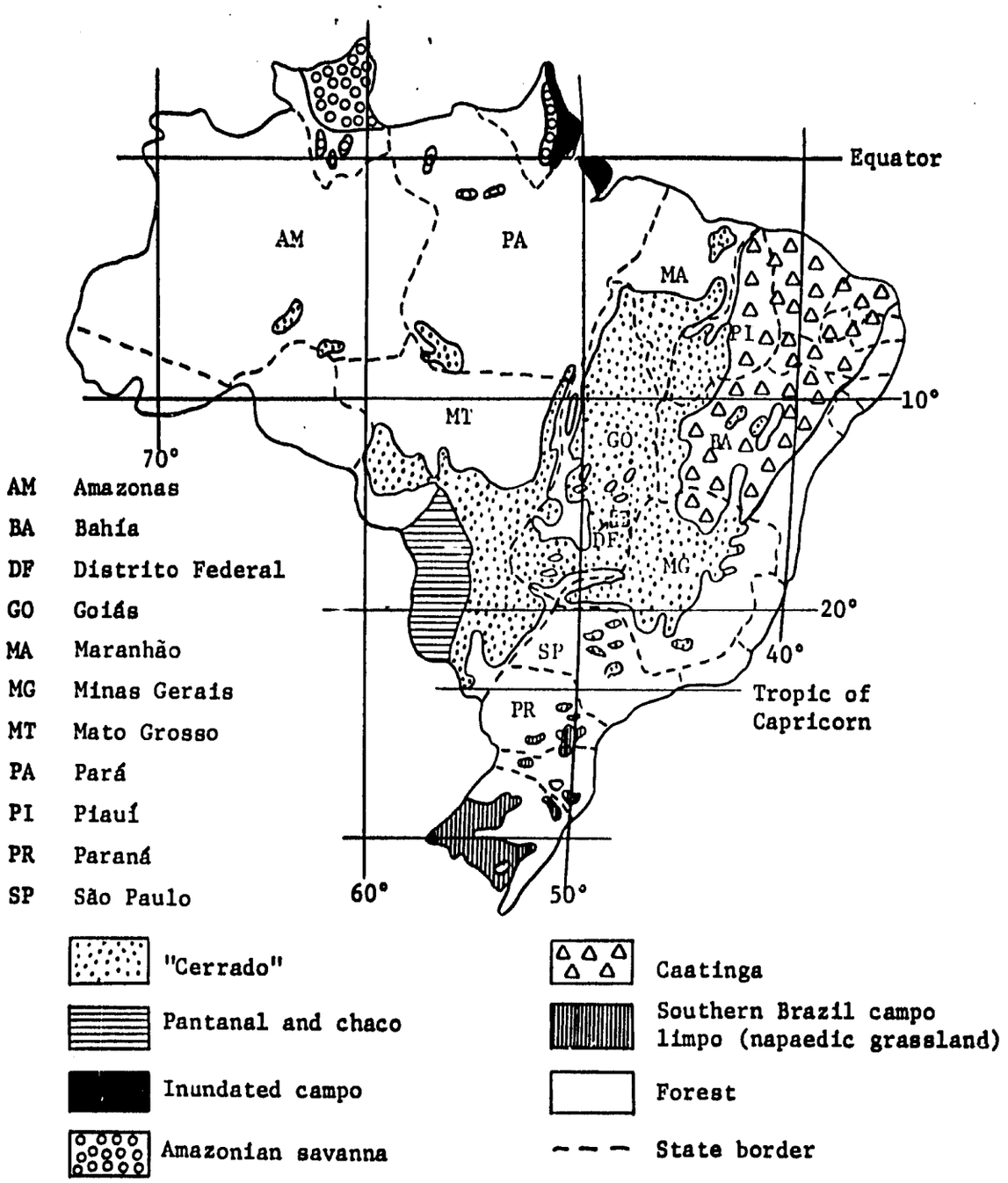

Figure 1. Native vegetation in Brazil (adapted from Azevedo, 1959 and Eiten, 1972)

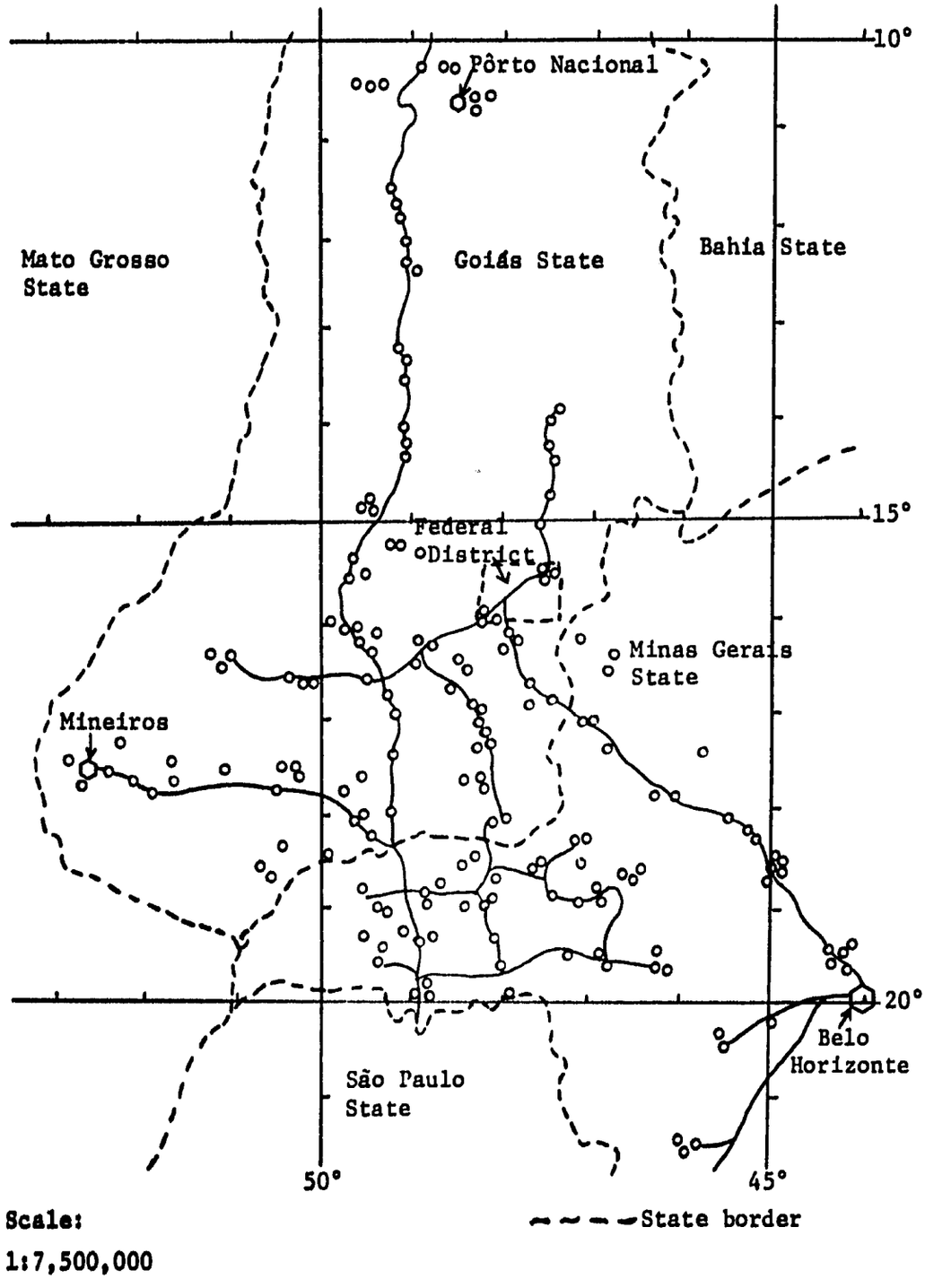

Figure 2. Route map and sample sites

According to this author, Brazilian "cerrados" can occur in a large variety of climatic types. Their classifications and descriptions are as follows: Am-humid and hot with short dry season; Aw-humid and hot with long dry season in the winter time; Cwa-humid mesothermal subtropical, with fresh summer and dry winter; Cfa-humid mesothermal, subtropical with hot summer and without dry season and Cfb-humid mesothermal, with fresh summer and without dry season.

The bulk of the "cerrado" area in Brazil is typically classified as Aw-humid and hot with long dry season, and the area considered in this survey is mainly included in this category.

The average annual temperature of the "cerrado" region is 20-26°C (Eiten, 1972), but in southern São Paulo which was not considered in this survey, it may be as low as 18°C. Rainfall varies from a yearly average from 750-800 mm on the dry side of the "cerrado" region (northeast side) to 2000 mm on the west side. There is a great variation not only in average precipitation but also in the distribution over this vast region. Water deficit by the method of Thornthwaite for soils under "cerrado" vegetation in Brazil can vary from 4 to 791 mm according to data presented by Reis (1971).

One typical annual distribution of precipitation and potential evapotranspiration for Brasília is shown in Figure 3. There is an average annual rainfall of 1626 mm which should represent a large area under "cerrado" vegetation in Brazil. The length and severity of the dry season, however, is another very important characteristic in this region. During the dry period that normally goes from May to August, only irrigated crops can be grown. Lack of uniform rainfall distribution

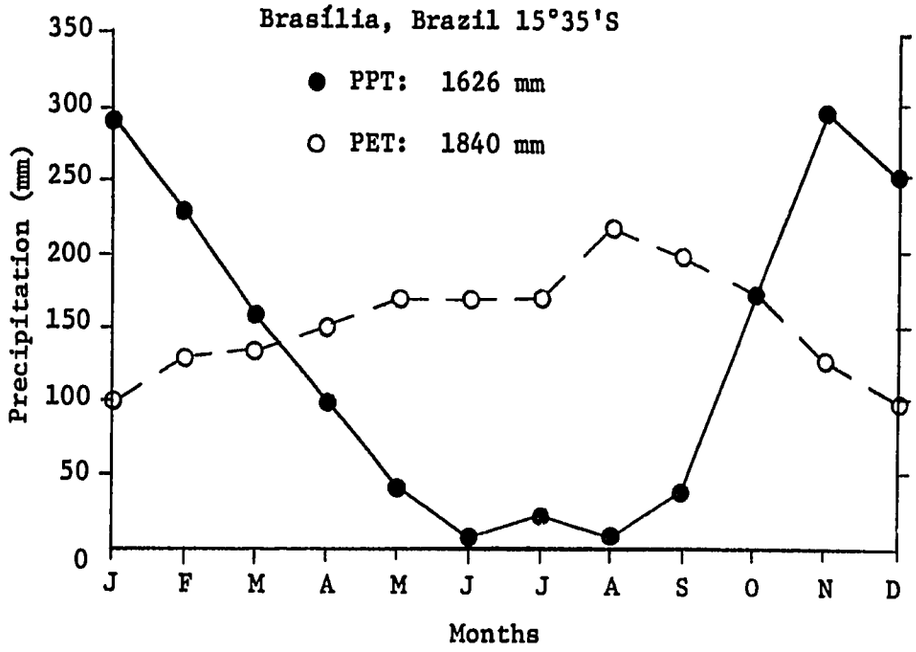

Figure 3. Annual distribution of precipitation (PPT) and potential evapotranspiration (PET) for Brasília Experimental Station, Brasília, DF (average of 5 years)

is one of the climatic aspects that needs to be emphasized as characteristic of this region.

Even during the months of December and January, those highest in rainfall intensity, it is not uncommon to experience two weeks of rainless days. These are often coupled with high solar radiation and high potential evapotranspiration (Wolf, 1974). They are known locally as "veranicos" and drought-sensitive crops can be seriously injured when no irrigation is available.

The soil moisture regime of the Central Plateau of Brazil is typically "Ustic," and the soil temperature regime is isohyperthermic according to U. S. Taxonomic Criteria (Soil Survey Staff, 1970).

Vegetation

Within the general vegetation class termed "cerrado," Brazilian geographers and others working in this area generally distinguish four types of vegetation based on ecological and physiognomic (structural) points of view. One of the best summarization of these types was presented by Eiten (1972) as follows (pp. 227-231):

> (1) Campo limpo: (Figure 4)--grassland with taller visible woody plants essentially absent, and whose flora is made up of practically the same species as the ground layer of campo cerrado. (Note that the use of "campo limpo" here is for a variation of the cerrado flora.) Sometimes, when a cerrado grassland has a few, very scattered, low but conspicuous shrubs or acaulescent palms it is distinguished as "campo sujo."
>
> (2) Campo Cerrado: (Figure 5)--includes several forms with the total woody plant cover rather open or sparse, that is, less than 30-40% cover, such as (a) quite open shrub, (b) low arboreal quite open woodland, and (c) true physiognomic savanna, i.e., scattered medium-tall or low trees, or shrubs, or usually both trees and shrubs intermixed, over a continuous or slightly open layer of grasses, herbs, dwarf shrubs, and semishrubs.
>
> (3) Cerrado (restricted sense): (Figure 6)--includes several forms with the total woody plant cover closed or down to about 30-40%, such as (a) closed or semi-open low arboreal forms (canopy generally less than about 7 m tall), (b) closed or semi-open shrub forms (canopy generally less than about 3 m tall), the elements of which may be definitely shrubby, arboriform, or the two mixed, (c) closed or semi-open shrub mixed with scattered trees of various heights. The trees may be emergents and form a single upper layer, or, usually, rise to varying heights along with varying heights of shrub elements so that the upper surface of the vegetation is "hilly."
>
> (4) Cerradão: (Figure 7)--the medium-tall arboreal form with a closed or semi-open canopy (down to about 30-40% tree crown cover).

In this survey in addition to these four types of vegetation referred to in our discussion in a broad sense as "cerrado," we also included some samples of the type called first-class forest, described by Waibel (1948) as follows (pp. 534-536):

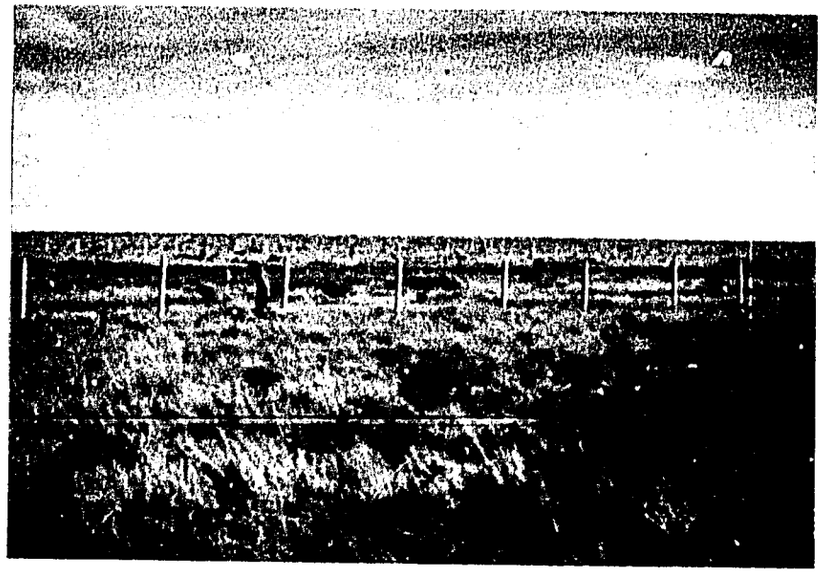

Figure 4. Campo limpo vegetation near Jataí, Goiás

Figure 5. Campo cerrado vegetation on a Red-Yellow Latosol at Anápolis, Goiás

Figure 6. Typical cerrado vegetation on a Dark-Red Latosol near Brasília, Federal District

Figure 7. Cerradão vegetation on a Dark-Red Latosol near João Pinheiro, Minas Gerais

(5) Forest: (Figure 8)--a dense tree story, semi-deciduous forest with an evergreen lower story of shrubs and some grass. The upper story is 20-30 m high and the middle story 5-15 m high. Trunks are straight in contrast with the typical tortuosity of the "cerrado" vegetation. The bark is greyish and smooth, buttresses are rare and lianas are few, in contrast to the taller equatorial forest.

Under the structural point of view, a normal gradation in vegetation in this area goes from campo limpo, to campo cerrado, cerrado, cerradão, and forest.

According to AIA (1963), 50% of the Central Plateau of Brazil consists of campo cerrado and cerrado, 20% of campo limpo (including campo sujo--dirty campo), 10% of cerradão and 20% of forest (including sections that have been cleared).

Figure 8. Semideciduous forest vegetation at Inhumas, Goiás

Origin of Cerrado Vegetation

According to Waibel (1948), the first time that the term "original vegetation" was used to when referring to this area was in 1831 in a paper published by the French botanist, Auguste de Saint Hilaire, who visited Minas Gerais and southern part of Goiás in 1819. Saint Hilaire is considered the father of the doctrine of plant succession. He explained how the various stages of second growth on forest lands cleared by burnings will, if burning continues, give way to artificial grasslands and, if left undisturbed, revert to forest.

The same concept is accepted by Rawitscher (1948) who quite logically stated (p. 265):

> The question whether the existence of their stunted and poor vegetation must be described to the dryness of the climate, or to human interference, specially the annual burnings, ... can be resolved only by examination of the water economy of these Campos.

According to this author, at least at Emas, São Paulo, where these studies were done, a permanent water table lies at a depth of 17 to 18 m and the subsoil below 2 or 2.5 m is permanently moist. Most of the trees and shrubs are deep-rooted, penetrating to the humid subsoil and even to the water table. This leads to reasonably normal transpiration rates by trees and shrubs in the driest part of the rainless period, a fact that was observed by physiological studies on plants in this area. Nevertheless, shallow-rooted plants, such as natural grass, are considerably affected by the dryness of the topsoil. Based on these data, Rawitscher accepted the fire climax theory.

Beard (1949) and Cole, mentioned by Denevan (1965), have maintained that vegetation such as campo cerrado is entirely or partly a result of periodic waterlogging due to unfavorable drainage. This

theory does not seem to be widely applicable since according to Feuer (1956), Cline and Buol (1973), and our personal observation during this survey, very little of the Central Plateau is subject to waterlogging. Such would require an impermeable layer such as indurated laterite. Most of the Brazilian Oxisols under "cerrado" vegetation are very deep, with good porosity and excessively well drained. Indurated laterite is believed to be occupying quite a small area in the Federal District according to Feuer (1956).

The great majority of the first observers tried to explain the occurrence of "cerrado" vegetation in Brazil is related to an adaptation of the natural vegetation to lack of water, at least during the dry season. Nevertheless, Ferri (1955), as related by Arens (1963), concluded that trees and shrubs of "campos-cerrados" do not have considerably restricted transpiration rates during the dry season, do not suffer from lack of available water, and are not the kind of vegetation adapted to a xeric environment. Similar conclusions were obtained by Grisi (1971), working with Ouratea spectabilis (Mart.) Engl., family Ochnaceae, and also by Andrade, Rachid-Edwards and Ferri (1957), working with Echinolaena inflexa and Tristachya leiostachya, both Graminea family, as mentioned by Ferri (1971). Also Ferri (1971) referred to the work done by Ferri and Coutinho (1958) who did not observe appreciable restriction in transpiration within the many species studied at three widely separated geographic locations. They concluded that water was not the limiting factor in developing "cerrado" vegetation in these three locations.

The current opinion held by most ecologists, plant physiologists, botanists, and soil specialists is that critical edaphic conditions

exist that inhibit forest growth and favor cerrado. These are the main factors determining the type of vegetation growing on these very deep and highly weathered soils (Alvin and Araujo, 1952; Feuer, 1956; Hardy, 1959; Arens, 1963).

The "oligotrophic scleromorphy" theory developed by Arens (1963) seems to be one of the most complete and comprehensive. He explains his theory by comparing the vegetation of serpentine soils with the vegetation of the campos cerrados in Brazil. Deficiency of mineral elements (N, P, S, K, Mo, Zn, and B) common to both soils was concluded to be the main factor in the formation of this typical kind of vegetation.

According to this theory, the "cerrado" plants are under an adequate supply of light, water, and air. Lack of available minerals leads to insufficient protein synthesis and consequently subnormal growth. An excess of carbohydrates results in thick cuticles and bark, formation of wax layers, abundant hypodermis and sclerenchyma, reduction in cell size, prominent veins, and resin formation. In short, the production of scleromorphic structures simulating xerophytic features. This theory is not based on direct experimental evidence, but some studies have been reported comparing chemical composition of "cerrado" soils and forest soils (Alvin and Araujo, 1952; Goodland and Pollard, 1972). In spite of the fact that basal area per hectare presented a positive correlation with P, N, and K, Goodland and Pollard did not believe that changes in nutrient levels were necessarily the cause of the physiognomic gradient.

More recently, Goodland (1971) proposed what he called "scleromorfism aluminotoxic" theory, which in a broad sense is an extension of Arens'

theory. He explained that aluminum in the soil may decrease availability of phosphate, calcium, magnesium, nitrogen, potassium, and possibly other nutrients, so that one of the principal effects of aluminum is mineral deficiency. He also refers to direct effects of aluminum, interfering with nuclear division, precipitating phosphate in the root and in cell wall, and inhibiting hexokinase.

Probably one of the most complete studies done about "cerrado" vegetation in recent years was published by Eiten (1972). After a complete discussion of all previous works related to theories about origin of "cerrado" vegetation, he concluded that (p. 327):

> The cerrado is a climax vegetation dependent upon the correct range of climate, topographic position and soil. Its secondary and regressive stages due to human disturbance are also part of the same vegetation type, and most of the species of the secondary stages are the same as those of the climax stage.

Geology and Geomorphology

Geology

The Central Plateau of Brazil[2] consists mainly of a core of ancient (pre-Cambrian) intrusive crystalline rocks (granite and gabbro) and metamorphic rocks (gneiss, schist, phyllite and quartzite), which are partly exposed and partly overlain by younger Paleozoic and Mesozoic sedimentary materials (AIA, 1963). Most of the area has been uplifted several times and then dissected and leveled by successive cycles of erosion. The undissected remnants of these erosion surfaces form tablelands and rolling plains of varying size.

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[2]Brazilian geographers refer to the Central Plateau in Brazil as the highlands between the Rio São Francisco in the east, the Rio Grande tributary of the Paraná in the south, and the Araguaia, a tributary of the Tocantins, in the west.

In contrast to the uplift of the crystalline area, the Paraná Basin has subsided and filled with sediments. After the Paleozoic era, a vast basalt plateau was formed in the basin by fissure flows of lava. These flows were subsequently covered by sand materials during the Mesozoic era, and today the basalt, which forms one of the richest soils in Brazil, is exposed only in the river valleys. On the valley slopes and terraces there are soils of mixed origin. A chronological geological picture of Central Plateau in Brazil is summarized in Table 1.

A geological map of the area considered in this survey adapted from AIA (1963) and Almeida (1970) is shown in Figure 9. Maps in a scale of 1:250,000 based on field work and photogeology, however, indicate that in most of the area shown as pre-Cambrian, the material forming the high chapadas is tertiary and/or quaternary detritic-lateritic.[3]

Geomorphology

The central part of the area under "cerrado" vegetation in Brazil (mainly Goiás and Minas Gerais) is characterized by the presence of two or three erosion surfaces. These have been described by Waibel (1948), Feuer (1956), and Cline and Buol (1973). Near Brasilia, the first erosion surface consists of flat (0-3% slope) interfluves at elevations of 1,000 to 1,100 m, with no evidence of erosion. These interfluves are called "chapadas" when they divide small rivers and "chapadões" when they lie between large rivers. The first erosion surface breaks into the second by a sharp escarpment 100 m high covered by rock outcrops and/or plinthite.

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[3]Prospec S. A. Geologia, Prospecções e Aerofotogrametria. 1968. Projeto Goiania--Geologia da região sul de Goiás. Unpublished data.

Table 1. Geologic time scale with associated rocks and soil characteristics in the Central Plateau from Brazil (AIA, 1963)

Era	Period	Geological material	Soil characteristic
Archeozoic	Early pre-Cambrian	Intrusive igneous (granite, gabbro), metamorphic (gneiss, schist, quartzite).	Deeply developed soils generally low fertility.
Proterozoic	Late pre-Cambrian	Metamorphic (schist, quartzite, gneiss) sedimentary (shale, limestone).	Considerable range of soil characteristics, but generally high clay content, red, variable soil fertility.
Paleozoic	Silurian	Metamorphic and sedimentary (shale, slate, limestone, schist--the Bambui series).	Source of good soils most extensive in Bahia and Minas.
	Devonian	Metamorphic and sedimentary (sandstone--Furnas series and shale--Ponta Grossa series).	Sand to clayey may have layers of plinthite and limestone. Low fertility.
	Carboniferous	Metamorphic and sedimentary (sandstone--Aquidauna series, some siltstone, shale and limestone	Soils of low fertility ranging from sand to clay textures.
	Permian	Metamorphic and sedimentary (shale, limestone and sandstone--Passadois series).	Soils generally low in fertility and shallow.
Mesozoic	Triassic	Sedimentary (mostly sandstone).	Good topography (level) but may be badly dissected; low fertility.
	Jurassic	Sedimentary (mostly sandstone).	Erodible, low fertility, sandy.
	Cretaceous	Sedimentary (mostly sandstone, some conglomerate, shale and limestone--Bauru series).	Sand texture, good topography, low fertility.
		Extrusive igneous: Prior to Cretaceous was the Rhaetic period of basaltic lava flows (São Benito series) alternating with wind-deposited sandstone (Botucatu series).	Clayey, dusk red; very good soils.

Table 1 (Continued)

Era	Period	Geological material	Soil characteristic
Cenozoic	Tertiary	Unconsolidated sedimentary materials; few spots in the area.	
	Quaternary	Unconsolidated sedimentary materials.	
	Pleistocene	Sedimentary--terrace sands and conglomerates.	
	Recent	Flood plain alluvium.	

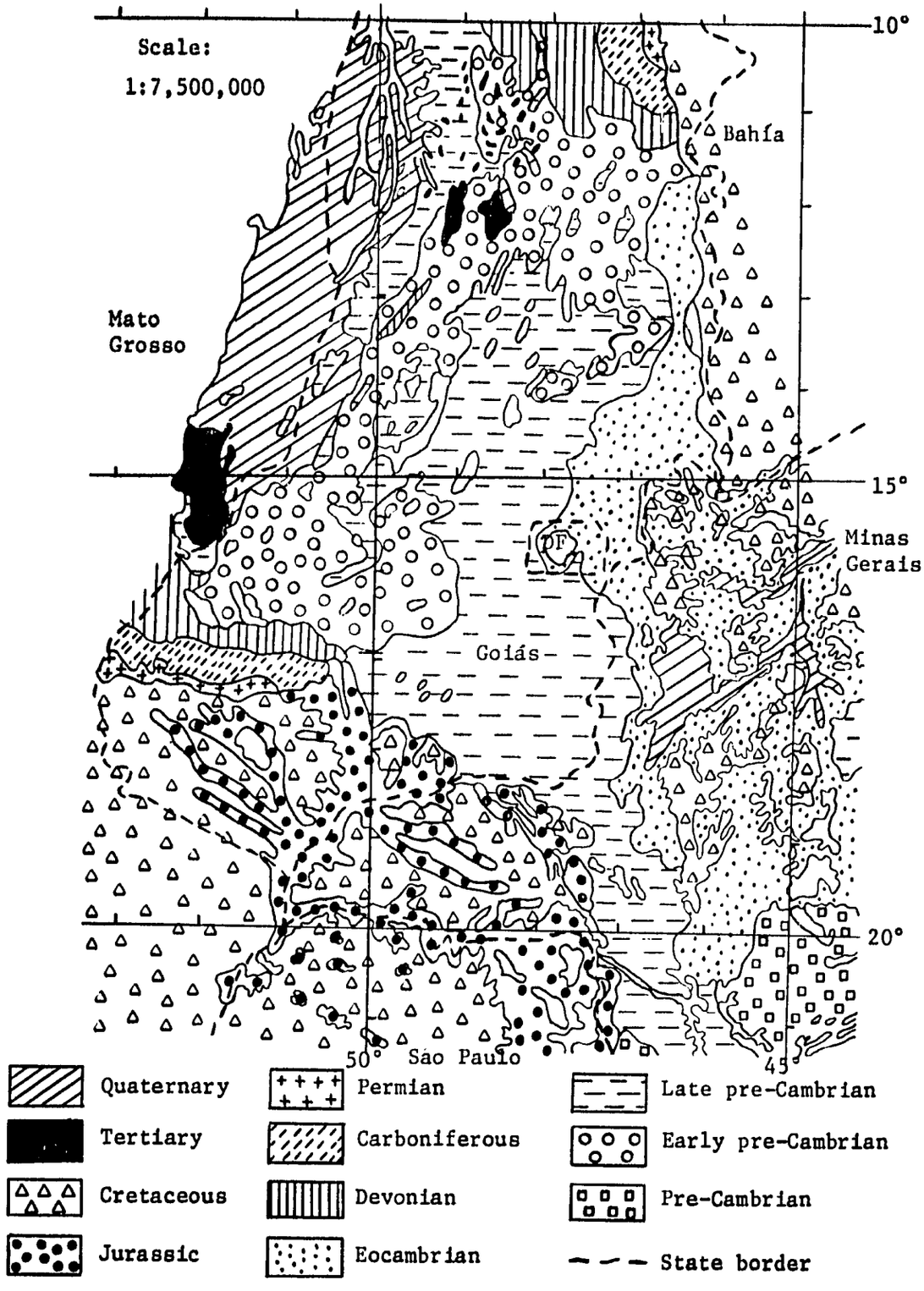

Figure 9. Geologic map of the area considered in this survey (adapted from AIA, 1963 and Almeida, 1970)

The second erosion surface is long (2 to 10 km) and has a gradual slope of 2 to 6%. It breaks into a third erosion surface in a similar form as the break between the first and second, also with rock outcrops and/or plinthite.

The third erosion surface consists of concave valleys of recent formation. If younger basaltic or limestone rocks are exposed, soils of high fertility are formed, as observed around Goiania, Goiás.

South of Brasília, the first erosion surface tends to disappear or remain in small isolated buttes. North of Brasília, there appears to be more rock outcrops.

Soil Characteristics

Soil Taxonomy

Soils under "cerrado" vegetation in Brazil may be classified in at least 13 great groups according to the Soil Classification nomenclature used in Brazil (Ranzani, 1971). This author suggests that the Red-Yellow Latosol and Dark-Red Latosol are predominant in this area.

According to FAO (1971), the total area under "cerrado" vegetation in Brazil comprises 1.8 million sq km, 20% of the whole country. The distribution of the main great groups and subgroups according to FAO nomenclature with the approximate equivalent U. S. Taxonomic System and Brazilian nomenclature is summarized in Table 2. The geographic distribution of these soils over the area considered in this survey is shown in Figure 10.

This survey, which covered over one-third of the total "cerrado" area in Brazil, was concentrated mainly in four of these groups: Acrustox, Quartzipsamments, Haplustox, and Eutrustox (Figure 10).

Table 2. Area of soil great groups and subgroups under "cerrado" vegetation in Brazil based on FAO Soil Map of the World with approximately equivalent U. S. System and Brazilian nomenclature

Area (%)	FAO nomenclature	U. S. System	Brazilian nomenclature
2.1	Orthic Acrisols	Tropustult	Red-Yellow Podzolics
2.9	Orthic Ferralsols	Haplustox	Dark-Red Latosols
4.6	Rhodic Ferralsols	Eutrustox	Dusky-Red Latosols
13.8	Lithosols	Lythic Dystropepts	Lithosols
18.1	Ferralic Arenosols	Quartzipsamment	Red-Yellow Quartz sands
21.1	Plinthic Acrisols	Plintic Tropustult	Hydromorphic laterites
37.3	Acric Ferralsols	Acrustox	Latosols

With the exception of the Eutrustox, which generally is influenced by mafic rocks and has forest vegetation, the soils present some typical characteristics that were summarized by Buol (1973) as follows (p. 2):

> Soil conditions of low fertility, often complicated by high iron and aluminum contents are prevalent. A dry season of at least 2-3 months or more is experienced in these areas. These areas have smooth topography and deep friable soils. The limited use of these areas may be attributed to almost total inadequacy of these soils, except for scattered high base status areas, to support primitive (no fertilizers) agriculture. Thus there is low intensity of inhabitation in most areas except for local occurrences of high base status soils as the Eutrustox areas of the Brazilian "cerrados."

Water Holding Capacity

In most of these soils the lack of available water is an extremely limiting factor for normal plant growth even in areas of high annual rainfall (1600 mm or more). This was explained by Lutz (1973) as due to

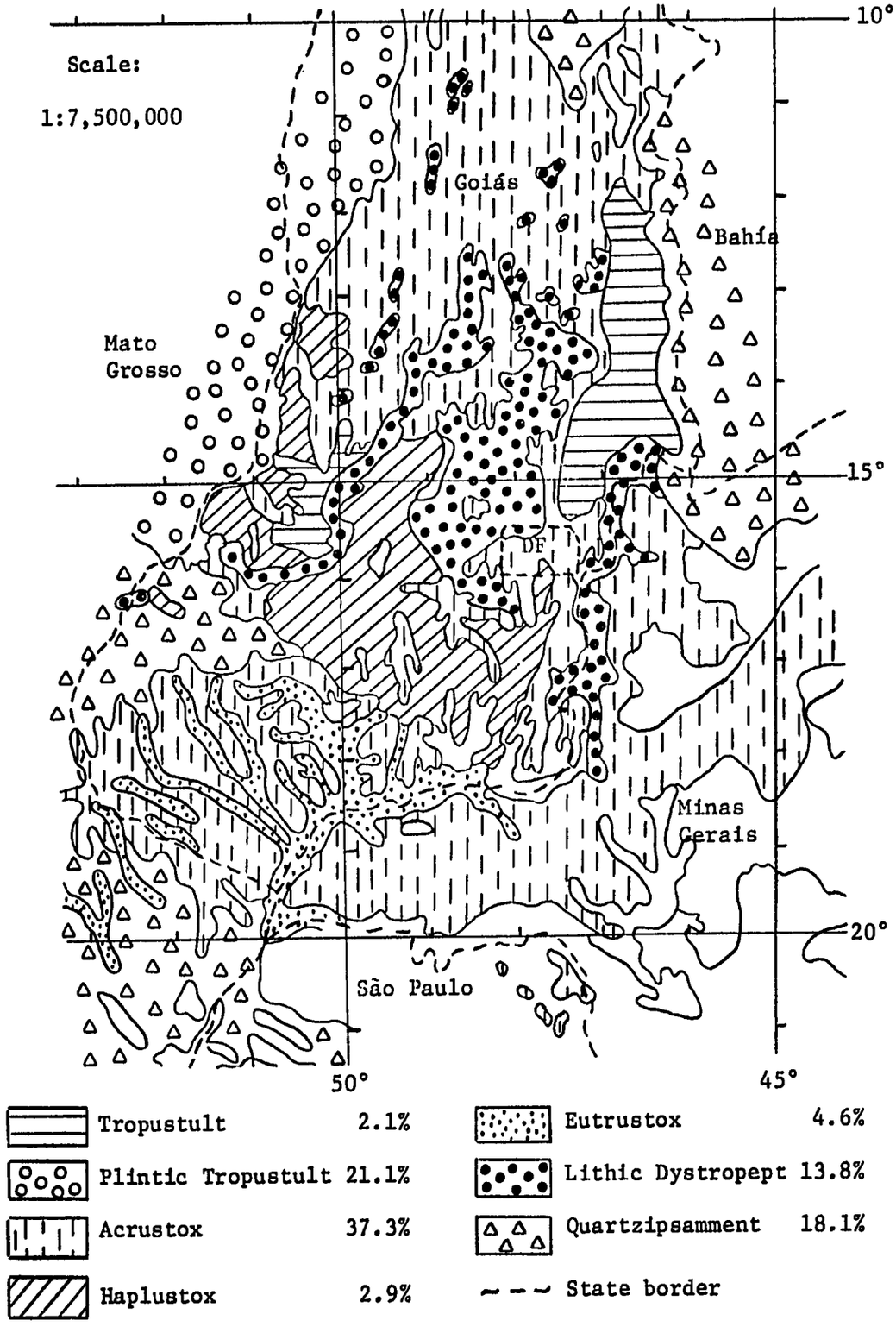

Figure 10. Main soils under "cerrado" and forest vegetation considered in this survey (after FAO, 1971)

poor distribution of rainfall or to deep seepage in soils with a low water holding capacity.

The relationship between particle size analysis and water holding capacity for these soils has been studied by many soil specialists. Ranzani (1971) found that the available water holding capacity of sand and loamy sand soils is very low, of sandy loam and sand clay loam soils is low, of loam soils is low to moderate, and of clay loam and clay is moderate. The criteria for this classification is presented in Table 3.

Table 3. Classification of "cerrado" soils according to level of available water (Ranzani, 1971)

Classification	Available water
	(mm/cm of soil)
Very low	Less than 0.5
Low	0.6-1.0
Moderate	1.1-1.5
High	1.6-2.0
Very high	More than 2.0

This relationship, however, cannot be generally accepted all over the "cerrado" area. Medina and Grohmann (1966) worked with seven soil profiles under "cerrado" vegetation in São Paulo State and found that loamy soils held the most available water for plants. The clayey soils held less and the sandy soils the least. It was also observed that the difference in the amount of available water was more marked between loamy and clayey soils than between clayey and sandy ones.

Both authors estimated the available water holding capacity of these soils based on the difference in water retention between 1/3 and 15-bar tension. The concept is acceptable for the 15-bar water content for estimation of the wilting point, but not for 1/3-bar as an evaluation of field capacity for Brazilian Oxisols. A value of 1/10-bar tension was more recently suggested to express the field capacity in these soils (Wolf, 1974; Uehara[4]).

Most of the soil specialists in Brazil agree in the point of view that these soils have an extremely low water retention capacity. This property coupled with irregular rainfall distribution is one of the most limiting factors for production of annual crops in this region.

Clay Mineralogy

There are few studies about clay mineralogy in these soils. Weaver (1974), working with six selected soil profiles from the Central Plateau of Brazil, found that, in general, the clay mineralogical composition in this area is predominantly kaolinite, iron oxides, gibbsite, amorphous material (alkali extractable), traces of 2:1 layer silicates, and titanium oxides. These minerals reflect the highly weathered stage of these soils that consequently is reflected in agronomic use and management of this area. Weaver also found that wide differences among the soils in the amounts of the predominant minerals is not related to soil texture or to soil color. Iron oxides, however, did show a tendency to increase as clay content decreased. Also, the presence of hematite in the Dark-Red Latosols, but not in the Red-Yellow

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[4]Uehara, G. Personal communication, 1974.

Latosols, may be an exception to this observation. The results obtained by Weaver are summarized in Table 4.

Similar mineralogical composition of the clay fraction with predominance of kaolinite, amorphous material, vermiculite + mica, and gibbsite also was found in a profile of a Dark-Red Latosol from Brasília, DF (Moniz and Jackson, 1967; Moniz, 1972).

Phosphorus Fixation

Some data summarizing phosphorus adsorption isotherms (Weaver, 1974) with 48 hours shaking are shown in Table 5. These data show that phosphorus adsorption for the Dark-Red Latosols and Red-Yellow Latosols included in this study varies widely. He concluded that the amount of P adsorbed at a solution concentration of 0.1 μg P/ml and the adsorption maxima, were, for the most part, proportional to the clay content of the soil. Apparently the clay fraction is responsible for P retention. The difference in P sorbed ranged from 125 μg/ml in the medium textured Dark-Red Latosol to 620 μg/ml in the clayey textured Red-Yellow Latosol. There seems to be an association between clay content and the different behavior upon adding P to these soils.

The high P fixation capacity of these soils was also observed by Bahia Filho (1974). He worked with 20 topsoil samples, most of them under "cerrado" vegetation from Minas Gerais State, and showed great variation in adsorption maxima for P with a change in texture. A summary of the results he obtained using a 6-day shaking period is presented in Table 6.

Table 4. Mineralogical composition of the clay size fraction (<0.002 mm) of soils from the Central Plateau, Brazil (Weaver, 1974)

Soil profile	Sample no.	Depth	Description	Free Fe_2O_3	Gibb.	Kaol.	Amorp.	Total
		-cm-		%				
I	2	0-20	Dark-Red	10.2	27	36	18	91
	3	40-60	Latosol, clayey	9.9	26	44	-	-
	4	100-120		8.3	27	44	20	99
II	5	0-20	Dark-Red	17.9	9	40	23	90
	6	40-60	Latosol, medium	-	9	34	-	-
	7	100-120		16.9	10	40	23	90
III	8	0-20	Dark-Red	12.2	58	5	10	85
	9	40-60	Latosol, clayey	-	60	5	-	-
	10	100-120		11.2	60	5	7	83
IV	11	0-20	Red-Yellow	5.6	24	39	25	94
	12	40-60	Latosol, clayey	5.9	27	40	-	-
	13	100-120		5.3	25	41	23	94
V	14	0-20	Red-Yellow	9.4	50	5	10	74
	15	40-60	Latosol, clayey	-	50	5	-	-
	16	100-120		10.5	51	5	7	74
VI	17	0-20	Red-Yellow	8.6	27	34	14	84
	18	40-60	Latosol, medium	-	33	41	-	-
	19	100-120		9.0	33	30	11	83

Table 5. Phosphorus adsorption data for surface horizons of soils from the Central Plateau, Brazil (Weaver, 1974)

Soil profile	Soil description	P sorbed at 0.1 μg P/ml	Adsorption maxima (μg P/ml)
I	Dark-Red Latosol, clayey	260	765
II	Dark-Red Latosol, medium	125	455
III	Dark-Red Latosol, clayey	240	790
IV	Red-Yellow Latosol, clayey	360	830
V	Red-Yellow Latosol, clayey	620	875
VI	Red-Yellow Latosol, medium	180	700

Table 6. Phosphorus adsorption maxima in 20 topsoil samples of Oxisols from Minas Gerais State, Brazil (Bahia Filho, 1974)

No. of samples	Soil description	Average adsorption maxima (μg P/ml)
9	Dark-Red Latosol, clayey	545
1	Dark-Red Latosol, medium	255
5	Red-Yellow Latosol, clayey	575
2	Red-Yellow Latosol, medium	431
2	Dusk-Red Latosol, medium	562
1	Dusk-Red Latosol, clayey (eutrophic)	600

Summarization of Soil Characteristics

Most of these soils are deep with no physical restriction to normal root growth for annual crops or arboreal vegetation. Occasionally a laterite layer occurs at variable depth or, in few cases, massive lateritic material is found (Feuer, 1956; Cline and Buol, 1973; and our personal observation).

A number of soil properties consistently lead to a common parameter of low natural fertility. They are acidity, low cation exchange capacity, low base saturation, high phosphorus fixation and aluminum saturation, highly weathered clay minerals, and low water holding capacity. There is, however, extreme variation in textural characteristics in these soils (Verdade, 1971; Ranzani, 1971). Soils under "cerrado" vegetation in Brazil can go from extremely sandy to extremely clayey, passing through all intermediate steps. This seems to be one of the main parameters that should differentiate these soils as to their management. Changes in texture have been related to differences in phosphorus fixation and water retention.

Land Use

Most of the area under "cerrado" vegetation in Brazil has been used as natural pasture. It is usually a low quality grass. Nevertheless, in large areas of the Triangle of Minas Gerais and in the southern part of Mato Grosso and Goiás, many crops have been introduced and large areas are now under cultivation. Upland rice, soybeans, corn, sorghum, cotton, beans, and pineapple are crops that now can be observed in this area under considerable acreage. Also, reforestation with eucalyptus and pines is being considered for these soils.

Responses to Nutrients

Phosphorus

Response to phosphate fertilizers in soils under "cerrado" vegetation in Brazil has been reported for many crops. One of the first experiments involving phosphorus application was conducted by Menezes and Araujo from 1947 to 1951 in soils from Sete Lagoas Experimental Station, Sete Lagoas, MG, as reported by Coimbra (1963). Working with soybeans, they found that an application of 400 kg/ha of simple superphosphate increased the yield 62%. The response to phosphate fertilizer was considerably enhanced, up to 200%, when applied with lime corresponding to half, one or two times the theoretical amount to bring the soil to pH 6.0, which was 9, 18, and 36 ton lime/ha, respectively.

Freitas *et al.* (1960), in two experiments carried out on Latosols at Anápolis, Goiás, and São Joaquim da Barra, São Paulo with 0.031 and 0.112 meq extractable PO_4^{-3}/100 g, respectively, found a highly significant response to 200 kg P_2O_5/ha at the first but not at the second location. The soil at the second site was classified as "Terra Roxa Estruturada." In the latter a highly significant depression in yield was observed. Similar results were obtained at Orlândia, São Paulo, where rates of P_2O_5 up to 180 kg/ha did not affect soybean yields significantly on a Dark-Red Latosol (regionally known as "Terra Roxa de Campo") containing 2.2 meq PO_4^{-3}/100 g (Freitas *et al.*, 1963). Nevertheless, in a deep Regosol at Pirassununga (0.03 meq PO_4^{-3}/100 g) and a Red-Yellow Latosol (Bauru sandstone inferior) at Matão (0.15 meq PO_4^{-3}/100 g), both in São Paulo State, they found considerable response to the same amount of P_2O_5 when applied in the presence of lime.

Other soils under "cerrado" vegetation in Brazil have also responded to phosphorus application for soybean production. In an experiment carried out at Itatinga, São Paulo, in soil containing 0.05 meq PO_4^{-3}/100 g derived from Botucatu sandstone, a significant linear effect was obtained from P_2O_5 rates up to 120 kg/ha. A positive lime x phosphorus interaction was observed (3.8 ton lime/ha), and the yield at the high rate of phosphorus plus lime was 1,771 kg/ha (Miyasaka et al., 1964a). Nevertheless, Mascarenhas and Miyasaka (1968), in a Dusky-Red Latosol, which was recently cleared cerradão and contained 0.05 meq P_2O_5/100 g, observed a considerable response to 100 kg P_2O_5/ha but no additional yield increase was obtained with 200 kg P_2O_5/ha. There was no lime x phosphorus interaction in this experiment.

More recently, Freitas et al. (1971) obtained 2,005 kg/ha as an average increase for soybean production in five experiments in the Federal District when a complete fertilizer mixture involving N, P, K, S, Zn, B, and Mo was used. The rate of phosphorus in this mixture was 300 kg P_2O_5/ha and all soils were very low in P (around 0.01 meq extractable PO_4^{-3}/100 g). A two-fold increase in P concentration in the leaf tissue was reported upon fertilization, probably confirming P as the most limiting factor.

Dry beans also is a crop which responds considerably to phosphorus application in "cerrado" soils. Miyasaka et al. (1964a) reported a significant linear response to rates of P up to 120 kg P_2O_5/ha in two experiments in soils derived from Botucatu sandstone at Itatinga, São Paulo, containing 0.05 mg extractable P_2O_5/100 g. The effect of P, although high in both unlimed and limed areas (3.8 ton lime/ha), was

much higher in the latter. Also, Miyasaka et al. (1965), working in a sandy soil derived from glacial material (0.05 meq extractable PO_4^{-3}/100 g) at Campinas, São Paulo, obtained a yield increase of 123% from use of phosphorus for an average of 2 years. Liming with 4 ton lime/ha enhanced the effect of simple superphosphate but depressed that of Olinda phosphate. Later on, Mascarenhas and Miyasaka (1967), in a Red-Yellow Podzolic var. Laras at Itararé and in a Dark-Red Latosol var. Orto at Itapeva, São Paulo, with 0.18 and 0.15 meq extractable PO_4^{-3}/100 g, respectively, reported yield increases of 59 and 295% with rates of P up to 160 kg P_2O_5/ha. The phosphorus effect was enhanced when combined with the use of 4 ton lime/ha.

More recently, studies by Miller et al. (1972) in a Red-Yellow Latosol from Uberaba, Minas Gerais, showed that a maximum yield for dry beans in this area can be reached with a rate of 210 kg P_2O_5/ha.

Responses to phosphorus for corn production have also been reported in many experiments in this area. A highly significant response to 150 kg P_2O_5/ha was reported by Freitas et al. (1960) in a Latosol from Anápolis, Goiás, with 0.031 meq extractable PO_4^{-3}/100 g. Also, Britto et al. (1971a) mentioned that the treatment including 60 kg P_2O_5, 120 kg N, and 60 kg K_2O/ha was the most adequate combination for corn production in a Red-Yellow Latosol at São Simao, São Paulo with 1.61 mg P_2O_5/100 g. These mixtures also had a considerable residual affect.

Freitas et al. (1971) reported a yield increase for corn of 4,950 kg/ha when a fertilizer mixture involving N, P, K, S, Zn, B, and Mo was used. The rate of phosphorus in this mixture was 300 kg P_2O_5/ha and in all four sites these Latosols were very low in P (around 0.01 meq extractable PO_4^{-3}/100 g.

Responses to phosphorus have been also reported in greenhouse studies with corn. A podzolic soil from Brasília, Federal District with 2.2 ppm extractable P gave a considerable response in dry matter production to a rate of P_2O_5 equivalent to 200 mg/kg of soil. A significant P x Ca and a highly significant N x P x Ca interaction was reported (Eira et al., 1972).

More recently, Freitas et al. (1972a) working with sweet corn in three Latosols under "cerrado" vegetation, two at Brasília, Federal District and one at Sete Lagoas, Minas Gerais and all very low in extractable phosphorus (0.02-0.03 meq PO_4^{-3}/100 g) found a large response to 200 kg P_2O_5/ha in all three experiments.

Upland rice is probably one of the most common crops grown in areas under "cerrado" vegetation in Brazil. The few experiments that have been conducted with this crop also show a considerable response to phosphorus. Novais and Defelipo (1971), in a Red-Yellow Latosol at Patos de Minas, Minas Gerais found a large effect from applying 40 kg P_2O_5/ha but only a medium effect of 80 kg. There were no N x P or P x K interactions in this experiment. Soil test for P was reported as 1 ppm with N.C. extractant.

A similar rate (40 kg P_2O_5/ha) gave a large yield response with upland rice in a Red-Yellow Latosol at Sete Lagoas, Minas Gerais with 3.5 mg extractable P_2O_5/100 g. In another experiment in a similar soil at Goiania, Goiás (2.7 mg extractable P_2O_5/100 g), the effect was medium (Coqueiro et al., 1972). Nevertheless, Pereira et al. (1972) in a Red-Yellow Latosol at Anápolis, Goiás found that higher yields were obtained with 120 rather than 60 kg P_2O_5/ha. Soil test level for this site was 1.3 mg extractable P_2O_5/100 g.

Another crop that has also been introduced in this area is cotton. Responses to phosphorus with this crop are quite variable. Freitas et al. (1963), working in São Paulo State, found yield responses from applying 180 kg P_2O_5/ha in a deep Regosol from Pirassununga (0.03 meq PO_4^{-3}/100 g), but not in a Red-Yellow Latosol (Bauru sandstone inferior) at Matão (0.15 meq PO_4^{-3}/100 g). A highly significant response to rates up to 200 kg P_2O_5/ha was reported in a Latosol at São Joaquim da Barra, São Paulo with 0.112 meq extractable PO_4^{-3}/100 g by Freitas et al. (1960). Nevertheless, in a series of eight experiments in "Terra Roxa Misturada," which had P soil test levels ranging from 0.04 to 0.29 meq PO_4^{-3}/100 g when extracted with 0.05 N H_2SO_4, only two showed responses from 120 kg P_2O_5/ha (McClung et al., 1961). The authors indicated that use of 3 to 4 ton lime/ha reduced phosphorus use.

A few experiments with root crops such as sweet potatoes, yams, and potatoes grown on these soils have been reported, but in most of them the direct effect of phosphate fertilizer was not reported. In an experiment with sweet potatoes and yams in soils derived from Botucatu sandstone (0.89 meq extractable PO_4^{-3}/100 g), Camargo et al. (1962) obtained a highly significant response to a mixture of N, P, and K fertilizers using 60, 100, and 40 kg/ha of N, P_2O_5, and K_2O, respectively. Later on, Breda Filho et al. (1966) found that sweet potato yields increased with rates up to 120 kg P_2O_5/ha in four areas not previously fertilized, but did not show a response in two other areas that had been fertilized.

Boock and Freire (1961) conducted three experiments with potatoes. Two were on soils derived from Botucatu sandstone (0.044% extractable

P_2O_5) and one was on a soil derived from glacial material (0.021% extractable P_2O_5). They found a considerable effect of a N-P_2O_5-K_2O mixture (80-120-60 kg/ha) in the absence of lime in the first two experiments, but on the third an appreciable increase in yield was noted only when lime was applied.

One of the main uses of the area under "cerrado" vegetation in Brazil has been for cattle production under extensive management. Some of the experiments carried out in this area involve forage crops, including both grasses and legumes. One of the first experiments with forage crops in these soils was reported by McClung and Quinn (1959). In a sandy loam soil derived from Bauru sandstone in São Paulo, they obtained a considerable yield response to 100 kg P_2O_5/ha with batatais grass (Paspalum notatum). When this was applied in combination with 40 kg sulfur/ha, a six-fold increase in dry matter production was observed.

Neme and Lovadini (1967), in a six-year field experiment with perennial soybean (Glycine javanica L.), found that a combination of 120 kg P_2O_5 plus 6 ton lime/ha gave a great increase in yield.

Considerable yield responses to phosphate fertilizers with four tropical legumes (Stylosanthes gracilis, Centrosema pubescens, Glycine javanica, and Phaseolus atropurpureous var. siratro) were reported by Jones and Freitas (1970). Working in a greenhouse with a Red-Yellow Latosol from Matão, São Paulo with 0.04 meq extractable PO_4^{-3}/100 g, they found that all four species reached maximum yields with 100 to 200 kg P/ha.

Similar results were obtained by França and Carvalho (1970) in greenhouse studies involving five tropical legumes (Glycine javanica L.

var. common, Glycine javanica L. var. tinaroo, Phaseolus atropurpureous D.C. var. siratro, Pueraria javanica Benth, and Centrosema pubescens Benth). With a Red-Latosol from Sete Lagoas, Minas Gerais (containing 0.75 mg P_2O_5/100 g), a minus P treatment yielded 0.92 g of dry matter as compared to 4.64 g for the complete treatment. The lack of P was also reflected in decreases in nodule weight and N production.

More recently, Teixeira et al. (1971), working with soil and samples of natural pasture from three farms near Morrinhos, Southern Goiás, observed that the soil available phosphorus levels (around 1.5 ppm P) were very low. This low natural phosphorus availability resulted in the grass P analysis being in below the suggested critical level of 0.15% for normal development of adult cattle.

Significant effects for phosphate fertilizers have been also reported for other crops such as pineapple (Santos et al., 1972), Pinus patula (Corrêa et al., 1973), and eucalyptus (Knudson et al., 1972).

Liming

One of the pioneer works involving lime in soils under "cerrado" vegetation in Brazil was carried out by Menezes and Araujo in experiments initiated in 1944 at the Sete Lagoas Experimental Station, as mentioned by Coimbra (1963). They obtained a highly significant increase in corn yield upon the use of 6 ton of lime/ha. Later on, for the period 1951 to 1954, the same authors reported that 9 ton of lime/ha gave a 27.2% increase in corn production.

Freitas et al. (1960), working in a Latosol from Anápolis, Goiás (pH 4.7, Ca^{++} trace, Mg^{++} 0.2 meq/100 g, no Al^{+++} results), reported a highly significant increase in corn yield from applying 5 ton of dolomitic lime/ha.

Responses to liming have been also reported for corn in other regions in Brazil. Freitas et al. (1963) worked with three different soils at São Paulo State (Dark-Red Latosol from Orlândia, Regosol from Pirassununga, and Red-Yellow Latosol from Matão). Their properties were: pH 4.9, calcium from 0.16 to 0.35 meq/100 g, and magnesium 0.03 meq/100 g. These areas received 8, 2, and 4 ton of dolomitic lime/ha, and all resulted in considerable increases in yield.

Similar results were obtained by Freitas et al. (1971) in three Latosols at Brasília, Federal District which had an average level of $Ca^{++} + Mg^{++}$ of 3.5 and of Al^{+++} of 0.7 meq/100 g, 28% Al^{+++} saturation, and a pH of 5.0. An average increase of 827 kg of corn/ha was reported for a two-year period upon application of 5 and 10 ton of calcitic lime/ha. One-fifth of this rate was made with dolomitic lime. They mentioned no effect of lime on phosphorus or potassium availability as measured by soil tests at harvest time, but there was an effect of liming on leaf tissue P (0.118% P with no lime and 0.150% P with 5 and 10 ton of lime).

Liming also increased corn dry matter production in a greenhouse study with a podzolic soil sample from Brasília having the following characteristics: pH = 4.0, $Ca^{++} + Mg^{++}$ = 0.35 meq/100 g, Al^{+++} = 2.25 meq/100 g, and Al^{+++} saturation = 83%. They applied 3 g of a 1/1 mixture of $CaCO_3$ and $MgCO_3$/kg of soil (calculated to bring to pH 5.5). The P x Ca and N x P x Ca interactions were also highly significant and positive (Eira et al., 1972).

Freitas and Van Raij (1974), working with a Red-Yellow Latosol sandy clay loam at Matão, São Paulo (pH = 5.7, Al^{+++} = 0.6 meq/100 cc, $Ca^{++} + Mg^{++}$ = 1.4 meq/100 cc), found a positive effect from the

application of 10 ton of dolomitic lime/ha (theoretically sufficient to reach pH 6.0). They also reported a residual effect lasting for 6 years. The second year after application the area with lime + fertilizer had a pH of 6.2, 0.1 meq Al^{+++}/100 cc and 2.4 meq Ca^{++} + Mg^{++}/100 cc.

The effects of rate and depth of incorporation of lime for corn were recently studied in a Dark-Red Latosol at Brasília Experimental Station (N.C.S.U., 1974a). Aluminum saturation in the unlimed soil was about 60 to 70%. The shallow treatment (incorporation to 15 cm) did not greatly change the aluminum saturation below 15 cm. Incorporation of lime to 30 cm depth in rates of at least 4 ton lime/ha reduced aluminum saturation to levels which are considered adequate for most crops. This extra deep lime application also increased yields in the approximate range of 0.8 to 1.3 ton of grain/ha. This treatment also increased the root length and gave more resistence to water stress for corn. The lime used was a finely ground calcitic limestone with more than 60% finer than 60 mesh and more than 40% finer than 100 mesh.

Responses to lime use for soybean production are not as definite as those related for corn. In some experiments there have been considerable responses, while in others no increase in yield has been observed.

Some of the first experiments involving liming and soybeans were carried out at the Sete Lagoas Experimental Station, Sete Lagoas, Minas Gerais. Menezes and Araujo observed a 200% increase in yield in one study as reported by Coimbra (1963), but in another experiment by the same authors carried out in similar soil from 1951 to 1954, they found only a 9% response to liming.

Compared with cotton and corn, soybeans seems to give lowest response to liming. This was observed by Freitas et al. (1963) in the same areas described earlier for liming experiments with corn. They found that, in spite of this expected difference in response due to different species, soybeans still showed a 77% increase in yield upon application of dolomitic lime.

Miyasaka et al. (1964a) found essentially no effect from applying 3.8 ton of dolomitic lime/ha on soybeans grown in a soil derived from Botucatu sandstone with pH = 5.2, Ca^{++} = 0.45 mg/100 g, Mg^{++} = 0.01 mg/100 g, and $H^{+} + Al^{+++}$ = 3.12 mg/100 g. A considerable response was obtained when lime was applied in combination with 60 or 120 kg P_2O_5/ha. Yields were 482 with lime only, 1218 with lime + 60 kg P_2O_5/ha, and 1771 kg/ha with lime + 120 kg P_2O_5/ha. Also, Mascarenhas and Miyasaka (1968), working in a Dusky-Red Latosol, found no significant response in soybean yield up to 4.8 ton of dolomitic lime/ha. There was no lime x P interaction in this case. The natural soil characteristics were pH = 4.8, Ca^{++} = 0.30 meq/100 g, Mg^{++} = 0.25 meq/100 g, $H^{+} + Al^{+++}$ = 4.90 meq/100 g.

Freitas et al. (1971) carried out field experiments with soybeans in the same area as mentioned earlier for corn and found a 415 kg/ha increase in yield related to liming (5 and 10 ton lime/ha, 1/5 dolomitic). There was no effect of liming on the leaf phosphorus level, but the nitrogen level increased from 4.24% at 0 lime to 4.58% for the average of 5 and 10 ton lime treatments.

Some of the experiments conducted on dry beans grown in soils under "cerrado" vegetation in Brazil have shown responses to liming. Most of

the results are from São Paulo State. Only 10% of that state has typical "cerrado" characteristics so extrapolation of the results is not recommended unless the site is well described.

Miyasaka et al. (1964a), working in the same area mentioned earlier for soybeans, also found that dry beans did not respond to an application of 3.8 ton of lime/ha. A lime x P interaction (60 and 120 kg P_2O_5/ha) was noted, though.

In a sandy soil (pH = 5.3) near Campinas, São Paulo, liming with 4 ton of lime/ha enhanced the effect of simple superphosphate but depressed that of Olinda phosphate (Miyasaka et al., 1965).

Later on, a definite positive effect of liming on dry bean yields was reported by Mascarenhas and Miyasaka (1967). Working in a Red-Yellow Podzolic, var. Laras (pH = 4.9, 5.7 meq Ca^{++}/100 g soil) and a Red-Yellow Latosol (pH = 4.0, 1.5 meq Ca^{++}/100 g soil) from Itararé and Itapeva, São Paulo, respectively, they found significant increases (33 and 43%, respectively) in dry bean yields upon application of 4 ton of lime/ha.

Cotton is probably one of the most responsive crops related to lime application in these soils. A response of 128% was reported with this crop upon application of 9 ton lime/ha at the Sete Lagoas Experimental Station, Sete Lagoas, Minas Gerais for the period 1951 to 1954 by Menezes and Araujo, as mentioned by Coimbra (1963). It was also reported that 5 ton of lime/ha was more economical than 10, 15, or 20 ton/ha for cotton grown in the same area.

Freitas et al. (1963) obtained a much higher yield response for cotton than for corn and soybeans in three different soils from São

Paulo State. The characteristics and locations of these soils are mentioned earlier concerning the liming effect for corn.

These results were very similar to those obtained previously by McClung et al. (1961) when a series of experiments were conducted in the region from Orlândia to Barretos, São Paulo. These soils had average chemical characteristics of pH = 5.0, Ca^{++} = 1.50 meq/100 g, Mg^{++} = 0.28 meq/100 g, Al^{+++} = 2.2 meq/100 g, and Al^{+++} saturation = 54%. The responses obtained with 4 ton of lime/ha were from 50 up to 300%. They also observed a strong tendency for lime to reduce the response to phosphorus.

In spite of the fact that upland rice is one of the most important crops being cultivated in these soils, there is little information about its behavior upon liming. Most of the research with upland rice is recent. Coqueiro et al. (1972) reported the results of a 3-year field experiment in a Red-Yellow Latosol at IPEACO, Sete Lagoas, Minas Gerais. This soil had a pH = 4.3, Ca^{++} = 1.0 meq/100 g, Mg^{++} = 0.46 meq/100 g, Al^{+++} = 2.6 meq/100 g, and Al^{+++} saturation = 59.3%. A significant increase in yield was obtained with 3 to 4 ton of calcitic lime/ha. This was one of the few studies in which the grade and size of lime particles has been mentioned.

A considerable response to 2 ton of lime/ha was reported in a Latosol at Uberaba, Minas Gerais by Rios et al. (1962). This soil that had a pH = 4.95, Ca^{++} = 0.67 meq/100 g, Mg^{++} = 0.12 meq/100 g, Al^{+++} = 0.24 meq/100 g, and Al^{+++} saturation = 20%. There was an increase in yield of 45.7% upon liming.

Forage crops, mainly tropical legumes, have shown large responses to liming in these soils. Neme and Lovadini (1967) found that rates

of 4, 6, and 8 ton of lime/ha favored the effect of phosphate fertilizers. Also, the effect of lime alone was superior to that of the natural phosphates, but not to simple superphosphate or bone meal.

Jones and Freitas (1970) studied the response of four tropical legumes (Stylosanthes gracilis, Centrosema pubescens, Glycine javanica, and Phaseolus atropurpureus, var. siratro) to lime application using a Red-Yellow Latosol from Matão, São Paulo (pH = 4.9, Ca^{++} = 0.35 meq/100 g, Mg^{++} = 0.03 meq/100 g) in the greenhouse. They obtained a maximum yield for stylosanthes with an application equivalent to 250 kg Ca and 30 kg Mg/ha. The other species increased the yield with rates up to 1,000 kg of Ca and 120 kg Mg/ha. They also reported a depression in yields with heavier application of lime.

Studies concerning liming responses of many other crops also have been reported for the "cerrado" area in Brazil. Boock and Freire (1961) obtained a considerable response with potatoes in two out of three experiments. Camargo et al. (1962) has found no significant effects of liming (3 ton lime/ha) for sweet potatoes and yams. In an experiment with eucalyptus, Knudson et al. (1972) found that growth tended to increase when 150 g of dolomitic lime were applied to each plant.

One of the main problems involving liming these soils is the almost complete lack of information or correlation studies dealing with evaluation of an adequate amount of lime to be used for each specific soil. One study considering soil chemical and physical characteristics was a greenhouse experiment conducted by Soares et al. (1974). Working with six levels of analytical grade $CaCO_3$ in rates equivalent to 0, 1/2, 1, 2, 3, and 4 times the amount chemically equivalent to the exchangeable Al^{+++}, they concluded that Al^{+++} saturation may be reduced

to less than 10% by the application of 1.5, 2, and 3 times exchangeable Al^{+++} for the Red-Yellow Latosol, medium texture; Dark-Red Latosol, clay texture and Red-Yellow Latosol, clay texture, respectively. They also mentioned the importance of deeper lime incorporation to improve yields on nonirrigated crops that are sensitive to water stress.

In most of the liming experiments not only on these soils under "cerrado" vegetation but also on those from other areas in Brazil, reference is made only to the chemical composition of material used. Very little data on the quality of lime in relation to grade of fineness is presented. An extreme variation in effectiveness of lime exists, at least for Minas Gerais State, that is due to variation in particle size. It has been the author's personal observation that a range from 30 to 80% effectiveness exists for lime in this state. An extremely high variation like this probably has a considerable effect in determining responses for different crops, rates, and residual effects that, unfortunately, have not been considered when liming these soils.

Also, only one experiment was mentioned that involves depth of lime application. This seems to indicate that not only aluminum saturation, type and fineness of lime, and species, but also depth of incorporation, have to be considered in liming these soils. The depth of liming seems to be one of the most important areas of research that needs to be emphasized.

Micronutrients

Most of the field experiments and greenhouse studies involving micronutrients in soils under "cerrado" vegetation in Brazil have not mentioned soil micronutrient levels nor levels in plant tissue. Very

few research studies have separated the effects of individual micronutrients. Most of the time the responses referred to were from a mixture of micronutrients.

One of the first studies involving micronutrients in these soils was conducted by Igue and Gallo (1960). Working with corn grown on a soil derived from the Bauru inferior, São Paulo, they found that 25 kg $ZnSO_4$/ha was as effective in correcting Zn deficiency as were rates up to 100 kg $ZnSO_4$/ha. Analysis of variance indicated a positive effect of zinc sulphate application on plant growth, dry weight of stalks, yield of grain, and zinc content on leaves (20 ppm on check plots and up to 60 ppm with 25 kg $ZnSO_4$/ha). There was a significant lime x zinc interaction on the zinc content of leaves, indicating that zinc application had a smaller effect on leaf zinc when lime was applied. In another experiment by the same authors also with corn, rates up to 40 kg $ZnSO_4$/ha were used. They concluded that as little as 5 kg $ZnSO_4$/ha were sufficient to prevent the occurrence of Zn deficiency symptoms, but there were no significant effects on yields or zinc content of leaves.

Freitas et al. (1960) reported highly significant yield responses due to applying 6 kg/ha of zinc in a complete treatment as compared with a minus zinc treatment for corn grown on a Latosol from Anápolis, Goiás. A similar response did not occur at São Joaquim da Barra, São Paulo in a "Terra Roxa Misturada" soil. For the first experiment leaf zinc content of the check was 23 ppm and it was 43 ppm Zn for the plus Zn treatment.

Responses to a mixture of micronutrients has been reported with corn in this area. Freitas et al. (1963), working in clayey Dark-Red

Latosol at Orlândia, a sandy Regosol at Pirassununga, and a Red-Yellow Latosol at Matão, all in São Paulo State, observed a considerable effect of a mixture involving boron, zinc, and molybdenum (2, 4, and 0.4 kg/ha, respectively). They found 5, 17, and 41% yield increases from applying the mixture to this crop on the three soils, respectively.

Britto et al. (1971b), in a series of four field experiments on clayey Dark-Red Latosols at Brasília, Federal District, found the best corn yield (2,540 kg/ha) was obtained when a mixture of Zn, B, Mn, and Mo (20 kg of zinc phosphate, 10 kg of borax, 30 of manganese sulphate, and 1 kg of ammonium molybdate/ha, respectively), was added to N-P-K fertilizers. This experiment also suggested that the most important fertilization would probably be N-P-K + Zn.

In another field experiment carried out on a sandy Red-Yellow Latosol, at São Simão, São Paulo, Britto et al. (1971a) showed that the addition of 26 kg $ZnSO_4$/ha to a N-P-K treatment (60 kg/ha each of N, P_2O_5, and K_2O) led to a 21% increase in corn yield. The same rate of zinc added to another N-P-K treatment (120 kg/ha each of N, P_2O_5, K_2O) yielded 41% more than the N-P-K treatment alone. In another experiment the same authors observed that a treatment of 90 kg N, 150 kg P_2O_5, 90 kg K_2O, and 10 kg of $ZnSO_4$/ha led to the highest corn yield.

Freitas et al. (1971) obtained a corn yield increase of 4,950 kg/ha with a complete fertilizer mixture involving N, P, K, S, Zn, B, and Mo. The rates of the micronutrients were 15, 1, and 0.2 kg/ha, respectively. These experiments were conducted on four Latosols from Brasília, Federal District. Later on, Freitas et al. (1972a) found yield responses to a mixture of Zn, Cu, Mn, B, and Mo at 10, 5, 5, 2, and 0.2 kg/ha, respectively, with sweet corn grown on three Latosols (two at Brasília,

Federal District, and one at Sete Lagoas, Minas Gerais. This same experiment was repeated at Matão, São Paulo, in "Terra Roxa Misturada," which is considered a better soil, and no response to the application of micronutrients was obtained.

Data from field experiments to evaluate micronutrient critical levels on these soils are almost completely lacking. N.C.S.U. (1974b) reported one study which was carried out at the Brasília Experimental Station on a clayey Dark-Red Latosol that suggested a soil critical level for zinc of 1 ppm when extracted by 0.05 N HCl + 0.025 N H_2SO_4. Also a rate of 3 kg of Zn/ha added to a complete (N-P-K-S) minus zinc fertilizer led to a 10-fold increase in corn yield. This soil, limed to pH 6.4, showed a typical response to Zn with three corn varieties. A rate of 3 kg Zn/ha seemed to be adequate with this soil for all those varieties (Figure 11). There was no significant decrease in yield due to lack of added boron nor to the highest level of Zn (27 kg/ha).

In a second experiment in the same area, a detrimental effect of higher lime rates (up to 22.5 ton $CaCO_3$ equivalent/ha) on yields was observed at both 3 and 9 kg Zn/ha (N.C.S.U., 1974b). The addition of up to 9 kg Zn/ha did not overcome the tendency of the higher lime rates to reduce yield (Figure 12). This is an indication that very high rates of lime may lead to reduction in yields due to induced deficiencies of other micronutrients in these soils.

Not all soils under "cerrado" vegetation have shown responses to micronutrients. Eira et al. (1972) reported from a greenhouse study with corn grown on a podzolic soil sample from Brasília, Federal District no response to a Zn, Cu, B, Mo, and Fe mixture of micronutrients. This

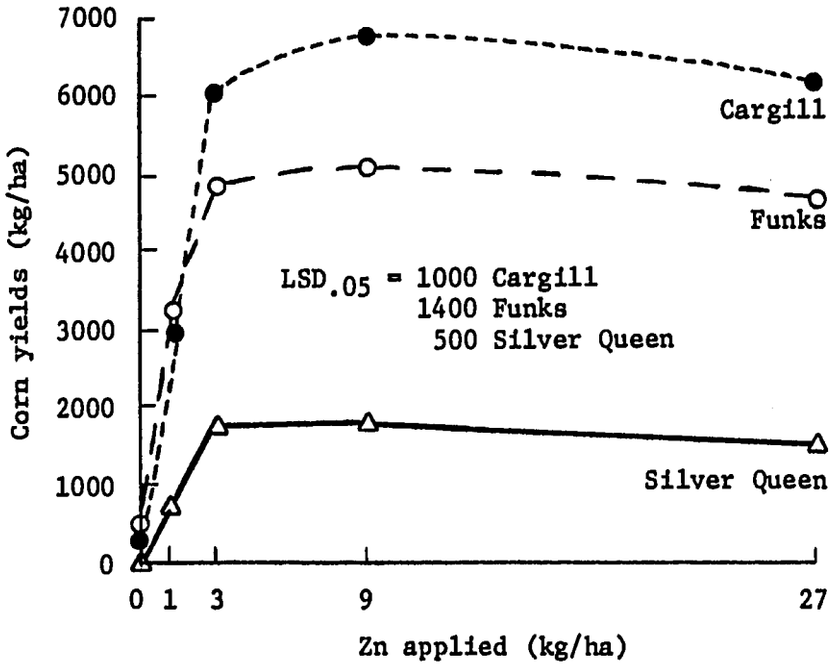

Figure 11. Varietal response to zinc rates in an Oxisol limed to pH 6.4 (N.C.S.U., 1974b)

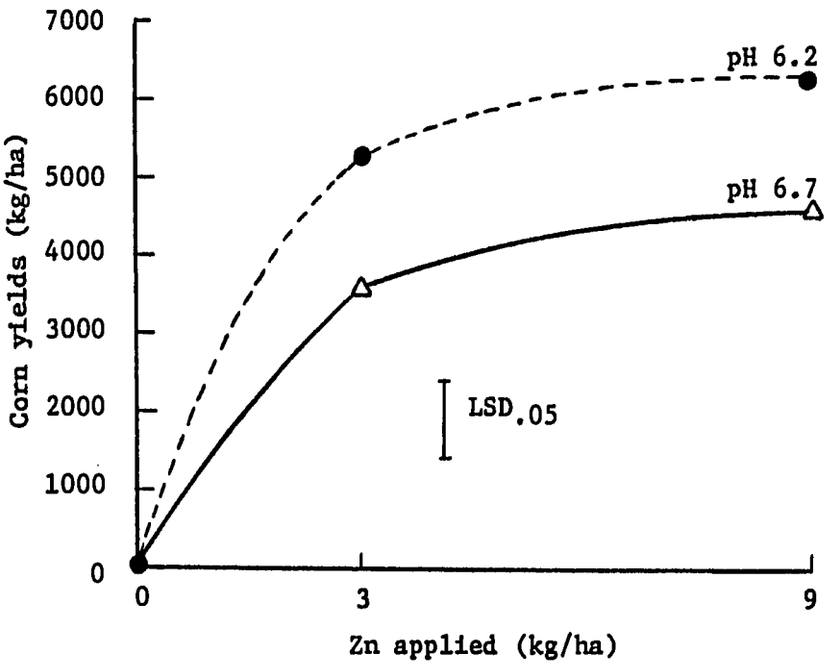

Figure 12. Zinc-soil pH interactions on Cargill 111 corn (N.C.S.U., 1974b)

was one of the few studies involving podzolic soils under "cerrado" vegetation in Brazil.

No response to a mixture of micronutrients involving Zn, Cu, B, and Mo (20 kg zinc sulphate, 20 kg copper sulphate, 3 kg borax, and 75 g sodium molybdate/ha, respectively) was obtained with soybeans by Miyasaka et al. (1964b). This experiment was carried out on a sandy soil derived from Botucatu sandstone at Itatinga, São Paulo.

Similar results were obtained by Mascarenhas et al. (1967) in a Dusky-Red Latosol from São Paulo, for the same crop.

Nevertheless, Freitas et al. (1960) reported a highly significant soybean yield response when 6 kg zinc were added to a complete minus zinc fertilizer in a Latosol from Anápolis, Goiás. In the same experiment there was no significant effect from applying 0.3 kg sodium molybdate/ha.

Considerable cotton yield responses to micronutrients have been obtained in some areas. Freitas et al. (1963) working in a clayey Dark-Red Latosol at Orlândia, a sandy Regosol at Pirassununga, and a Red-Yellow Latosol at Matão, all in São Paulo State, reported a considerable yield response from a mixture involving B, Zn, and Mo (2, 4, and 0.4 kg/ha, respectively). Yield increases of 14, 12, and 72% were obtained when they used the mixture on those sites, respectively. They did not, however, separate the effects of the particular micronutrients.

Britto et al. (1971b) found the highest yield of cotton was obtained in a Dark-Red Latosol from Brasília, Federal District with a complete fertilizer mixture that included Zn, Mn, B, and Mo (20 kg zinc sulphate, 30 kg manganese sulphate, 10 kg borax, and 1 kg ammonium molybdate/ha, respectively). Nevertheless, a different result was

obtained by McClung et al. (1961) in a series of seven experiments with cotton in "Terra Roxa Misturada" between Orlândia and Barretos, São Paulo. They reported no response to 10 kg zinc sulphate/ha for any experiment. A response to boron (20 kg borax/ha) was obtained in two out of seven of these experiments.

Upland rice is one of the main crops that has been cultivated in these soils. At least for the Triangle of Minas Gerais and southern Goiás, the use of 25 kg zinc sulphate/ha is a typical fertilization practice.[5] These recommendations, however, are not based on experimental evidence. Souza and Hiroce (1970), working in São Paulo State in soils with pH varying from 5.7 to 5.9, tested the effect of Zn up to 10 kg zinc sulphate/ha. They concluded that a rate of 5 kg zinc sulphate/ha was sufficient to prevent deficiency symptoms from appearing. Deficiency symptoms were observed up to 15.0 ppm zinc in plant dry matter. The tissue Zn level was 21.4 ppm upon application of 5 kg zinc sulphate/ha.

Forage crops, both grain and legumes, have shown different responses to micronutrients in soils under "cerrado" vegetation in Brazil. Britto et al. (1971b) found that, in a Dark-Red Latosol from Brasília, Federal District, treatments with no zinc tended to have a smaller green mass with perennial soybean (*Glycine javanica* L.) than one which received a rate equivalent to 20 kg zinc sulphate/ha. There also were observable effects from the application of an equivalent to 1 kg of ammonium molybdate/ha.

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[5]Personal observation.

Similar responses were obtained by Santos (1971) working with three Latosols from Sete Lagoas, Minas Gerais with perennial soybean. Applying zinc in a nutrient solution increased dry matter production in one out of two clayey Dark-Red Latosols and had no effect on a clayey Red-Yellow Latosol. Boron and molybdenum application did not affect dry matter production in any of these soils. Levels of zinc, boron, and molybdenum in these soils are given in Table 7.

Table 7. Levels of zinc, boron, and molybdenum in three soils from Sete Lagoas, Minas Gerais (Santos, 1971)

Soil	Zinc		Boron		Molybdenum	
	Total	Extr.[a]	Total	Extr.[a]	Total	Extr.[a]
	ppm					
a. Red-Yellow Latosol, clayey	86	0.6	33	0.84	0.031	0.024
b. Dark-Red Latosol, clayey	66	0.6	48	0.95	0.037	0.016
c. Dark-Red Latosol, clayey	81	0.8	30	1.02	0.050	0.010

[a]Extractable by 1% Na-EDTA.

These results for perennial soybeans were considerably different from the data reported previously by França and Carvalho (1970). In the latter greenhouse study, which involved five tropical legumes (*Glycine javanica* L. var. common, *Glycine javanica* L. var. tinaroo, *Phaseolus atropurpureus* D. C., *Pueraria javanica* Benth, and *Centrosema pubescens* Benth), a considerable effect of micronutrients (Zn, B, Fe, and Cu) was observed. Average dry matter production for the five legumes was 0.92 g for the treatment minus these micronutrients and 4.64 g when they were

added. This study was carried out in a Red Latosol from Sete Lagoas, Minas Gerais. There is no reference as to the micronutrient levels in this soil.

Deficiency of copper was suggested by Teixeira et al. (1971) for two out of three areas of Morrinhos, Goiás. The values for the total copper for these two areas were 16.9 and 32.0 ppm with available levels of 0.68 and 0.96 ppm, levels considered adequate by the authors. Nevertheless, natural pasture in these areas contained less than 3.1 ppm copper in the dry matter. This is considered low as the critical level suggested for normal conditions is 5 ppm.

Responses to micronutrients have also been reported for perennial crops in at least one experiment. In a sandy Red Latosol from Lagoa Santa, Minas Gerais, Knudson et al. (1972) obtained a growth rate response with Eucalyptus saligna from the addition of 2 g of boron per plant to a N-P-K fertilizer. The addition of zinc to a N-P-K fertilizer also tended to result in more growth.

Other Nutrients

Nitrogen. Experiments involving other nutrients have been carried out in soil under "cerrado" vegetation in Brazil. Responses to nitrogen were obtained for cotton by Menezes and Araujo (1952), as mentioned by Coimbra (1963) and by Freitas et al. (1963). A considerable response to N was also obtained for cotton by McClung et al. (1961) up to 120 kg N/ha. In another experiment, however, Freitas et al. (1960) reported no effect of rates up to 200 kg N/ha.

Corn yields have been increased considerably by N fertilization in many experiments in this area. Freitas et al. (1963) reported a linear

response for this crop up to 240 kg N/ha. Britto et al. (1971a) found a positive response to N with 120 kg N/ha plus a complete fertilization. Eira et al. (1972), in a greenhouse study, however, found no significant effect on corn dry matter production from application of 200 mg N/kg of soil. A series of experiments involving sweet corn showed highly significant responses to 240 kg N/ha in three out of five areas as reported by Freitas et al. (1972a).

Soybeans and dry beans have also responded to nitrogen in most of the experiments conducted in these soils. Miyasaka et al. (1964b) reported increases of 761 and 542 kg of soybeans/ha in limed and unlimed areas, respectively, upon using a N-P-K fertilizer that included 60 kg N/ha. In another experiment Miyasaka et al. (1964a) found no response of beans and soybeans to N (30 and 60 kg N/ha). In this last experiment the N x K and N x P interactions were not significant. Later on, Mascarenhas and Miyasaka (1967) found a positive effect of N (up to 40 kg/ha) in dry bean yields. This was similar to the results obtained by Rios and Santos (1971) who found a considerable response from 40 to 60 kg N/ha applied at the beginning of flowering. A response to N with soybeans was also obtained by Freitas et al. (1960, 1971). More recently, Miller et al. (1972) estimated that a maximum predicted yield for dry beans would be obtained with 101 kg N/ha and 210 kg P_2O_5/ha.

Most of the root crop experiments related to nitrogen response have been conducted in São Paulo State. The work by Boock and Freire (1961) with potatoes showed a highly significant effect for a mixture including N-P-K fertilizers. Similar results were obtained by Camargo et al. (1962) with sweet potatoes and yams. Their results were considerably different from those obtained by Breda Filho et al. (1966) who found

that only one out of six trials with sweet potatoes responded to nitrogen fertilizers (rates up to 80 kg N/ha).

Considerable effects of nitrogen have been reported for pineapple (Santos et al., 1972), eucalyptus (Knudson et al., 1972), and upland rice (Coqueiro et al., 1972). In another experiment conducted in recently cleared area by Novais and Defelipo (1971), upland rice did not respond to N up to 80 kg N/ha. Also, Corrêa et al. (1973) obtained no effect of 150 kg of ammonium sulphate/ha in Pinus patula growth.

Potassium. One of the first potassium experiments in soils under "cerrado" vegetation was conducted by Menezes and Araujo (1952) with cotton, as mentioned by Coimbra (1963). They found no significant response to a rate of 50 kg/ha of potassium fertilizer, but the P x K and N x P x K interactions were significant. Freitas et al. (1960) reported highly significant effects to rates up to 50 kg K_2O/ha in soil with 0.12 meq K^+/100 g. Also, a considerable response from up to 120 kg K_2O/ha was observed in four out of eight experiments with cotton in São Paulo by McClung et al. (1961) in soil averaging 0.09 meq K^+/100 g. Later on, working in soils in São Paulo State low in potassium (0.04 meq K^+/100 g), Freitas et al. (1963) found significant responses in two experiments.

Most of the experiments involving potassium fertilizers in corn production have shown significant responses. One of the first experiments with potassium on corn was conducted by Freitas et al. (1960) in soil very low in extractable K (0.02 meq K^+/100 g). A large response was obtained with 75 kg K_2O/ha. Later on, Freitas et al. (1963) obtained considerable effects from applying potassium in two out of

three soils of São Paulo State, all of which were low in potassium (0.04 meq K^+/100 g). Britto et al. (1971a) reported a response from a N-P-K fertilizer that included 60 kg K_2O/ha in a soil with low values for extractable potassium (0.04 meq K^+/100 g). Similar results were obtained by Freitas et al. (1971) in soils ranging from 0.05 to 0.16 meq K^+/100 g. A significant response for potassium fertilizers up to 200 kg K_2O/ha was reported for sweet corn in four areas under "cerrado" vegetation, all with extractable potassium values ranging from 0.09 to 0.12 meq K^+/100 g. Nevertheless, a podzolic soil with 0.15 meq K^+/100 g, used in greenhouse study by Eira et al. (1972), gave no significant response in corn dry matter production from application of 200 mg K_2O/kg of soil.

The response of root crops to potassium has been studied mainly in São Paulo State. Boock and Freire (1961) found that potatoes did respond to a N-P-K mixture in two experiments when lime was not applied, but the response was favorable in a third experiment only in the presence of lime. Results similar to the first two experiments were obtained by Camargo et al. (1962) with sweet potatoes and yams. Later on, Breda Filho et al. (1966) found a significant response to 60 kg K_2O/ha on sweet potatoes. Soil test levels for these studies were 0.08% K_2O, 0.06 meq K^+/100 g, and ranging from 0.12 to 0.26 meq K^+/100 g, respectively.

Responses to K for beans and soybeans have not been noted often. Working in three different soils from São Paulo State, all low in extractable potassium (approximately 0.04 meq K^+/100 g), no response was obtained in the first year for rates up to 180 kg H_2O/ha (Freitas

et al., 1963). An 82% increase in soybean yield was found, though, when applied in the second year. Miyasaka et al. (1964a) reported no effect of rates up to 90 kg K_2O/ha with soybeans and dry beans in soils extremely low in extractable potassium (0.01 meq K^+/100 g). Similar results were reported by Mascarenhas and Miyasaka (1967) for dry beans and by the same authors in 1968 working with soybeans. For these last two experiments the potassium levels on soils were reported as high (0.30 or more meq K^+/100 g). In contrast with these data, Freitas et al. (1971), working in five areas in the Federal District, obtained increases of 2,000 kg for soybeans when a complete treatment including potassium was used in soils ranging from 0.05 up to 0.16 meq K^+/100 g. According to previous work by Freitas et al. (1960), a rate of 150 kg K_2O/ha increased soybean yields in soils at Anápolis, Goiás that tested 0.02 meq K^+/100 g. No effect was observed by the same authors in soils in São Paulo State that tested 0.12 meq K^+/100 g.

A considerable effect of potassium fertilizers on pineapple yields has been reported by Santos et al. (1972), whereas no effect for pinus (Corrêa et al., 1973) was shown. A depressive effect of applying potassium fertilizer on eucalyptus was reported by Knudson et al. (1972).

Sulfur. Sulfur deficiencies and responses to sulfur in these soils have also been reported for many crops. Very little data are available, though, that refer to sulphate levels in soil or in leaf tissue. There also seems to be a great difference in response between species.

One of the first studies involving sulfur in these soils was carried out in the greenhouse by McClung and Freitas (1959). Working with ryegrass and alfalfa using the technique complete minus one,

sulfur was the second only to phosphorus as a nutritional factor affecting the growth of grasses. In another greenhouse study, McClung et al. (1959), using millet as a test plant, found that all four topsoils studied (except for one Dusky-Red Latosol) gave highly significant responses to 40 kg sulfur/ha. They also postulated that responses to S in these soils will not be common unless N and P levels are improved. Extractable sulfur levels (NH_4OAC extractant) in the topsoil range from 1.8 up to 7.2 ppm. The subsoil levels ranged from 2.1 to 21.7 ppm, suggesting considerable leaching of sulfur.

Responses of soybean yield to 30 kg gypsum/ha were reported in two out of three soils from São Paulo State by Freitas et al. (1963). Also, Miyasaka et al. (1964b) obtained a 350-kg/ha soybean yield increase when 100 kg of gypsum added to a N-P-K mixture. Similar results were found by Mascarenhas et al. (1967).

Freitas et al. (1960), in soils from Anápolis, Goiás and São Joaquim da Barra, São Paulo, found no response from applying 40 kg of sulfur/ha for cotton. They also reported that corn did not respond to this application but cotton yields were increased at the São Paulo location. Freitas et al. (1972a) found no response to application of 80 kg sulfur/ha with soybeans and sweet corn at five locations. They did not discuss the possibility that 20 kg/ha of a mixture of zinc, copper, and manganese sulphate could have masked the results.

Most of the field experiments related to responses to sulfur with cotton have been carried out in São Paulo State. McClung et al. (1961), working with cotton in a "Terra Roxa Misturada" soil, obtained significant responses only in three out of 21 experiments one year, and

four out of eight experiments another year. This study indicated that the maximum response was obtained with 30 kg sulfur/ha.

Little information is available concerning sulfur responses on forage crops grown on these soils. McClung and Quinn (1959) obtained a significant increase in dry matter production of batatais grass (Paspalum notatum) with 40 kg sulfur/ha. They reported a sixfold increase in dry matter when this amount of sulfur was combined with 100 kg P_2O_5/ha. Nevertheless, França and Carvalho (1970), in a greenhouse study with five tropical legumes, found no response in dry matter production when sulfur was applied to a Red Latosol from Sete Lagoas, Minas Gerais.

There are little data on upland rice in relation to sulfur use from this region. In one experiment at Sete Lagoas, Minas Gerais, no response to 150 kg of sulfur/ha was observed by Coqueiro et al. (1972).

Perennial crops such as coffee have shown considerable responses to sulfur in soil under "cerrado" vegetation. Freitas et al. (1972b) in soils with 35 ppm total sulfur and 3 ppm extractable found an 82% increase in yield due to sulfur application. A rate of 30 to 60 kg/ha applied annually was considered adequate for this crop in these sandy soils. Similar results were obtained by Lott et al. (1960).

Magnesium. One of the nutrients that has not been studied in these soils is magnesium. Since liming experiments usually involve the use of dolomitic lime, the effect due to acidity correction and that due to magnesium supply may not be separated. There are a few experiments involving evaluation of the direct effect of magnesium. In one of those, Britto et al. (1971b), working with a Dark-Red Latosol, found no response to 50 kg magnesium/ha for corn, perennial soybeans and

cotton. These results are similar to those obtained by Freitas et al. (1972a) who found no response to 200 kg MgO/ha for most of the experiments with corn and soybeans at Brasília, Matão and Sete Lagoas.

MATERIALS AND METHODS

Field Work

Five hundred eighteen topsoil samples (0-15-cm depth) were taken over an area of approximately 600,000 (six hundred thousand) square kilometers from soils under "cerrado" vegetation in central Brazil. These samples were taken in 57 selected areas: 33 in Goiás State, 22 in Minas Gerais State, and 2 in the Federal District. In each of the areas an average of three representative soils were sampled. Each of these was sampled in three positions according to slope: high, medium, or low. For each slope position 10 to 12 field borings were taken, since this number has been considered satisfactory when uniform soils are sampled for soil fertility studies (Fitts and Nelson, 1956).

Preliminary selection of the areas and soils was made through observations and studies of available maps (Dudal, 1970; FAO, 1971; Camargo and Bennema, 1966). The main factors used for this selection of sites were: kind of soil, natural vegetation, soil color, and texture. The final area covered and the soil sample sites are shown in Figure 2.

The natural vegetation of each site was recorded in one of the five categories suggested by Eiten (1972) and Waibel (1948): campo limpo, campo cerrado, cerrado, cerradão, and forest.

Sample Preparation

The samples were air-dried, ground in a stainless steel tray using a plastic roller, and then passed through a 2-mm stainless steel sieve. One portion of each sample (250 g) was kept at the Centro

de Pesquisas Agropecuarias de Brasilia (EMBRAPA), Brazil, and another portion was sent to the Soil Science Department, North Carolina State University at Raleigh, where all chemical and physical determinations were conducted.

Chemical Analyses[6]

Soil Reaction

Values for pH were obtained by stirring 10 cc of air-dried soil in 25 cc water or 25 cc 1 N KCl solution, letting it stand for 30 min, and measuring pH with a glass-calomel combined electrode.

Exchangeable Acidity

Exchangeable acidity was determined by stirring 2.5 cc of soil in 1 N KCl solution for 10 min, filtering, and then titrating a 10-cc aliquot with 0.01 N NaOH. Phenolphytalein was used as the indicator.

Calcium and Magnesium

A 1-cc aliquot of the filtrate from the exchangeable acidity determination, 9 cc H_2O, and 15 cc 1.0% lanthanum solution were combined and mixed. Calcium and magnesium were then determined by atomic absorption.

Samples with an extremely low concentration of magnesium were repeated with less dilution.

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[6]Methods used in the control laboratory, International Soil Fertility Evaluation and Improvement Program, Department of Soil Science, North Carolina State University at Raleigh.

Potassium

Potassium was determined by stirring 5 cc of soil in 25 cc North Carolina Extracting Solution (0.05 N HCl + 0.025 N H_2SO_4) for 5 min, filtering, and then reading with a flame photometer using lithium as an internal standard.

Phosphorus

Phosphorus was determined by stirring 5 cc of soil in 25 cc North Carolina Extracting Solution (0.05 N HCl + 0.025 N H_2SO_4) for 5 min and filtering. A 10-cc aliquot of the filtrate was then mixed with 10 cc color solution B. The composition of color solution B was 200 cc solution A diluted to 1,000 cc and adding 1 g ascorbic acid. Solution A contained 1 g potassium antimony tartrate, 125 cc concentrate H_2SO_4, and 7.5 g ammonium molybdate/1,000 cc. The blue color of the phosphomolybdate complex using ascorbic acid as a catalyst was measured by colorimetry. Since extremely low values for extractable P occur in these soils, a dilution of 1:2 was used rather than 1:8 as originally suggested.

Micronutrients

Zinc, copper, manganese, and iron were determined in the same filtrate used for potassium, but without dilution. Analyses were by atomic absorption.

Organic Matter

Organic matter level was obtained with a modified wet combustion method suggested by Waugh and Hunter (1974) as follows: 1 cc of soil was placed in a 60-cc Florence flask and 10 cc of acid dichromate solution were added. The mixture was heated to 300°C for 1 hour. After

cooling, 25 cc of Superfloc 127 solution were added and mixed. As soon as the solids settled out, a 2-cc aliquot of the supernatant liquid was taken, 10 cc H_2O added, the colorimetric measurement made at 650 mμ wavelength.

Based on some of the chemical analyses mentioned above, other soil characteristics were evaluated as follows:

Effective CEC

Effective CEC was obtained by summation of the values in meq/100 cc for calcium, magnesium, potassium and acidity, as suggested by Coleman *et al.* (1959).

Percent Aluminum Saturation

The percent aluminum saturation was obtained by the equation suggested by Kamprath (1967):

$$\% \, Al^{+++} \text{ saturation} = \frac{Al^{+++}}{Al^{+++} + Ca^{++} + Mg^{++} + K^{+}} \times 100$$

with the amounts of cations expressed as meq/100 cc.

Since very little exchangeable hydrogen exists in mineral soils (Lin and Coleman, 1961) and most of the exchangeable acidity that is extracted with a neutral unbuffered salt solution such as 1 N KCl is due to Al^{+++}, the terms "exchangeable acidity" and "exchangeable aluminum" are used interchangeably.

Delta pH

Delta pH (ΔpH) was obtained as suggested by Mekaru and Uehara (1972) by the equation:

$$\Delta pH = pH \text{ in KCl} - pH \text{ in } H_2O$$

According to these authors when the ΔpH value is negative, the soil has a net negative electrical charge.

Mechanical Analysis

Mechanical analysis was carried out by the hydrometer method described by Day (1956). Soil samples were dispersed in a $NaPO_3$ solution (Calgon) by using a Hamilton Beach stirrer. Sand, silt, and clay percentages were calculated.

Other Characteristics

Silt/clay ratio was calculated by dividing percent silt by percent clay.

Soil color if air-dried samples was determined using a Munsell Soil Color Chart.

Latitude and longitude for each soil sampled was estimated based on exact location description of sample sites and road maps of the area considered in this survey.

Statistical Analysis

Statistical analysis used in studying these data was basically as follows:

1. Relative frequency distribution. Histograms and other frequency graphs were prepared for 22 of the variables included in this survey. They were pH (H_2O), pH (KCl), ΔpH, calcium, magnesium, potassium, exchangeable acidity, effective CEC, percent aluminum saturation, phosphorus, organic matter, zinc, copper, manganese, iron, sand, silt, clay, hue, value, chroma, and type of vegetation. All 518 topsoil samples collected and analyzed were placed into classes (up to 12) in each case and the percentage occurring in that class calculated.

Minimum and maximum measured or observed values are also presented for some of these variables, as well as levels suggested by PIPAEMG (1972) for soil testing interpretation. The latter are now being used in soil testing laboratories at least in the State of Minas Gerais.

2. Simple correlation analysis. This statistical analysis was carried out for all previously mentioned 22 variables plus silt/clay ratio, longitude and latitude, to study the relationship between vegetation, zinc, magnesium, and phosphorus and all other variables included in this survey.

In order to use vegetation in correlation and regression analysis, the classes were coded from 1 to 5 going from campo limpo to forest.

3. Regression analysis. Regression analysis was the statistical technique used to detect possible amount of change in the dependent variable vegetation (the unique measurement of growth involved in this survey) in relation to other variables involved. There were 19 independent variables of the original data (as previously mentioned for correlation analysis) less longitude, latitude, pH in KCl, silt and exchangeable acidity. The "best" basic regression model was selected by using the maximum R^2 improvement procedure (SAS, 1972), which is one of the stepwise regression procedures (Draper and Smith, 1966). In this procedure the single variables were added one by one to the model according to their significance as measured by the F-test (5% level of significance for entry). At every stage all variables incorporated are examined for significance and the model yielding the highest R^2 value is selected. All variables for which the F-value did not exceed the 5% level of significance were excluded from the basic model.

The final model of the regression equation with vegetation as the dependent variable was obtained by including the single variables obtained in this preliminary statistical analysis plus their quadratic terms and interactions. When the increase in the R^2 was 1% or less due to adding another variable, a final model was selected.

Since phosphorus, magnesium and zinc were the important chemical variables included in this final model, similar statistical techniques were used to obtain regression models for those variables.

By using this technique a variable which was entered at an early stage may become insignificant because of its relationship to other variables which enter the regression.

RESULTS AND DISCUSSION

Relative Frequency Distribution

Frequency data for 22 of the variables considered were calculated and are presented as histograms. The median soil pH in H_2O was 5.0. The range for pH in H_2O was 4.3 to 6.2 (Figure 13). If pH 5.0 is considered as the upper limit for high acidity 48.3% of the samples were in this category. Those with medium acidity, pH from 5.0 to 5.9, were found in 50.2% of the samples. Only 1.5% had a pH of 6.0 or more. This clearly indicates the typical acidic characteristic of these soils.

The median soil pH in KCl was 4.2. The range for this soil characteristic was from 3.7 to 5.5 (Figure 14). These values were less than the pH in H_2O for all samples except for one that was equal.

One of the main uses of the pH in KCl determination is to compare it with the values for pH in H_2O. The difference between these is referred to as ΔpH. The frequency distribution for ΔpH of these topsoils is presented in Figure 15. Values for ΔpH ranged from 0.0 up to -1.4 pH units. For most of the samples (61.8%), ΔpH was between -0.6 and -1.0. All calculated values for this soil characteristic except one were negative, indicating a net negative charge in these topsoil samples.

There have been a few soil profile descriptions for soils under "cerrado" vegetation in Brazil that have shown a positive ΔpH at some depth. One such observation was made by Jacomine (1969). Also, Van Raij and Peech (1972), studying electrochemical properties of two Oxisols and one Alfisol, found a net positive charge in the B2 horizon of one of the Oxisols. None of the three Ap horizons showed a net positive charge, though.

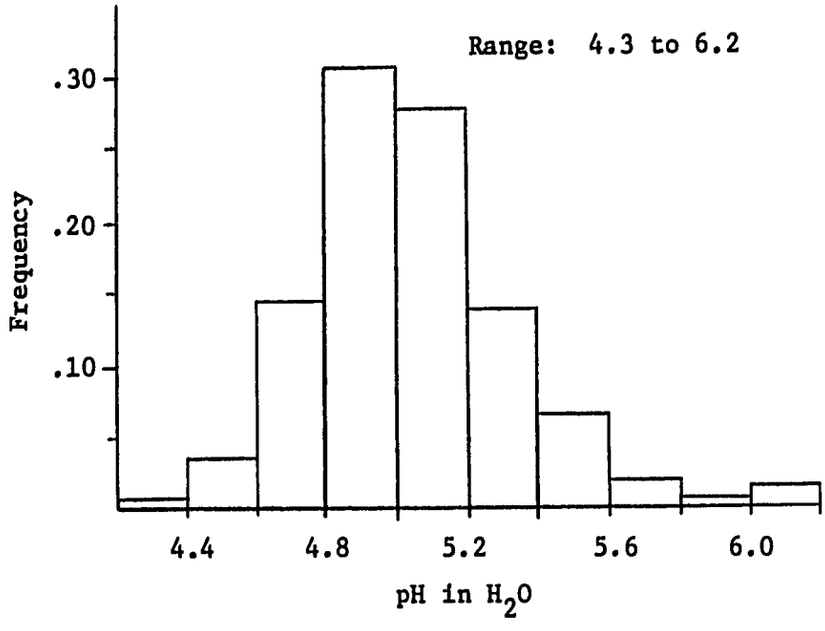


Figure 13. Frequency distribution of pH in H_2O

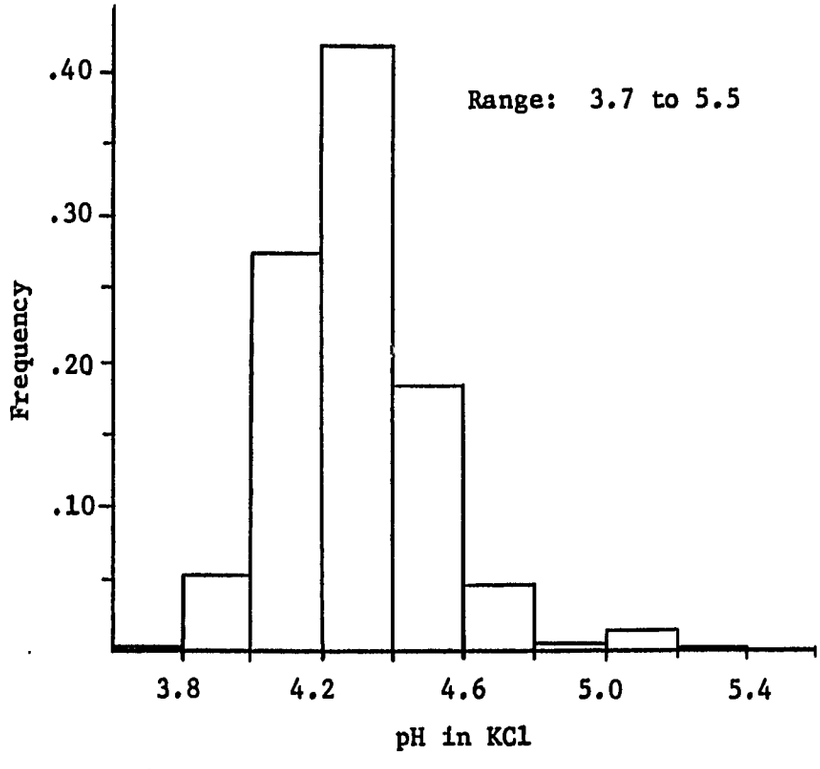


Figure 14. Frequency distribution of pH in KCl

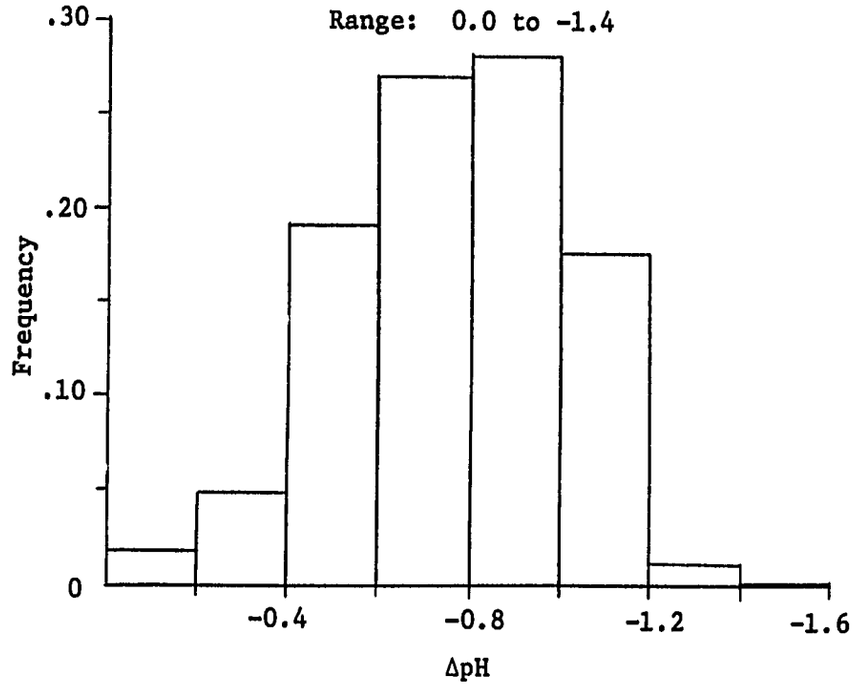


Figure 15. Frequency distribution of delta pH

The potential determining ions in soils with constant surface potential are mainly H^+ and OH^- in the pH range normally encountered (Mekaru and Uehara, 1972). Therefore, the pH of the soil will determine if the charge will be positive or negative and the amount of that charge. None of the 518 topsoil samples considered in this survey had a positive ΔpH. This indicates that at least for the top 15-cm layer of these soils, even at the low natural pH values normally observed, there is a net negative charge. This is probably due to the negative charge of the organic complex being great enough so that it would offset a positive charge that possibly might exist due to the mineral fraction in these soils. With increasing depth in the soil the amount of organic matter decreases and there is a possibility of obtaining a net positive

charge at very low pH values. However, this has not been observed often as indicated in the studies by Jacomine (1969).

The median value for exchangeable calcium was 0.25 meq/100 cc. The observed range was from 0.04 to 6.81 meq/100 cc (Figure 16). Considering the level of 1.5 meq/100 cc as the upper limit for the low class, the analytical results showed that 95.6% of the samples were under this level. These values reflect low levels of available calcium in these soils, and that liming should be one of the main fertilization practices suggested to improve yields in this area.

The median exchangeable magnesium level was 0.09 meq/100 cc. The distribution of magnesium among these samples is summarized in Figure 17. The observed range for this element was from 0.00 up to 2.02 meq/100 cc. Suggested levels for magnesium soil test interpretation are considered low up to 0.5 meq Mg^{++}/100 cc. The data for exchangeable magnesium indicate that 89.8% would be classified as low and only 3.3% of the samples would be considered naturally high for this nutrient.

The fact that 55.2% of the samples gave values equal to or less than 0.1 meq Mg^{++}/100 cc indicates an extremely low level of extractable magnesium. Only few studies involving evaluation of the direct effect of magnesium have been carried out in these soils (Britto _et al._, 1971b; Freitas _et al._, 1972a). In the latter study only two out of eight experiments showed response to magnesium.

It has been suggested that the absolute value of exchangeable magnesium is not an effective way to evaluate the availability of this nutrient for crop growth. Henderson (1969) worked with cotton in North Carolina soils having more than 60% aluminum saturation and an effective

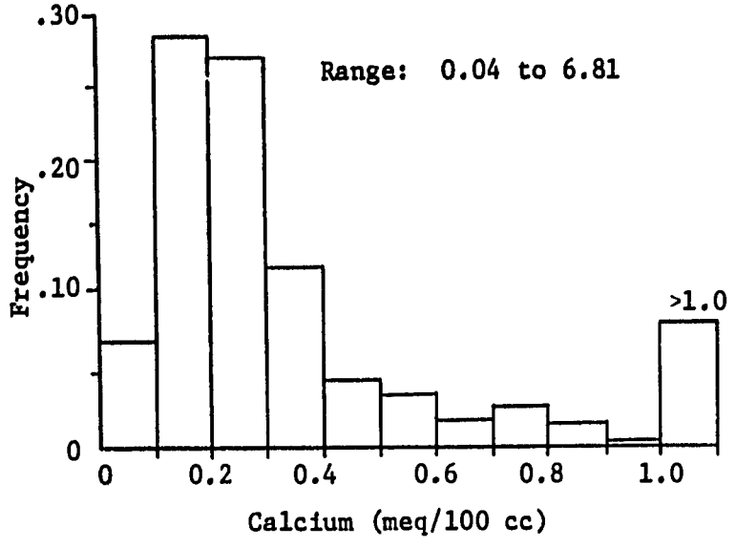


Figure 16. Frequency distribution of exchangeable calcium

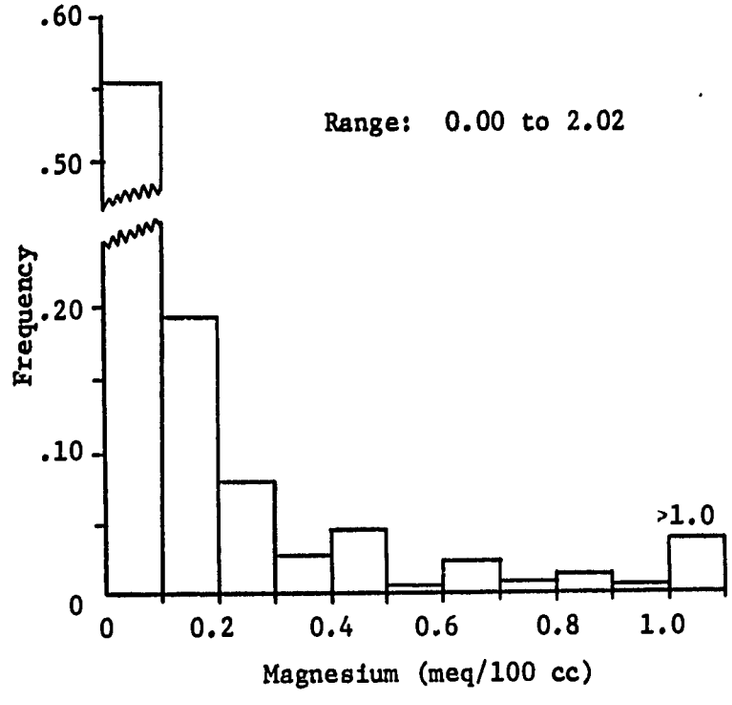


Figure 17. Frequency distribution of exchangeable magnesium

CEC of 1.6 meq/100 g (very similar to the levels observed in these samples from Brazil). He observed magnesium deficiency when less than 4% of effective CEC was occupied by magnesium. A similar level (4% magnesium saturation) had been mentioned previously by Adams and Henderson (1962) as critical for sudangrass and ladino clover in soils from Alabama. Similar studies involving magnesium saturation in comparison with the absolute value of exchangeable magnesium have not been reported for soils under "cerrado" vegetation in Brazil. The extremely low values of magnesium found in this survey when using the criteria of the absolute value for this nutrient suggest an urgent need for re-evaluation of criteria and critical levels for many crops in this area.

The median level of extractable potassium was 0.08 meq/100 cc. The range observed in these results were from 0.02 up to 0.61 meq/100 cc (Figure 18). Considering values less than 0.15 meq K^+/100 cc as low for available potassium, it was observed that 84.9% of the samples were included in this category. Nevertheless, responses to potassium fertilizers in these soils are not as common nor as great as those from application of lime and phosphorus. This is probably due to lack of specific greenhouse and field data to properly identify the critical level of potassium in these soils.

The median value obtained for exchangeable acidity was 0.56 meq Al^{+++}/100 cc. The observed range for this determination was from 0.08 to 2.40 meq Al^{+++}/100 cc (Figure 19). These data showed that 91.5% of the samples had more than 0.25 meq Al^{+++}/100 cc of soil, the minimum level for a medium classification. There were 15.2% of the samples with more than 1.0 meq Al^{+++}/100 cc. These would be classified

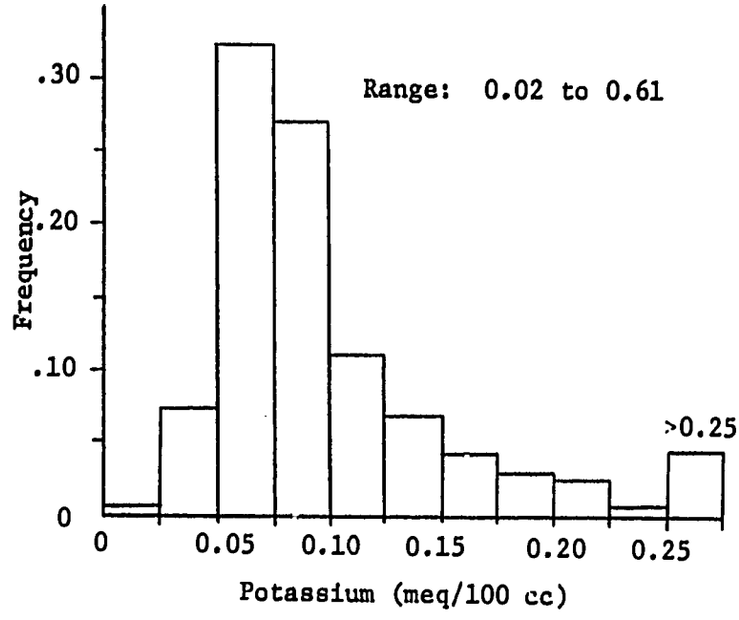


Figure 18. Frequency distribution of exchangeable potassium

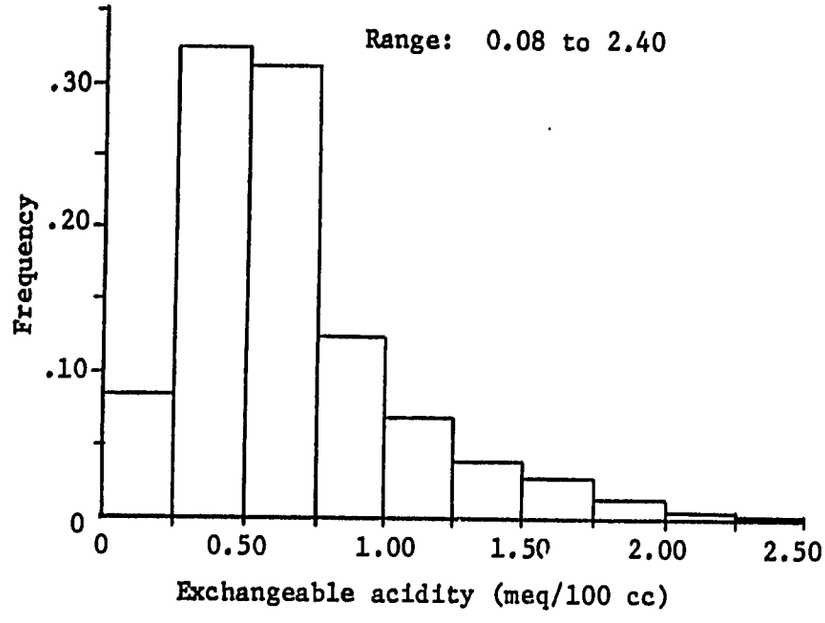


Figure 19. Frequency distribution of exchangeable acidity

as high in exchangeable acidity. Only 8.5% were low in exchangeable acidity having less than 0.25 meq Al^{+++}/100 cc. The fact that most of these soils are ranged from 0.25 to 1.00 meq Al^{+++}/100 cc seems to indicate that, in spite of the quite acidic status of these soils as mentioned earlier, the absolute value for exchangeable acidity itself is not extremely high. However, there also are very low levels of bases such as calcium and magnesium, so the relatively high value for exchangeable acidity will play an important role in these soils.

The median value for effective cation exchange capacity was 1.1 (meq/100 cc). The observed range for this characteristic was from 0.35 to 8.10 meq/100 cc (Figure 20). There are no criteria in Brazil being used to interpret such data, but Boul[illegible] et al. (1974) suggested a value of 4 meq/100 cc for CEC measured by a neutral unbuffered salt extraction as the upper limit for the low class of effective CEC. By using this level as acce[illegible] interpretation of this soil characteristic, 96.5% of th[illegible] included in this category.

The freq[illegible]n of effective CEC indicates that 84.0% have less th[illegible] such an extremely low level reflects how highly [illegible] are in soils under "cerrado" vegetation in Brazil. [illegible]re is very little charge present at ambient pH values in the soil complex and, in conjunction with the low base status, this permits only a very small reserve of plant nutrients.

The frequency distribution of percent aluminum saturation is presented in Figure 21. These data show a range from 1.0 up to 89.4% aluminum saturation in the soil complex. The median was 59.0%.

According to Kamprath (1967) the yield of most Al^{+++}-sensitive crops is decreased in soils with more than 20% aluminum saturation.

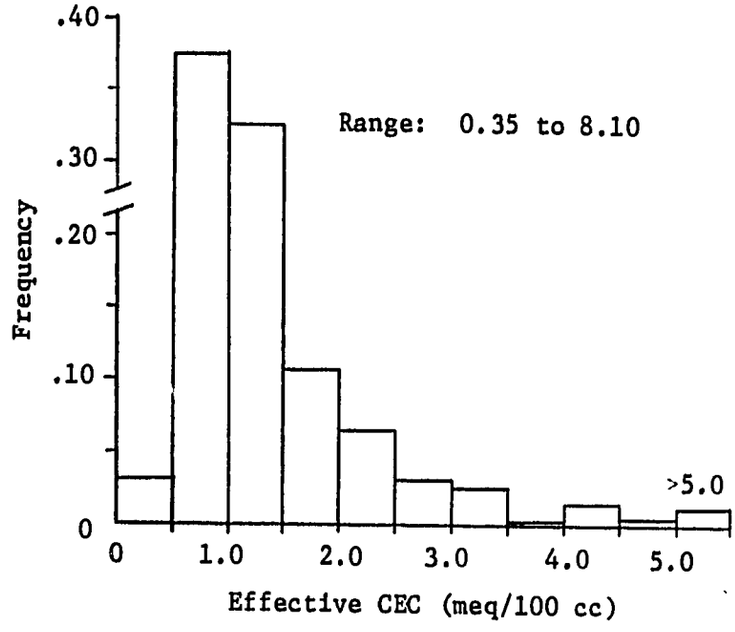


Figure 20. Frequency distribution of effective CEC

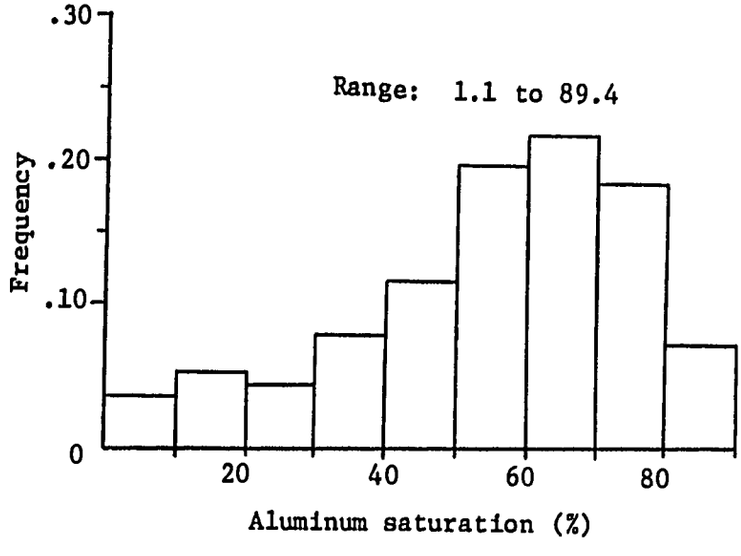


Figure 21. Frequency distribution of percent aluminum saturation

Considering this level, the data show that 91.0% of the samples are over this value.

If one considers 40% aluminum saturation as a point where most cultivated crops begin to suffer due to the lack of equilibrium between bases and aluminum concentration, then 78.6% of the samples are included in this category.

The frequency distributions for calcium, magnesium, exchangeable acidity, effective CEC, and percentage of aluminum saturation show that the absolute values for calcium and magnesium are quite low (95.6% below 1.5 meq Ca^{++}/100 cc and 89.8% below 0.5 meq Mg^{++}/100 cc). Nevertheless, the absolute value for extractable acidity is between 0.25 and 1.00 meq Al^{+++}/100 cc, which is medium, in 76.3% of the total samples. Values with more than 1.0 meq Al^{+++}/100 cc were found in only 15.2% of the samples. This shows that the absolute value for exchangeable acidity is not extremely high.

Although most of these soils have a very low net negative charge (effective CEC in 96.5% of the cases was less than 4 meq/100 cc) and also very low absolute values for calcium and magnesium, the low charge and lack of bases may not be as important as the medium absolute values for aluminum (91.0% of the samples had more than 20% aluminum saturation and 78.6% more than 40.0%).

The absolute value for exchangeable acidity is often used in estimating amounts of lime to be used in these soils, but it may not be the only parameter that should be considered. In most cases the percent of aluminum saturation in the soil complex should be considered first. A considerable difference in crop response may be expected upon liming

these low charge soils if they have the same absolute value for Al^{+++} but different percentages of aluminum saturation. For example, if one considers three soils with the same value for exchangeable acidity, say 1 meq Al^{+++}/100 cc, but different aluminum saturation, say 20, 40, and 60%, the same amount of lime often would be recommended for all three soils. Probably, a multiplication factor of about 2 would be used (meq Al^{+++}/100 cc x 2) and 2 ton lime/ha would be suggested for each soil. If this were done, these three soils would probably behave completely different in relation to crop responses.

The degree of fineness of lime used in most field experiments in these soils has not been reported. When coarse lime is used, there is a slow effect on neutralization of aluminum and, consequently, any excessive rate of lime is not very critical. Nevertheless, there is evidence of overliming effects and application of very high rates have caused a depression in yield (N.C.S.U., 1974b; Jones and Freitas, 1970). It would seem that the correct amount of lime and its physical characteristic needs to be studied in more detail.

Levels of extractable phosphorus for these soils are presented in Figure 22. The median level of extractable P was 0.4 ppm. The range was from 0.1 to 16.5 ppm, with 92.1% of the samples having less than 2 ppm, a value considered as one-fifth of the critical level that is suggested for phosphorus soil test interpretation in this region. The very low available P is probably one of the most critical conditions in these soils.

This situation of an almost absolute lack of available phosphorus has been reflected in many experiments all over the "cerrado" area.

There have been a few exceptions, such as on some soils influenced by a mixture of basic and ultra-basic materials (Freitas et al., 1960, 1963) and in one experiment with sweet potatoes grown in a previously fertilized area (Breda Filho et al., 1966).

A high phosphorus fixation capacity of these soils also has been reported in some studies (Weaver, 1974; Bahia Filho, 1974). This fact, combined with the extremely low natural availability of extractable phosphorus, is one of the main problems related to increasing the fertility status of these soils.

The results for organic matter are shown in Figure 23. The median percentage organic matter was 2.2%. The range was 0.7 to 6.0%. Most of the samples (60.4%) had 1.5 to 3.0% organic matter, which is considered a medium level. Only 17.4% were found to be low in organic matter (less than 1.5%) and 22.2% had more than 3.0% high level.

In spite of the fact that most of these soils are considered medium in organic matter level, and that organic matter seems to be the main soil fraction involved in cation exchange, very low values were observed for the effective CEC in these topsoil samples. There are several explanations for the relatively small effect of the organic fraction as measured by the low effective CEC in these soils. Oxides and hydrous-oxides of iron and aluminum are often abundant in the clay fraction of highly weathered soils. They occur as discrete particles and/or as coatings on the actual clay particles. These particles can have a positive charge at the low natural pH condition of these soils (Keng, 1974). It has also been observed that the sum of the negative charges of organic-inorganic compounds is less than the sum of the

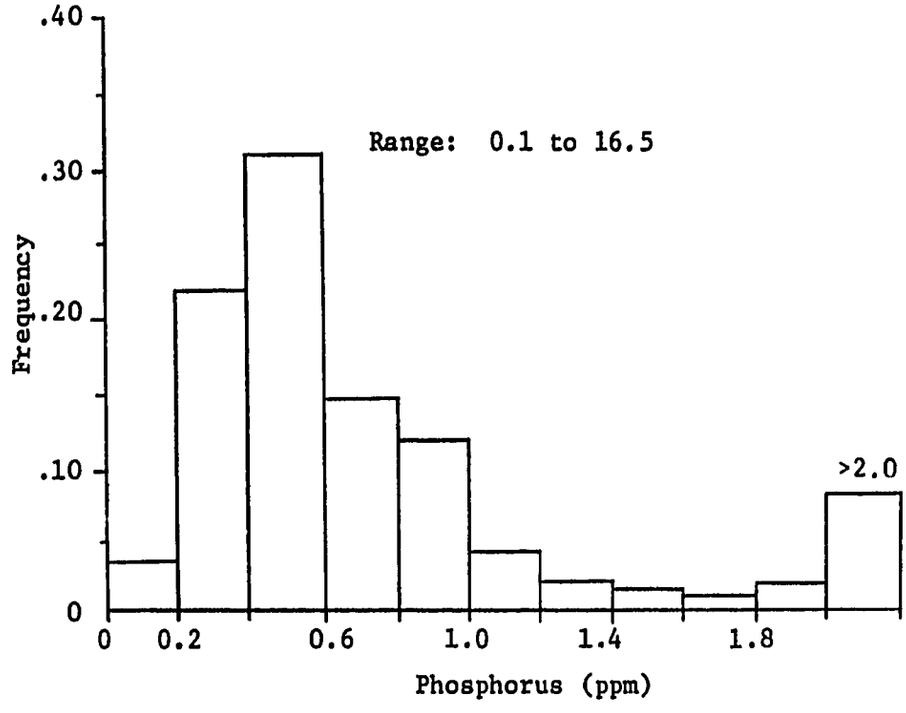


Figure 22. Frequency distribution of extractable phosphorus

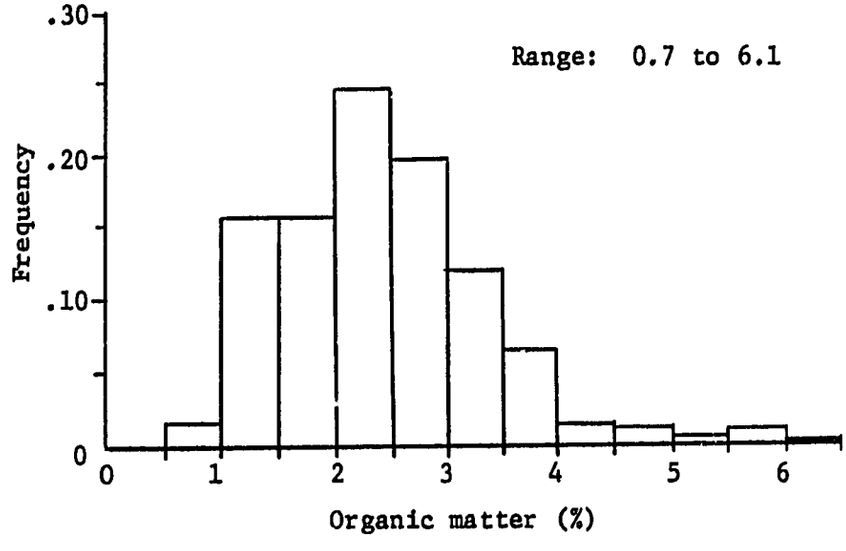


Figure 23. Frequency distribution of organic matter

negative charges measured individually (Sen, 1960; Alexandrova, 1960; Broadbent and Bradford, 1952). This suggests an interaction between effects of the organic and inorganic components of these soils, with a smaller negative charge when the two components occur together.

Broadbent and Bradford (1952) estimated that 54% of the negative sites of the organic complex are attributable to carboxyl groups, 36% to phenolic and enolic hydroxyl groups, and 10% to imide nitrogen groups. Another possible explanation of this behavior of organic compounds in these soils can be that under the edaphic-biotic-climatic conditions that occur in the area under "cerrado" vegetation in Brazil, less functional groups are formed. This would result in a smaller cation exchange capacity in these soils. Black (1968) mentioned the work by Heinonen (1960) and Renger (1965) who found that the cation-exchange capacity of organic matter decreased with an increase in the content of clay. One of the explanations for this behavior was that the nature of organic matter varies with the amount of clay present.

The participation of different functional groups of organic matter in cation-exchange reactions varies with the pH and also with the nature of cations (Black, 1968). Most of the soils under study had pH values ranging from 4.8 to 5.2. In this pH range there may not be enough ionization of functional groups of organic matter (carboxylic, phenolic, enolic, and imide) to result in a very high net negative charge.

Effective CEC in these samples was studied as a function of organic matter and pH. There was a considerable effect of pH on the cation exchange capacity of these soils under "cerrado" vegetation in Brazil (Figure 24). It was calculated that at low pH values, such as less than

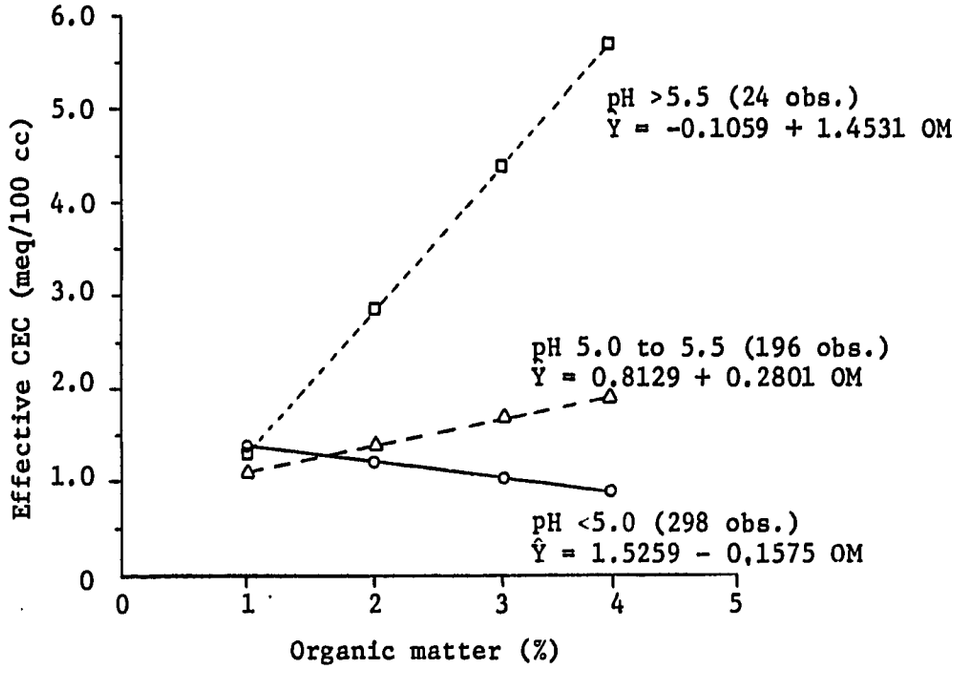


Figure 24. Effective CEC as a function of organic matter content at various ranges of pH

5.0, there is a tendency for effective CEC to decrease as organic matter increases. At pH values ranging from 5.0 to 5.5, there is a little tendency for effective CEC to increase with an increase in organic matter content. At pH values higher than 5.5, this tendency is much more accentuated. This aspect seems to be very important when considering the merits of liming these soils. These data suggest that it is necessary to have the soil pH at a certain level in order to achieve sufficient ionization of organic matter compounds and consequently increase the number of negative charges in the soil colloidal complex.

The frequency distribution for the micronutrients Zn, Cu, Mn, and Fe in these soils are presented in Figures 25-28. For most of these elements there are no previous data or experimental evidence suggesting

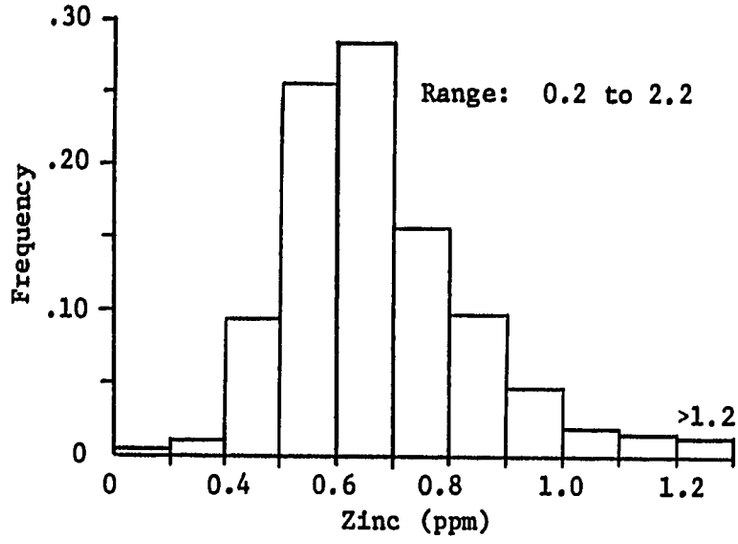


Figure 25. Frequency distribution of extractable zinc

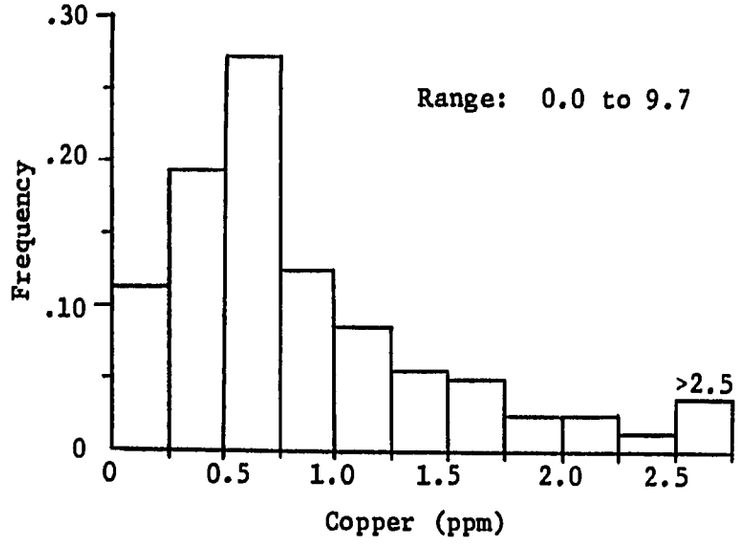


Figure 26. Frequency distribution of extractable copper

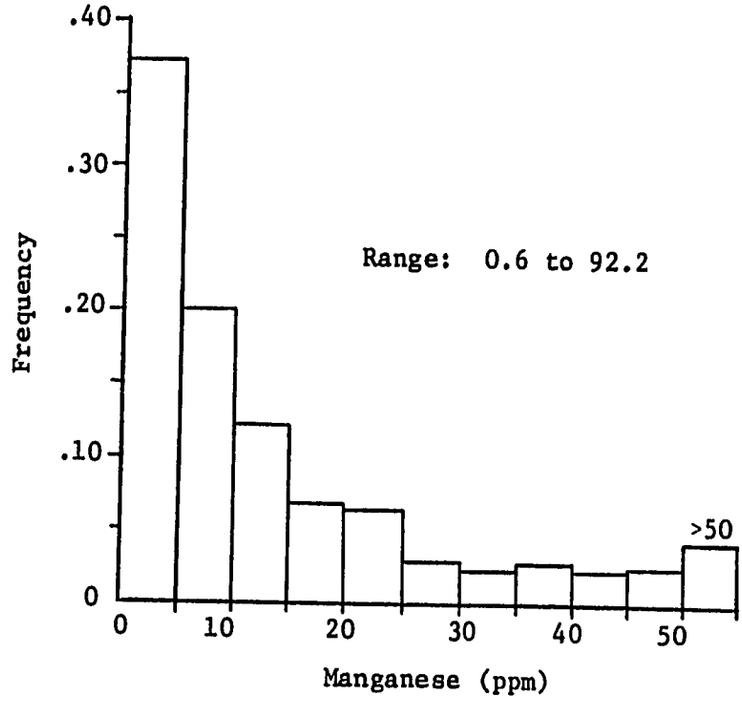


Figure 27. Frequency distribution of extractable manganese

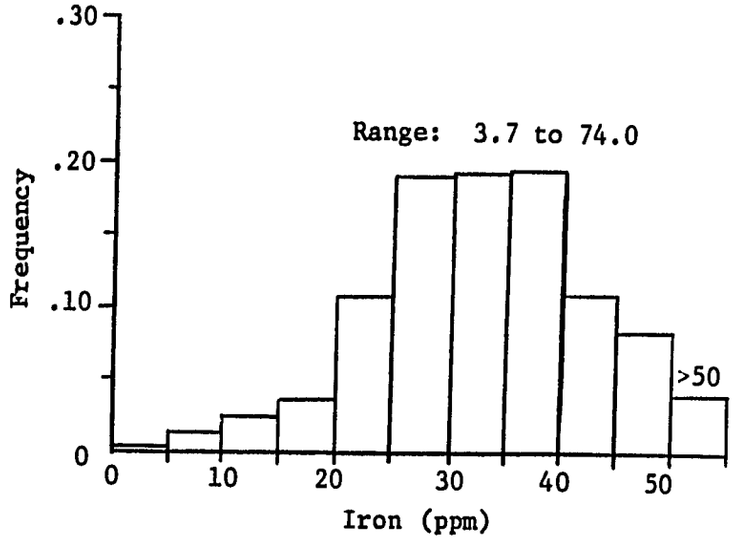


Figure 28. Frequency distribution of extractable iron

critical levels in this region. Nevertheless, tentative interpretations are discussed.

The zinc distribution among these soil samples is shown in Figure 25. The median level was 0.6 ppm. The range for this micronutrient was from 0.2 to 2.15 ppm. Considering the critical level to be 1 ppm, as suggested by N.C.S.U. (1974b) for a zinc-sensitive crop like corn, 94.8% of the samples would be classified as low. For most of these soils the level was from 0.5 to 0.8 ppm Zn.

Of the four micronutrients studied, zinc seems to be the most limiting for plant growth in these soils. Responses to zinc have been observed in many greenhouse and field experiments (Igue and Gallo, 1960; Freitas et al., 1960; Britto et al., 1971b; N.C.S.U., 1974b; Souza and Hiroce, 1970; Santos, 1971).

The median level of extractable copper was 0.65 ppm. The range of observed values was from 0.00 to 9.7 ppm (Figure 26).

According to the International Soil Fertility Evaluation and Improvement Program, N.C.S.U., a critical level of 1 ppm is suggested when the North Carolina double acid extractant is used. Considering this level for these soils, it was observed that 70.3% of the samples would be considered low in this element. Nevertheless, specific studies to evaluate the effect of this nutrient and to determine its critical level are lacking. Most of the studies in the greenhouse and field involving copper have also included other micronutrients (Freitas et al., 1972a; Eira et al., 1972; Miyasaka et al., 1964b; Mascarenhas et al., 1967; França and Carvalho, 1970). There was one exception to this in a study by Teixeira et al. (1971), who suggested that copper deficiency

occurred in one area at Goiás. Although the actual status of research in relation to copper in these soils is nebulous, there have been good yields for many crops in these areas with no use of copper fertilizers. This is probably one indication that the critical level for extractable copper in these soils should be less than 1 ppm.

The median level of extractable manganese was 7.6 ppm. The levels for this nutrient among these samples ranged from 0.6 up to 92.2 ppm (Figure 27).

According to Cox (1973), there are ordinarily two stages in the development of manganese deficiencies in soils: first, reducing conditions leading to reduced forms of manganese and subsequent leaching; and second, deficiencies induced by overliming. Neither condition is common in these highly weathered, well drained soils, so it is not likely that manganese deficiencies will exist.

At a soil pH of 6.0 a critical level of 5.0 ppm has been proposed for extractable manganese when using the North Carolina extractant (Cox and Kamprath, 1973). Since the range for soil pH for these samples was mostly from 4.8 to 5.2, the critical level will be less. There have been no studies concerning the critical level of Mn in this region for these soils. If 5.0 ppm is used as the critical level, the data obtained for this nutrient show that only 37.3% are under this level. These data agree with the previous observation by Cox (1973) that these soils are sufficiently well supplied with manganese. In fact, in some areas, when combined with very acidic conditions, toxic levels may exist. No studies, however, related to evaluation of manganese toxicity in these soils have been reported.

The median level of extractable iron in these soils was 32.5 ppm. The range of values observed for this nutrient was from 3.7 up to 74.0 ppm (Figure 28). There is no suggested critical levels for iron in these soils. Most of the samples contained between 25.0 and 40.0 ppm of iron (58.1%).

Conditions of iron deficiency are usually encountered on calcareous soils (Murphy and Walsh, 1972). Iron deficiencies have not been reported for the "cerrado" area in Brazil, and iron fertilizers are not included in fertilizer formulations for this region. It seems that most of these soils have no problem related to a lack of this nutrient.

Iron toxicity problems also are not likely in these soils. Murphy and Walsh (1972) mentioned that even with 5% iron (extraction procedure not reported), toxicity problems are not common. There may be an indirect effect of high iron content, however. A high Fe level may be one of the main factors involved in the high phosphorus-fixing capacity of these soils.

The median sand, silt, and clay percentages were 48.6, 15.3, and 33.5, respectively. A summary of the textural characteristics among these soils is shown in Figure 29. The range for the sand fraction (2 to 0.05 mm) was from 4.3 up to 93.9%. The vast majority of the soils (90.0%) contained from 20 to 60% sand. For the silt fraction (0.05 to 0.002 mm) the observed range was from 1.6 up to 57.4%. Most of the samples contained less than 30% silt, as 93.4% was found in this range. The data for the clay fraction (<0.002 mm) in these soils showed the range from 4.5 to 72.4%. There was a broad distribution for this

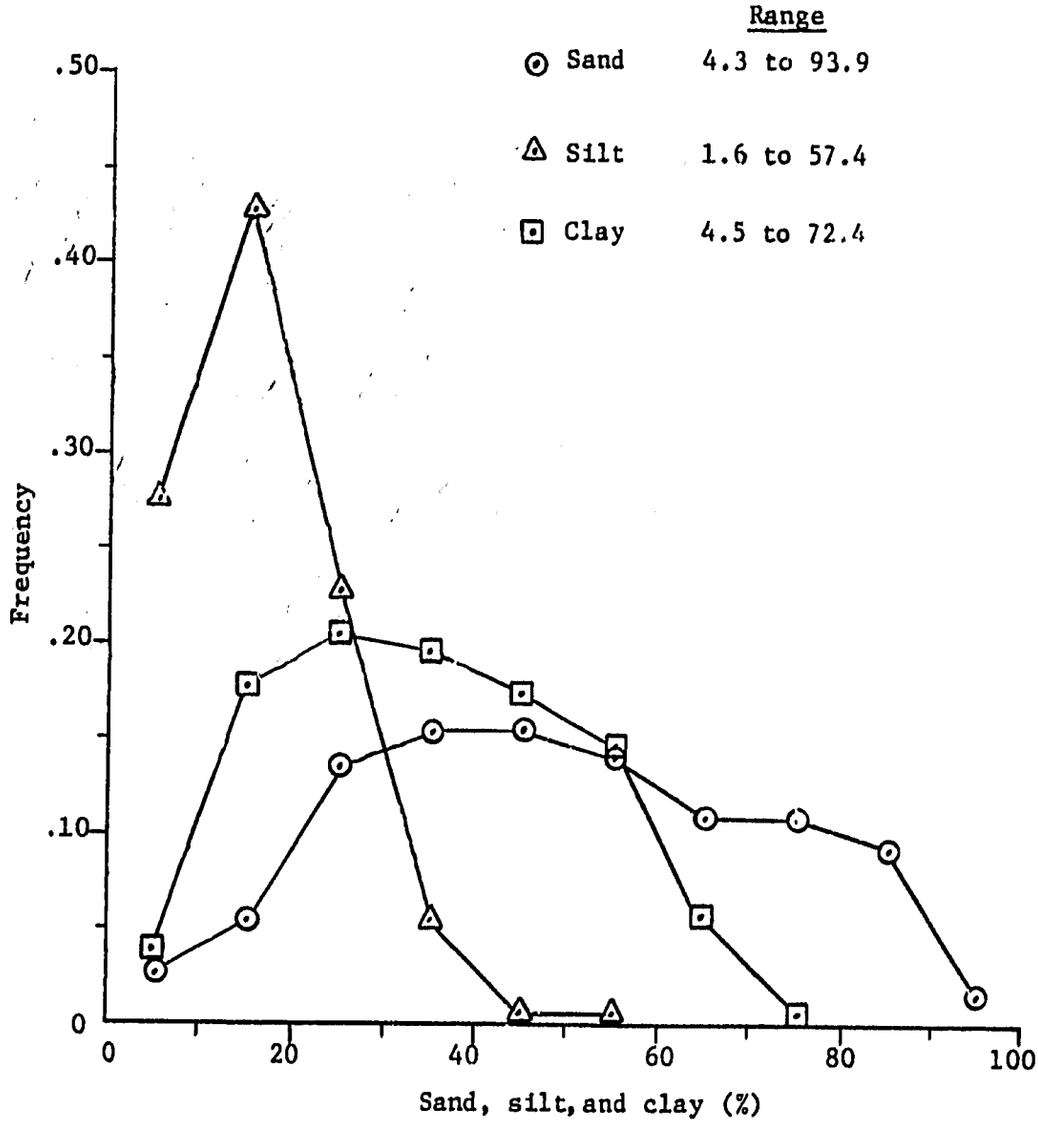


Figure 29. Frequency distribution of the texture components (sand, silt, and clay)

variable with 89.8% of the samples being in the range of 15 to 60% clay.

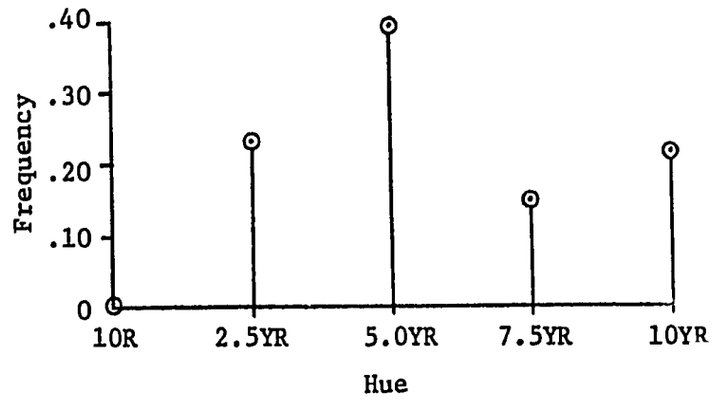
These data show that soils under "cerrado" vegetation in Brazil vary quite widely in surface texture. They range from clayey to sandy and include most other intermediate classes. This extreme variation in texture seems to be one of the most important parameters that should be considered in the characterization and management of these soils.

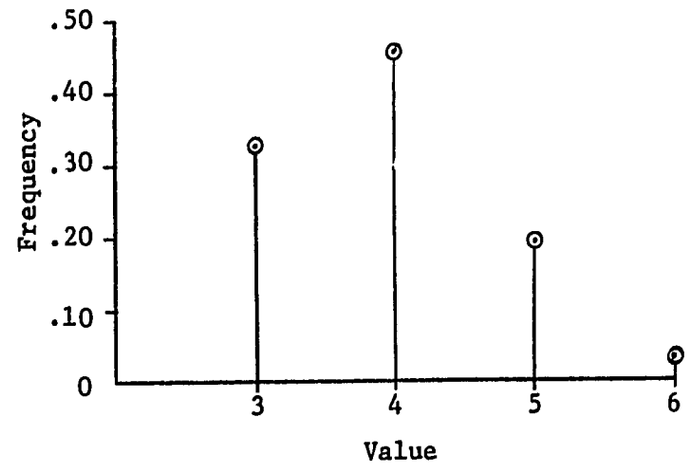
Variation in texture is reported to have a direct effect on the water holding capacity of these soils (Medina and Grohmann, 1966; Ranzani, 1971; Wolf, 1974). Also, the variation in phosphorus fixation has been related to variation in texture (Weaver, 1974; Bahia Filho, 1974). Textural changes may also be involved in the different behavior and responses to P fertilizer application.

Since the cost of fertilizer for improvement of these soils is relatively high and since good yields normally can be obtained only with rather large rates of fertilizer, efforts must be made to determine the correct economical rates of fertilizer to be used on each soil. It seems that texture will be one of the main parameters to be considered in achieving an adequate quantification of these rates.

Color characteristics of the air-dried samples considered in this survey are summarized in Figure 20. A wide range for the color component hue was observed. Most of these topsoils were from 2.5YR to 10YR. A few samples were considered as 10R, but none were 2.5Y or 5Y.

The frequency distribution of value is also presented in Figure 30. Most of the samples were included in the range of value from 3 to 5 (97.1%). Only 2.9% were classified as 6 for value and none were classified as 2.5.





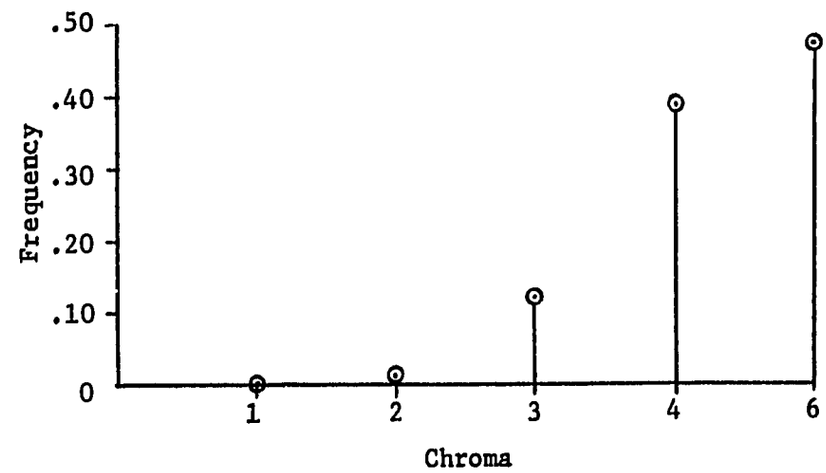


Figure 30. Frequency distribution of the color components: hue (upper), value (middle), and chroma (lower)

Chroma characteristics of these soils also are shown in Figure 30. It was observed that most of the samples (86.3%) had a chroma of 4 to 6. This is an indication that these soils are well drained.

In a broad sense these soils can be divided into three main groups: (1) the red soils that include hue = 10R and hue = 2.5YR (these colors are generally related to unhydrated iron oxide, although manganese dioxide and partially hydrated iron oxides may also contribute red colors) (Soil Survey Staff, 1951); (2) the red-yellow soils that include the 7.5YR and 10YR hues (they have brown and related colors in the top-soil mainly due to the effect of organic matter); and (3) those with hue equal to 5YR may be considered as an intermediate step between the red and red-yellow soils.

A frequency distribution of the kinds of vegetation over the soils involved in this survey is shown in Figure 31. For the area under study most of the samples were taken under vegetation that is considered as campo-cerrado and cerrado (77.8%). Areas under cerradão and forest were observed in 11.8% of the samples and that for campo limpo in approximately 10.4%.

Simple Correlation and Regression Analyses

As mentioned earlier, estimates of production potential used in this survey are based on the gradation in growth and vigor of vegetation going from campo limpo through campo cerrado, cerrado, and cerradão to forest.

Many people who have studied these soils seem to agree that the change in vegetation from campo limpo to forest is probably, among other factors, an indication of increasing natural soil fertility, the

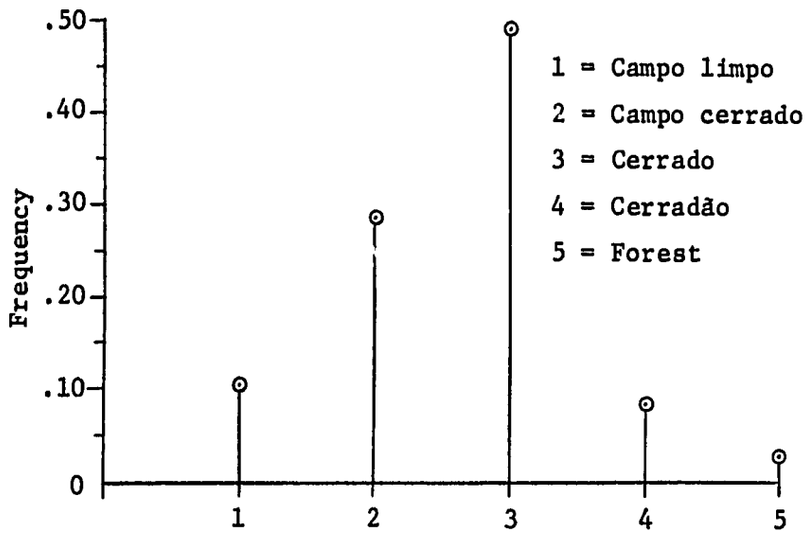


Figure 31. Frequency distribution of the kinds of vegetation involved in this survey

poorest soils being under campo limpo and the most fertile soils under forest vegetation. This observation was made by Goodland and Pollard (1972), who obtained a positive correlation between the levels of N, P, and K and these various kinds of "cerrado" vegetation.

This classification, although it is very subjective, is the basis for the correlation and regression analyses that are to be presented and discussed.

A complete simple correlation matrix among all variables is presented in Appendix Table 1 for reference.

Simple Correlation Analysis for Vegetation

Results from simple correlation analysis for the dependent variable vegetation with each of the independent variables are presented in Table 8.

All of the ccrrelation coefficients were quite low, indicating considerable scatter over the range of observations. Significant relations between vegetation and a number of variables were observed, however. Density and height of vegetation increased with an increase in the level of most of the nutrients. Those showing this relation, in order of their importance, were zinc, magnesium, manganese, calcium, potassium, phosphorus, and copper. The same relationship was observed with effective cation exchange capacity and soil reaction, but an inverse relationship with vegetation was shown with the level of extractable iron in these soils. This suggests a decrease in vegetation with an increase in extractable iron content.

One point that seems to be very conclusive is that the correlation coefficient for exchangeable acidity ($r = -0.011$) was not significant with changes in vegetation. The highly significant ($P = 0.0001$) correlation that was obtained in relation to percentage of aluminum saturation is more important than the absolute value of exchangeable acidity in evaluating the fertility status of these soils.

The relationship between type of vegetation and the topsoil color characteristics (hue, value, and chroma) were determined. The data seem to show a tendency for higher vegetation, such as cerradão and forest, to occur in redder soils and for lower vegetation, such as campo limpo and campo cerrado, to occur in the red-yellow soils.

Table 8. Relation between vegetation and various soil and location variables[a]

Independent variable	Simple correlation coefficient (r)
Zinc (ppm)	0.339****
Magnesium (meq/100 cc)	0.333****
Hue	-0.318****
Value	-0.314****
Manganese (ppm)	0.299****
Effective CEC (meq/100 cc)	0.298****
Aluminum saturation (%)	-0.273****
Calcium (meq/100 cc)	0.273****
pH H_2O	0.270****
Phosphorus (ppm)	0.252****
Potassium (meq/100 cc)	0.218****
ΔpH	-0.203****
Copper (ppm)	0.162**
pH KCl	0.158**
Silt/clay ratio	-0.135**
Silt (%)	-0.129**
Chroma	0.127**
Iron (ppm)	-0.117**
Organic matter (%)	0.104*
Longitude	0.084 NS
Sand (%)	0.068 NS
Latitude	0.038 NS
Clay (%)	-0.021 NS
Exchangeable acidity (meq/100 cc)	-0.011 NS

[a]****P = 0.0001, $r \geq 0.180$; **P = 0.01, $r \geq 0.113$; *P = 0.05, $r \geq 0.086$; NS not significant, $r < 0.086$.

A final observation of the data concerns the textural components sand, silt and clay. No significant correlation was observed between vegetation and sand or clay, but it was significant at 1% level for silt ($r = -0.129$). This is very difficult to explain. Since there was a positive relationship between vegetative growth and effective cation exchange capacity, a positive correlation with clay might be expected. Nevertheless, the r value for clay was the lowest among the three textural components. There was, however, a significant positive correlation coefficient for organic matter content ($r = 0.104$) in relation to vegetation. This seems to indicate that the two main sources of negative charges in these soils are the organic and the silt fractions. The clay fraction seems to be quite inactive in relation to cation exchange.

Another method of looking at the change in type of vegetation in relation to the level of each particular topsoil characteristic is shown in Table 9. This system also allows a more detailed summarization of the data. For each of the five types of vegetation, the means for each soil property are given. Tests for differences between means were made and the interpretation is expressed by letters adjoining each mean. If the means are not followed by the same letter, they differ significantly at the 0.05 probability level.

The previous method using correlation coefficients was based on regression analyses and, if significant, linear components were indicated with their appropriate sign. Similar relations may be noted by the method used in Table 9. Additional insight is given, however, if linear relation is not consistent throughout the range of the five types

Table 9. Relationship between types of native vegetation in central Brazil and average topsoil characteristics[a]

Soil property	Campo limpo 64[b]	Campo cerrado 148[b]	Cerrado 255[b]	Cerradão 45[b]	Forest 16[b]
pH (H_2O)	4.87a	4.94ab	5.00b	5.14b	5.28c
pH (KCl)	4.16a	4.25b	4.25b	4.32b	4.35b
ΔpH	-0.71ab	-0.69a	-0.76bc	-0.82dc	-0.93d
Organic matter (%)	2.21a	2.33a	2.35a	2.32a	3.14b
Exch. Ca (meq/100 cc)	0.20a	0.33ab	0.45b	0.69c	1.50d
Exch. Mg (meq/100 cc)	0.06a	0.13a	0.21b	0.38c	0.55d
Extr. K[c] (meq/100 cc)	0.08a	0.10ab	0.11b	0.13b	0.17c
Exch. Al (meq/100 cc)	0.74a	0.63a	0.66a	0.61a	0.78a
Eff. CEC (meq/100 cc)	1.08a	1.19a	1.43b	1.81c	3.00d
Al saturation (%)	66a	58b	54b	44c	40c
Extr. P[c] (ppm)	0.5a	0.5a	0.9b	2.1c	1.4bc
Extr. Zn[c] (ppm)	0.58a	0.61a	0.66b	0.67b	1.11c
Extr. Cu[c] (ppm)	0.60a	0.79ab	0.94b	1.32c	0.95bc
Extr. Mn[c] (ppm)	5.4a	10.3b	15.9c	22.9d	24.1d
Extr. Fe[c] (ppm)	35.7a	33.9a	33.0a	27.1b	37.2c
Clay (%)	33a	36a	34a	32a	37a
Silt (%)	20a	16b	15b	16b	16b
Sand (%)	46a	48a	51a	53a	47a
Hue	7.3YRa	6.7YRa	5.4YRb	4.4YRc	4.4YRc
Value	4.3a	4.2a	3.8b	3.5c	3.6bc
Chroma	4.5a	4.7a	4.9a	4.7a	5.7b

[a]Means for each line not followed by the same letter are significantly different at the 0.05 probability level.

[b]Number of samples.

[c]Extracted by 0.05 N HCl + 0.025 N H_2SO_4.

of vegetation. This was the case with organic matter and silt. The simple correlation coefficient for organic matter in relation to the change in type of natural vegetation in these topsoils was 0.104, significant at 5% level. Data presented in Table 9 indicate that there was not a significant change in organic matter content when the vegetation varied from campo limpo up to cerradão. Nevertheless, a much higher level of organic matter was observed for the samples taken under forest vegetation, probably due to greater biomass cycling. These data now may be interpreted that the positive relationship observed for organic matter in relation to vegetation (Table 8) is mainly due to the higher organic matter content of soils under forest vegetation, and not due to a gradual increase in this soil characteristic when going from campo limpo up to forest.

In relation to silt content, a significant inverse relationship with vegetation was suggested by the simple correlation coefficient ($r = -0.129$) (Table 8). Data presented in Table 9 indicate that this inverse relationship exists primarily because of the higher level of silt naturally occurring under campo limpo vegetation. The average values for this soil characteristic were very uniform for samples taken under campo cerrado, cerrado, cerradão, and forest vegetation.

The data presented in Table 9 clearly indicate that there is usually a fairly uniform gradient for many of the soil properties in relation to changes in natural vegetation. These observations, however, are not sufficient to establish a cause and effect relationship between soil properties and vegetation.

Regression Analysis for Vegetation

Two multiple regression analyses were conducted on the data for the dependent variable vegetation. Three independent variables were dropped first: latitude and longitude, which were location, not soil, variables and which did not correlate with vegetation; and silt, since the textural components must add to 100% and since the use of percentage of silt is less common.

In a preliminary analysis with the remaining independent variables, eight were significantly (P = 0.05) related to a change in vegetative growth (Appendix Table 2). In order of their importance, these were: zinc, magnesium, chroma, phosphorus, hue, copper, silt/clay ratio, and sand. These eight variables accounted for 29% of the variation in vegetation.

In a second regression analysis, the above eight variables were included plus their quadratic terms and first-order interactions. In the stepwise procedure of this particular analysis, variables continued to be significant as they were added, although the final ones did little to help explain the variation in vegetation. The final model selected did not include any variable that contributed less than a 1% increase in the variation accounted for when it was added.

The final model selected was composed of 12 variables and included seven of the eight main effects entered. Only soil copper level was eliminated. In addition, there were five first-order interactions and squared terms. The results of these analyses are shown in Table 9, and the final equation is as follows:

$$\hat{Veg} = -2.1127 - 0.7929 \text{ silt/clay} + 0.2301 \text{ P} - 0.0581 \text{ chroma x hue} + 0.9533 \text{ Zn} + 1.3290 \text{ chroma} + 0.2323 \text{ hue} - 0.1615 \text{ Mg x P} + 1.7751 \text{ silt/clay x Mg} - 1.0067 \text{ Mg}^2 - 0.0911 \text{ chroma}^2 + 0.9229 \text{ Mg} + 0.0034 \text{ sand.}$$

This equation had a coefficient of determination (R^2) of 0.370, and explains 82% of the variation in vegetation of the maximum R^2 of 0.420 obtained by a complete regression model that included all eight linear effects and their quadratic and first-order interaction terms.

As would be expected in a natural ecological system, there is some intercorrelation of variables as shown in Appendix Table 1. When there is a correlation between independent variables in a model, the regression coefficients (b's) may not be reliable. However, by considering the regression model with the simple correlation coefficients between each independent variable and vegetation and the F-values and partial sum of squares obtained by the analysis of variance table (Table 10), some insight as to the effect of each variable on variation in vegetation may be obtained.

This equation suggests three definite groups of independent variables that are related to the dependent variable vegetation: (1) chemical variables--phosphorus, zinc, and magnesium; (2) textural variables--silt/clay ratio and sand; and (3) color variables--hue and chroma.

In relation to the chemical variables, the highest F-value was obtained in relation to phosphorus (30.07), exceeding the probability level of 0.01%, followed by zinc with a F-value of 20.47, also exceeding the probability level of 0.01% (Table 10). The independent variable magnesium, with a F-value of 6.05, exceeded the probability level of 5%

Table 10. Analysis of variance table, regression coefficients and statistics of fit for the dependent variable vegetation[a]

Source	df	Sum of squares	F-value	R^2	CV (%)
Regression	12	152.3347	24.77****	0.370	26.9
Deviations	505	258.8101			
Total	517	411.1448			

Source	Regression coefficient (b)	Partial sum of squares	Standard error of b	F-value
Intercept	-2.1127			
Silt/clay	-0.7929	20.5887	0.1251	40.17****
P	0.2301	15.4117	0.0420	30.07****
Chroma x hue	-0.0581	11.8755	0.0121	23.17****
Zn	0.9533	10.4921	0.2107	20.47****
Chroma	1.3290	9.8970	0.3024	19.31****
Hue	0.2323	8.1355	0.0583	15.87***
Mg x P	-0.1615	7.3029	0.0428	14.25***
(Silt/clay) x Mg	1.7751	5.9185	0.5224	11.55**
Mg^2	-1.0067	5.8603	0.2977	11.43**
$Chroma^2$	-0.0911	5.0414	0.0290	9.84**
Mg	0.9229	3.1022	0.3751	6.05*
Sand	0.0034	2.3418	0.0016	4.56*

[a]*Exceeds tabular F at significance level of 5%; **exceeds tabular F at significance level of 1%; ***exceeds tabular F at significance level of 0.1% and ****exceeds tabular F at significance level of 0.01%.

and was the third of the chemical independent variables included in this regression model. These observations suggest the relative importance of these three chemical variables in an attempt to quantify the changes in vegetation in this region.

The importance of the textural variable silt/clay ratio can be observed by the fact that the F-test for this property gave the highest value of all independent variables involved in this regression model. The negative value for the regression coefficient of silt/clay ratio indicates an increase in vegetation with a decrease in the value for this variable. Since there was no significant simple correlation for clay in relation to vegetation, the data on silt/clay ratio can be interpreted as an indication that as the silt content increases, the vegetation would decrease. This agrees with the previous simple correlation analysis between silt and the dependent variable vegetation. Caution must be used when regarding data on silt levels in these soils. It is possible that there was not complete dispersion of the soils when running mechanical analysis on these samples. Under these circumstances most of the silt fraction would actually be formed by very stable small aggregates of clay particles. A complete dispersion of Oxisols in Brazil is extremely difficult to obtain with standard dispersing agents such as 10% Calgon which was used for mechanical analysis in these soils (Lepsch[7]). The fact that silt has a significant correlation with effective CEC and that clay fraction has not, however, may simply be an indication that the silt fraction is actually more important than the clay fraction in relation to cation exchange in these soils.

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[7]Lepsch, I.F. Personal communication. 1974.

It is also possible that a lower percentage of actual silt, which would give a smaller silt/clay ratio, could have some physical effect, as for example, more available water as a result of more clay in the relation silt/clay. This physical effect may act in combination with the increase in effective CEC related to the mineral colloids in the silt fraction.

A complete physical study of these samples as well as other chemical characterization is needed to clarify these ideas and test these hypotheses.

The interaction between silt/clay ratio and magnesium exceeded the significance level of 1% in the regression model. The data indicate that at low levels of exchangeable magnesium an increase in the silt/clay ratio is associated with a decrease in vegetation. At high levels of magnesium, which are not typical in these soils, the level of silt/clay ratio is not associated with changes in vegetation. This seems to be another indication of the importance of the silt/clay ratio in the prediction equation for changes in natural vegetation in these highly weathered soils.

Finally, in relation to the color components that were included in this regression model, chroma and hue were the most important.

The regression equation for the dependent variable vegetation included three chemical variables: zinc, magnesium and phosphorus. Additional information on factors related to vegetation may be obtained by relating levels of these variables to other properties. Simple correlation analysis and also regression analyses for zinc, magnesium, and phosphorus as dependent variables are presented.

Simple Correlation Analysis for Zinc

Data of simple correlation analysis for zinc as the dependent variable in relation to all independent variables is summarized in Table 11.

The order of the coefficient of correlation (r) values indicates a strong positive relationship between the levels of extractable zinc and the number of available sites on the soil complex. The correlation with effective CEC (r = 0.533) is highly significant. Since there also is a highly significant correlation between effective CEC and pH (r = 0.572), this may explain the positive correlation of zinc in relation to the basic components of effective CEC (calcium, magnesium, and potassium) and the negative correlation with percent aluminum saturation, which generally increases with more acid soil conditions. A similar explanation may apply to the negative correlation between extractable zinc and extractable iron in these soils.

The simple correlation for clay in relation to extractable zinc in these soils (r = 0.097) was considerably smaller than that for organic matter (r = 0.404). This may indicate that most of the negative charges that hold this micronutrient are related to organic matter rather than to the clay colloids in these highly weathered soils.

Another observation in relation to the texture components in relation to zinc availability is that there was higher positive relationship for silt (r = 0.250) than for clay (r = 0.097). Similar behavior was observed for copper and manganese with r values of 0.304 and 0.193, respectively, in relation to the silt fraction, but with no significant relationship to the clay fraction. These data are indications that, at

Table 11. Relation between extractable zinc and various soil characteristic and location variables[a]

Independent variables	Simple correlation coefficient (r)
Effective CEC (meq/100 cc)	0.533****
Calcium (meq/100 cc)	0.524****
Magnesium (meq/100 cc)	0.493****
Manganese (ppm)	0.492****
Potassium (meq/100 cc)	0.453****
Organic matter (%)	0.404****
pH H_2O	0.395****
Aluminum saturation (%)	-0.391****
pH KCl	0.364****
Phosphorus (ppm)	0.353****
Copper (ppm)	0.293****
Silt (%)	0.250****
Longitude	0.194****
Silt/clay ratio	0.186****
Sand (%)	-0.170***
ΔpH	-0.169***
Value	-0.163***
Iron (ppm)	-0.147***
Hue	-0.128**
Clay (%)	0.097*
Chroma	-0.043 NS
Exchangeable acidity (meq/100 cc)	-0.022 NS
Latitude	-0.008 NS

[a]****P = 0.0001, $r \geq 0.180$; ***P = 0.001, $r \geq 0.143$; **P = 0.01, $r \geq 0.113$; *P = 0.05, $r \geq 0.086$; NS not significant, $r < 0.086$.

least for the release of micronutrients such as zinc, copper, and manganese, the organic matter and the silt fraction are probably the most important soil characteristics. The clay fraction seems to be quite inactive in relation to the availability of these micronutrients.

Among the color components, no significant relationship for chroma was observed in relation to extractable zinc. The simple correlation coefficients for hue ($r = 0.128$) and value ($r = 0.163$) indicate a tendency for the red-yellow soils to present a lower natural availability of zinc when compared with the red and dark-red soils.

The location variables tended to show a higher zinc availability in the western part of the area sampled, but there was no relationship with latitude.

Regression Analysis for Zinc

Two multiple regression analyses were conducted on the data for the dependent variable extractable zinc. Two independent variables were dropped first: vegetation, which was initially considered as the dependent variable; and silt, since the textural components must add to 100%. Also, the use of percentage of silt is less common and the silt/clay ratio can give an indirect indication of any relationship to zinc for both the silt and clay variables.

In a preliminary analysis with the remaining 23 independent variables, five were highly significant ($P = 0.001$) in relation to a change in the natural availability of zinc in these soils (Appendix Table 3). In order of their importance, these were: effective CEC, organic matter, manganese, magnesium, and pH. No texture variable, color variable or location variable was included in the results of this

regression analysis. The five included variables accounted for 46% of the variation of extractable zinc.

In a second regression analysis the above five variables were included plus their quadratic terms and first-order interactions. Among all quadratic terms and interactions, only the quadratic term for organic matter led to more than a 1% increase in the R^2 and was included in the final regression model. The final model selected was composed of six variables and included all five main effects entered and one quadratic term. The results of this analysis are shown in Table 12, and the final equation is as follows:

$$\hat{Zn} = -0.3580 + 0.0918 \text{ Eff. CEC} + 0.0032 \text{ Mn} + 0.1482 \text{ Org. Matter} + 0.1235 \text{ pH} - 0.1997 \text{ Mg} - 0.0143 (\text{Org. Matter})^2$$

This equation had a coefficient of determination (R^2) of 0.472 and would explain 90.5% of the variation in extractable zinc of the maximum R^2 of 0.522 obtained by a complete regression model that included all linear effects and their quadratic terms and first-order interaction terms.

The above equation suggests that most of the variability of extractable zinc can be explained by the values of exchangeable sites in the soil complex as measured by effective CEC, a variable that presented a positive regression coefficient and had the highest F-value among the variables involved.

Since the amount of charge in the colloidal system in these soils is related more to organic matter than to clay content, and since the charges resulting from organic matter are highly pH dependent, the

Table 12. Analysis of variance table, regression coefficients and statistics of fit for the dependent variable extractable zinc[a]

Source	df	Sum of squares	F-value	R^2	CV (%)
Regression	6	8.7533	76.05****	0.472	21.2
Deviations	511	9.8023			
Total	517	18.5556			

Source	Regression coefficient (b)	Partial sum of squares	Standard error of b	F-value
Intercept	-0.3580			
Eff. CEC	0.0918	0.9841	0.0128	51.30****
Mn	0.0032	0.9241	0.0005	48.17****
Org. matter	0.1482	0.5391	0.0280	28.11****
pH	0.1235	0.3323	0.0297	17.33***
Mg	-0.1997	0.2625	0.0540	13.69***
Org. matter^2	-0.0143	0.1585	0.0050	8.26**

[a]**Exceeds tabular F at significance level of 1%; ***exceeds tabular F at significance level of 0.1% and ****exceeds tabular F at significance level of 0.01%.

inclusion of pH and organic matter in this model seems to be an indication of the importance of these variables in a prediction equation for the dependent variable zinc in these soils.

The positive regression coefficient for the independent variable manganese seems to express a relationship with the parent material of some of these soils. Lepsch (1972) mentioned that one of the best soils in Brazil, a Dusky-Red Latosol, has high amounts of iron and manganese oxides. The parent material of these soils includes mafic basic rocks. It seems that the parent material of these soils varies within this region and results in this extremely high importance of manganese in the regression equation. The highly significant ($P = 0.0001$) coefficient of correlation between zinc and manganese ($r = 0.492$) presented in Appendix Table 1 is also evidence of this behavior.

One final consideration in relation to the suggested regression model for the dependent variable zinc is the fact that none of the texture variables nor color components were included. This is probably more evidence of the small influence of these variables when predicting zinc availability in these soils. It should be noted, however, that silt showed much higher correlation with zinc than did clay or sand, as discussed in the simple correlation analysis.

Simple Correlation Analysis for Magnesium

Results from simple correlation analysis for the dependent variable magnesium are presented in Table 13. This simple correlation analysis gives strong evidence of the relationship between the dependent variable magnesium and the increase in available sites on the soil colloidal complex, similar to that previously explained for extractable zinc.

Table 13. Relation between exchangeable magnesium and various soil characteristic and location variables[a]

Independent variables	Simple correlation coefficient (r)
Effective CEC (meq/100 cc)	0.876****
Calcium (meq/100 cc)	0.839****
Aluminum saturation (%)	-0.765****
Potassium (meq/100 cc)	0.759****
pH H_2O	0.696****
Manganese (ppm)	0.568****
Zinc (ppm)	0.492****
Phosphorus (ppm)	0.485****
pH KCl	0.473****
Iron (ppm)	-0.460****
ΔpH	-0.459****
Organic matter (%)	0.211****
Value	-0.204****
Longitude	0.176***
Copper (ppm)	0.167***
Hue	-0.146***
Exchangeable acidity (meq/100 cc)	-0.139**
Silt/clay ratio	0.104*
Chroma	-0.097*
Silt (%)	0.093*
Latitude	0.070 NS
Clay (%)	-0.044 NS
Sand (%)	-0.004 NS

[a]****P = 0.0001, $r \geq 0.180$; ***P = 0.001, $r \geq 0.143$; **P = 0.01, $r \geq 0.113$; *P = 0.05, $r \geq 0.086$; NS not significant, $r < 0.086$.

Since effective CEC is a complex variable involving many factors, it seems quite logical the positive signs for the r values in relation to other basic components of effective CEC (calcium, magnesium, and potassium), in contrast with the negative signs for exchangeable acidity, percent of aluminum saturation, and extractable iron on these highly weathered soils.

These differences in signs of the correlation coefficients for these variables in relation to exchangeable magnesium probably can be explained by the highly significant ($P = 0.0001$) correlation coefficient between pH and effective CEC in these soils ($r = 0.572$). At low pH values there are considerable increases in exchangeable acidity and extractable iron, aluminum saturation is very high and, consequently, there is a reduction in adsorption of magnesium and other bases.

In relation to the color components, an inverse relationship was observed between magnesium and value ($r = -0.204$), and also with hue ($r = -0.146$) and chroma ($r = -0.097$). This relationship can be summarized as a tendency for more natural availability of magnesium in the dark-red soils than in the red-yellow soils, and also less availability of magnesium under more oxidized (higher chroma) than under reduction conditions within a typical hue category.

The observation that there was not a significant relationship between the clay fraction and the levels of exchangeable magnesium in these soils ($r = 0.044$) is further evidence of the small contribution of the clay fraction to the net negative charge in these topsoil samples. Since there was a positive relationship ($P = 0.01$) for organic matter in relation to magnesium ($r = 0.211$), this indicates that the organic

fraction is more important than the clay fraction in relation to the natural availability of magnesium for soils under "cerrado" vegetation in Brazil.

In relation to the location variables (longitude and latitude), behavior similar to that with zinc was observed. There tended to be more available magnesium in the western part of the area sampled. But, since most of the samples were taken in the central part of the longitudinal range, this can be an overestimation for this correlation data. There was no relation between latitude and available magnesium in this area.

Regression Analysis for Magnesium

Two multiple regression analyses were conducted on the data for the dependent variable magnesium. The independent variables vegetation and silt were dropped for the reasons previously mentioned.

In a preliminary analysis with the remaining 23 independent variables, three were highly significantly related to a change in the levels of extractable magnesium. In order of importance these were: effective CEC, percent aluminum saturation and calcium (Appendix Table 4). No texture, color or location variables were included in this preliminary analysis. The three included variables accounted for 90% of the variation in exchangeable magnesium.

In a second regression analysis the above three factors wei included plus their quadratic terms and first-order interactions. In the stepwise procedure of this particular analysis, the variables were added one by one but the final ones helped little to explain the variation in magnesium. The final model did not include any variable that contributed less than a 1% increase in the variation accounted for.

The final model selected was composed of four variables and included only one first-order interaction. The results of these analyses are shown in Table 14 and the final equation is as follows:

$$\hat{Mg} = -0.0097 + 0.7652 \text{ Eff. CEC} - 0.7470 \text{ Ca} - 0.0077 \text{ Eff. CEC} \times \% \text{ Al} - 0.0005\% \text{ Al}$$

This equation had a coefficient of determination (R^2) of 0.983, and therefore would almost completely explain the variation in magnesium.

This regression equation indicates that the main factors that can explain the variation of magnesium in these soils are effective CEC, exchangeable calcium and the first-order interaction effective CEC x percent Al saturation.

Since the effective CEC, that is an estimation of the effective number of negative charges in the soil colloidal complex, is obtained by the summation of exchangeable bases (calcium, magnesium, and potassium) plus exchangeable acidity, the signs of the regression coefficients in this equation seem quite understandable. The positive b value for the variable effective CEC and the negative b value for calcium and percent Al saturation suggests competition for the few available sites in these soils. An imbalance of calcium and/or aluminum in relation to magnesium can lead to less adsorption of Mg and, consequently, lowering the levels of exchangeable magnesium in these soils.

Similar to the regression equation model presented for zinc, the suggested model for magnesium did not include texture or color variables. Both models indicate there is little influence of the clay content or color in the natural availability of magnesium and zinc in these soils.

Table 14. Analysis of variance table, regression coefficients and statistics of fit for the dependent variable exchangeable magnesium[a]

Source	df	Sum of squares	F-value	R^2	CV (%)
Regression	4	40.8084	7287.21****	0.983	19.0
Deviations	513	0.7200			
Total	517	41.5284			

Source	Regression coefficient (b)	Partial sum of squares	Standard error of b	F-value
Intercept	-0.0097			
Eff. CEC	0.7652	6.3308	0.0114	4510.45****
Ca	-0.7470	3.6880	0.0146	2627.57****
Eff. CEC x % Al	-0.0077	3.3265	0.0002	2369.99****
% Al	-0.0005	0.0142	0.0002	10.09**

[a]**Exceeds tabular F at significance level of 1% and ****exceeds tabular F at significance level of 0.01%.

Simple Correlation Analysis for Phosphorus

Results from simple correlation analysis for the dependent variable phosphorus with each of the independent variables is presented in Table 15. There is a highly significant positive relation between most of the chemical variables studied and phosphorus level. Iron level and percent of aluminum saturation gave highly significant negative correlations with phosphorus level.

Exchangeable acidity did not correlate with the level of extractable phosphorus in these samples. The fact that a highly significant negative correlation was obtained in relation to percent Al saturation ($r = -0.328$) seems to be further evidence that this characteristic may be more important than the level of exchangeable acidity in trying to evaluate the natural fertility status of these soils.

In relation to the texture components, the negative correlation of P level with clay was highly significant with a coefficient of correlation (r) of -0.205. This is an indication that the clay fraction, which is very ineffective in production of negative charges in these soils, is very effective in reducing the amount of extractable phosphorus as measured by the N.C. double acid-extracting solution. A highly significant positive correlation was also observed between clay and extractable iron and exchangeable acidity ($r = 0.180$ and $r = 0.355$, respectively) as shown in Appendix Table 1. This suggests that with higher amounts of clay size materials, phosphorus fixation is increased in these soils and consequently there is less extractable phosphorus.

These data suggest that in spite of very little influence in relation to adsorption and release of most of the cations, the clay fraction

Table 15. Relation between extractable phosphorus and various soil characteristic and location variables[a]

Independent variables	Simple correlation coefficients (r)
Calcium (meq/100 cc)	0.518****
Effective CEC (meq/100 cc)	0.498****
Magnesium (meq/100 cc)	0.485****
Manganese (ppm)	0.455****
pH H_2O	0.438****
Zinc (ppm)	0.353****
Aluminum saturation (%)	-0.328****
Potassium (meq/100 cc)	0.312****
pH KCl	0.300****
ΔpH	-0.287****
Silt/clay ratio	0.280****
Copper (ppm)	0.253****
Iron (ppm)	-0.231****
Chroma	-0.219****
Clay (%)	-0.205****
Organic matter (%)	0.155***
Value	-0.153***
Longitude	0.152***
Sand (%)	0.130**
Latitude	0.129**
Hue	-0.120**
Exchangeable acidity (meq/100 cc)	-0.071 NS
Silt (%)	0.054 NS

[a]****P = 0.0001, $r \geq 0.180$; ***P = 0.001, $r \geq 0.143$; **P = 0.01, $r \geq 0.113$; *P = 0.05, $r \geq 0.086$; NS not significant, $r < 0.086$.

will probably be one of the most important factors in relation to different responses to phosphate fertilizers in these highly weathered, high phosphorus-fixing capacity soils. This behavior has been observed in some of these soils. Weaver (1974) and Bahia Filho (1974) observed a considerable increase in phosphorus fixation with an increasing clay content in many soils under "cerrado" vegetation in Brazil.

The highly significant positive correlation with extractable manganese ($r = 0.455$) can be explained, probably, in relation to changes in the parent material of these soils. The parent material ranges from very acid rocks to basic and ultrabasic rocks. It is generally agreed that the last group, generally under forest vegetation, is higher in total forms of MnO_2 and P_2O_5 and probably also higher in the extractable levels of these elements (Verdade, 1972).

In relation to the color components, a negative correlation was observed between extractable phosphorus and hue, value, and chroma. This can be summarized as a tendency for the red-yellow soils to have a lower availability of phosphorus than the dark-red soils. It also suggests less available phosphorus under higher chroma (more oxidized conditions) than lower chroma (more reduced conditions) levels. This seems to be another indication that red-yellow and yellow soils of the same textural class will probably fix more phosphorus than the red and dark-red soils. This has been shown by Weaver (1974) and Bahia Filho (1974).

Regression Analysis for Phosphorus

Two multiple regression analyses were conducted on the data for the dependent variable phosphorus. The independent variables vegetation and silt were initially dropped as previously explained.

In a preliminary analysis with the remaining 23 independent variables in the stepwise procedure, variables continued to be significant as they were added although the final ones did little to help explain the variation in extractable phosphorus in these samples. After seven independent variables were added, addition of other independent variables led to an increase in the R^2 of less than 1%. The seven independent variables chosen in order of their importance were: calcium, chroma, manganese, hue, percent Al saturation, silt-clay ratio, and clay. These seven variables accounted for 43% of the variation in phosphorus. This preliminary analysis is presented in Appendix Table 5.

In a second regression the above seven variables were included plus their quadratic terms and first-order interactions.

Also, in this particular analysis by the stepwise procedure, variables continued to be significant as they were added although the final one did little to help explain the variation in phosphorus. The final model selected did not include those variables that contributed less than 1% increase in the variation accounted for.

The final model selected was composed of 13 variables and included all seven main effects entered. In addition, there were six first-order interactions. The results of these analyses are shown in Table 16, and the final equation is as follows:

$$\hat{P} = -4.2287 + 0.1901\ \text{Mn} - 0.0255\ \text{Mn} \times \text{chroma} - 0.0119\ \text{Mn} \times \text{hue} - 0.3971\ \text{silt/clay} \times \text{hue} + 0.2696\ \text{hue} + 5.1965\ \text{silt/clay} + 0.0357\ \text{Ca} \times \%\ \text{Al} - 0.0136\ \text{clay} + 0.0157\ \text{Mn} \times \text{Ca} + 0.0151\ \%\ \text{Al} + 0.4100\ \text{chroma} - 0.4852\ \text{silt/clay} \times \text{chroma} + 0.3139\ \text{Ca}.$$

Table 16. Analysis of variance table, regression coefficients and statistics of fit for the dependent variable extractable phosphorus[a]

Source	df	Sum of squares	F-value	R^2	CV (%)
Regression	13	638.5262	53.75****	0.581	108.1
Deviations	504	460.5302			
Total	517	1099.0564			

Source	Regression coefficient (b)	Partial sum of squares	Standard error of b	F-value
Intercept	-4.2287			
Mn	0.1901	94.1539	0.0187	103.04****
Mn x chroma	-0.0255	82.6494	0.0027	90.45****
Mn x hue	-0.0119	55.3180	0.0015	60.54****
(Silt/clay) x hue	-0.3971	43.2916	0.0577	47.38****
Hue	0.2696	38.2730	0.0417	41.89****
Silt/clay	5.1965	32.3980	0.8727	35.46****
Ca x % Al sat.	0.0357	24.6768	0.0069	27.01****
Clay	-0.0136	20.1411	0.0029	22.04****
Mn x Ca	0.0157	19.7658	0.0034	21.63****
% Al sat.	0.0151	18.9577	0.0033	20.75****
Chroma	0.4100	18.3606	0.0915	20.09****
(Silt/clay) x chroma	-0.4852	14.5026	0.1218	15.87***
Ca	0.3139	2.6905	0.1829	2.94 NS

[a]***Exceeds tabular F at significance level of 0.1%; ****exceeds tabular F at significance level of 0.01% and NS not significant.

This equation had a coefficient of determination (R^2) of 0.581 and would explain 83% of the variation in phosphorus of the maximum R^2 of 0.697 obtained by a complete regression model that included all seven linear effects and their quadratic terms and first-order interaction terms.

The high coefficient of variation for this regression model, the inclusion of many first-order interactions, and also the changes in sign of the regression coefficient for hue, chroma, and percentage of aluminum saturation, when compared with previous simple correlation analysis, all indicate the complex nature of the behavior of phosphorus in these highly weathered soils.

Nevertheless, a tentative insight in relation to some of these variables will be discussed. The inclusion of extractable manganese in this complex model as the variable with highest F-value may be considered evidence of the importance of the variation in parent material in relation to the natural availability of extractable phosphorus and manganese in these soils as previously discussed for the correlation analysis.

Another point that seems to be important is the inclusion of texture variables, clay and silt/clay ratio, in this regression model. The highly significant F-values for these two variables suggest that a decrease in silt/clay ratio and an increase in clay content are very important concerning the reduction in available phosphorus in these soils.

One final point in relation to the proposed regression model is that there is not a single variable nor a small group of variables that accounts for a majority of the change in phosphorus in these soils. The high number of variables included suggests greater complexity of phosphorus behavior for these topsoil samples when compared with that of zinc

and magnesium. This is further evidence that more detailed studies and more variables are needed to better quantify available phosphorus in relation to other chemical and physical characteristics.

SUMMARY AND CONCLUSIONS

This study attempts to characterize the natural soil fertility status of topsoils in a vast area of Brazil under "cerrado" vegetation. Chemical determinations, mechanical analyses, and other soil characterizations were studied as relative frequency distributions for 518 samples considered in a survey. The results indicated the following:

1. The soil reaction was highly acidic (pH <5.0) in about 48.3% of the samples and moderately acid (pH = 5.0 to 5.9) in 50.2%. Only eight out of 518 samples had a pH above 6.0.

2. The ΔpH (pH in KCl -pH in H_2O) was negative for all samples except one. A majority of the samples (61.8%) had ΔpH values of -0.6 to -1.0.

3. The vast majority of these topsoils (95.6%) had less than 1.5 meq Ca^{++}/100 cc of soil, a level considered low for exchangeable calcium.

4. Most (89.8%) of the topsoil samples had exchangeable magnesium levels below 0.5 meq Mg^{++}/100 cc. This range is below the critical level for this nutrient.

5. Considering 0.15 meq K^{+}/100 cc as the critical level for this nutrient, 84.9% of the samples had low values for exchangeable potassium.

6. Most of the values for exchangeable acidity (76.3%) were from 0.25 to 1.0 meq Al^{+++}/100 cc, a level considered as medium. Nevertheless, since the amount of bases in these soils is extremely low, the percent Al^{+++} saturation reached values of 20.0% or more in the vast majority of the samples (91.0%). Most (78.6%) of these topsoils had more than 40.0% Al^{+++} saturation, which would be toxic for most crops.

7. The vast majority of the samples (84.0%) had effective CEC values of less than 2.0 meq/100 cc. These extremely low values reflect the highly advanced weathering stage of these soils and the ineffective influence of organic matter at the ambient low level pH values.

8. Extremely low natural availability of extractable phosphorus seems to be one of the most critical characteristics of these soils, since 92.1% of the samples had less than 2 ppm. That is one-fifth of the suggested critical level for extractable phosphorus normally used in these regions (10 ppm P).

9. In spite of their being medium to well supplied with organic matter (60.4% of the samples between 1.5 to 3.0% organic matter), the net negative charge of these soils, as reflected by the effective CEC, seems to be extremely low. Therefore, the ability for cation adsorption is low.

10. In regard to the natural availability of micronutrients, zinc deficiency represents the primary problem, since 94.8% of the samples were below the suggested critical level of 1 ppm zinc in the soil when using North Carolina extracting solution. This substantiates reports from greenhouse and field experiments.

11. Levels for extractable copper were observed below the suggested critical level of 1 ppm copper in 70.3% of the samples. However, no consistent data about copper fertilizer response have been obtained in these soils and the critical level may be subject to question.

12. There are no previous studies regarding manganese and iron critical level evaluation in these soils. Nevertheless, the natural availability of these micronutrients seems to be high according to levels used in other countries.

13. Extreme variation in the textural components was observed especially for the sand and clay fractions. It was observed that 90% of the samples were in the range from 20 to 60% sand, 93.4% had less than 30% silt, and 89.8% were in the range from 15 to 60% clay.

14. The frequency distribution for the color components (hue, value, and chroma) showed that hue ranged widely from 2.5YR up to 10YR. No sample was included in 2.5Y and 5Y hue. In relation to value, 78% of the samples were included in classes 3 and 4. A good indication of how well drained these soils are is the fact that 86.3% were included in classes 4 and 6 for chroma.

15. A total corresponding to 49.2% of the samples were from cerrado and 28.6% were from campo cerrado vegetation areas. Campo limpo, cerradão, and forest vegetation areas accounted for 10.4, 8.7, and 3.1% of the samples, respectively.

The following observations were made in relation to the correlation and regression analyses:

1. The change in vegetation from campo limpo up to forest vegetation was related to increase in levels of Zn, Mg, Mn, Ca, P, K, Cu, and organic matter. The amount of vegetation was also positively related to effective CEC, pH, and chroma.

2. An inverse relationship was observed between the independent variables percent Al saturation, ΔpH, Fe, hue, value, silt/clay, and silt and the density and height of vegetation.

3. Percent of clay did not correlate with vegetation, but organic matter content and effective CEC were positively related to vegetative development. Also, the observation was made that effective CEC did not

correlate with clay content but it did with organic matter level. These factors indicate the low activity of the clay fraction in these soils concerning cation adsorption.

4. A regression model including 12 variables was calculated to predict quantitative changes in vegetation. It could explain only 37% of the variation, which may limit its application, and suggests that other variables not included in this study (for example: S, N, B, Mo, availability of water, etc.) can be very important to improve the prediction equation. Nevertheless, the inclusion of the variables silt/clay, P, Zn, and Mg with extremely high F-values, especially for the first three, seems to be strong evidence of the importance of these variables in relation to a change in type of vegetation.

5. There is a direct relationship between zinc, magnesium and phosphorus as dependent variables and most of the chemical variables involved except for Al saturation (%) and Fe (ppm). The latter two gave an inverse relationship in correlation studies for all three dependent variables. Also, a significant inverse relationship was observed between exchangeable acidity and magnesium.

6. Since percent Al saturation was inversely related to zinc, magnesium and phosphorus levels, and since the absolute value of exchangeable acidity was only slightly significant in relation to magnesium and not significant in relation to phosphorus and zinc, the relative proportion of aluminum in the soil complex is more important than the absolute value of exchangeable acidity.

7. A negative simple correlation coefficient between clay content and the dependent variable phosphorus is strong evidence of a decrease

in P availability upon increasing clay content in these soils. This is probably related to more phosphorus fixation when there is an increase in surface area. It was also shown that the clay fraction is very ineffective in relation to adsorption of cations.

8. The inverse relationship between hue and zinc, magnesium and phosphorus levels suggests that redder soils are more fertile than the red-yellow and yellow soils.

9. Organic matter content seems to be an extremely important chemical characteristic in these soils. It is probably the main active source of negative charges and its level is highly correlated, not only with these three nutrients, but also with all others, including copper and manganese.

10. The regression equation for zinc as dependent variable showed that effective CEC, organic matter, Mn, and pH are the main chemical characteristics of importance when estimating the quantity of zinc in these soils. Nevertheless, the regression model including these variables plus Mg and a quadratic term for organic matter only explained 47% of the variation in the availability of zinc.

11. A quantitative estimation of magnesium can be obtained almost perfectly ($R^2 = 0.983$) by a regression model that included effective CEC, Ca, percent Al saturation and an interaction (effective CEC x percent Al saturation). Effective CEC was the variable that explained most of the variation in magnesium.

12. In comparison with zinc and magnesium, factors related to the availability of phosphorus are extremely complex in these soils. To obtain a $R^2 = 0.581$, no less than 13 independent variables were included

in a regression model, showing that there is no single or small group of variables that can be used in predicting the natural availability of extractable phosphorus in these soils.

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APPENDIX

Appendix Table 1. Simple correlation coefficients for interproperty relationships, "cerrado" soils[a]

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11
X2	.339										
X3	.333	.493									
X4	-.318	-.128	-.146								
X5	-.314	-.163	-.204	.835							
X6	.299	.492	.568	-.336	-.366						
X7	.298	.533	.876	-.072	-.109	.480					
X8	-.273	-.391	-.765	.102	.190	-.496	-.533				
X9	.273	.524	.839	-.054	-.140	.459	.905	-.677			
X10	.270	.395	.696	-.093	-.193	.466	.572	-.776	.696		
X11	.252	.353	.485	-.120	-.153	.455	.498	-.328	.518	.438	
X12	.218	.453	.759	-.094	-.075	.518	.738	-.548	.633	.446	.312
X13	-.203	-.169	-.459	.008	-.012	-.263	-.430	.345	-.331	-.688	-.287
X14	.163	.293	.167	-.301	-.320	.530	.086	-.236	.081	.123	.253
X15	.158	.364	.473	-.119	-.277	.362	.334	-.702	.607	.650	.300
X16	-.135	.186	.104	.062	.130	.271	.106	-.134	.161	.159	.280
X17	-.129	.250	.093	-.035	.054	.193	.176	.031	.086	-.177	.054
X18	.127	-.043	-.097	-.527	-.274	.041	-.107	.110	-.130	-.206	-.219
X19	-.117	-.147	-.460	.228	.208	-.346	-.354	.494	.444	-.472	-.231
X20	.104	.404	.211	-.105	-.192	.167	.168	-.179	.208	.026	.155
X21	.084	.194	.176	-.123	-.259	.139	.066	-.331	.158	.464	.152
X22	.068	-.170	-.004	.080	.044	-.041	-.125	-.174	.025	.404	.130
X23	.038	-.008	.070	-.293	-.246	.159	.125	.171	.032	-.071	.129
X24	-.021	.097	-.044	-.089	-.090	-.046	.075	.221	-.080	-.452	-.205
X25	-.011	-.022	-.139	.039	.144	-.113	.171	.546	-.221	-.401	-.071

[a] $P = 0.0001$, $r \geq 0.180$; $P = 0.001$, $r \geq 0.143$; $P = 0.01$, $r \geq 0.113$; $P = 0.05$, $r \geq 0.086$; Not significant, $r < 0.086$.

X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22	X23	X24
-.350												
.142	.109											
.244	.105	.283										
.084	.042	.432	.261									
.260	.296	.304	.068	.559								
.005	.185	.119	-.089	.016	.260							
-.227	.232	-.124	-.403	-.153	-.093	-.121						
.187	.374	.293	.427	.218	.445	.013	.083					
-.051	-.309	.021	.312	-.009	-.300	-.314	-.204	-.044				
-.251	-.433	-.153	.100	-.031	-.775	-.267	-.095	-.483	.432			
.151	-.044	.193	-.144	-.170	-.009	.041	.152	.078	-.299	-.148		
.200	.427	.044	-.173	-.262	.511	.219	.180	.414	-.423	-.939	.207	
.015	-.115	-.078	-.669	-.115	.193	.032	.285	-.139	-.249	-.100	.196	.355

Legend

X1	Vegetation	X14	Extr. copper
X2	Extr. zinc	X15	pH KCl
X3	Extr. magnesium	X16	Silt/clay ratio
X4	Hue	X17	Silt
X5	Value	X18	Chroma
X6	Extr. manganese	X19	Extr. iron
X7	Effective CEC	X20	Organic matter
X8	Aluminum satur.	X21	Longitude
X9	Extr. calcium	X22	Sand
X10	pH H_2O	X23	Latitude
X11	Extr. phosphorus	X24	Clay
X12	Extr. potassium	X25	Exchangeable Al
X13	Delta pH		

Appendix Table 2. Basic analysis of variance table, regression coefficients and statistics of fit for the dependent variable vegetation[a]

Source	df	Sum of squares	F-value	R^2	CV (%)
Regression	8	121.2388	26.61****	0.295	28.4
Deviations	509	289.9059			
Total	517	411.1447			

Source	Regression coefficient (b)	Partial sum of squares	Standard error of b	F-value
Intercept	1.4532			
Silt/clay	-0.7811	22.0832	0.1254	38.77****
Zn	1.1797	17.4373	0.2132	30.61****
Sand	0.0062	8.0543	0.0016	14.14***
Mg	0.4647	5.7124	0.1467	10.03**
Chroma	0.1051	4.8828	0.0359	8.57**
P	0.0828	4.6825	0.0289	8.22**
Hue	-0.0438	4.0900	0.1254	7.18**
Cu	0.1118	3.6248	0.0443	6.36*

[a]*Exceeds tabular F at significance level of 5%; **exceeds tabular F at significance level of 1%; ***exceeds tabular F at significance level of 0.1% and ****exceeds tabular F at significance level of 0.01%.

Appendix Table 3. Basic analysis of variance table, regression coefficients and statistics of fit for the dependent variable extractable zinc[a]

Source	df	Sum of squares	F-value	R^2	CV (%)
Regression	5	8.5948	88.36****	0.463	21.4
Deviations	512	9.9608			
Total	517	18.5556			

Source	Regression coefficient (b)	Partial sum of squares	Standard error of b	F-value
Intercept	-0.2118			
Organic matter	0.0705	1.8670	0.0072	95.97****
Eff. CEC	0.0959	1.0881	0.0128	55.93****
Mn	0.0034	0.9980	0.0005	51.30****
pH	0.1114	0.2758	0.0296	14.18***
Mg	-0.2033	0.2723	0.0543	13.99***

[a]***Exceeds tabular F at significance level of 0.1% and ****exceeds tabular F at significance level of 0.01%.

Appendix Table 4. Basic analysis of variance table, regression coefficients and statistics of fit for the dependent variable exchangeable magnesium[a]

Source	df	Sum of squares	F-value	R^2	CV (%)
Regression	3	37.4819	1587.01****	0.903	45.0
Deviations	514	4.0465			
Total	517	41.5284			

Source	Regression coefficient (b)	Partial sum of squares	Standard error of b	F-value
Intercept	0.2726			
Eff. CEC	0.2459	5.2944	0.0095	672.51****
% Al sat.	-0.0068	5.1076	0.0003	648.78****
Ca	-0.1134	0.4200	0.0155	53.35****

[a]****Exceeds tabular F at significance level of 0.01%.

Appendix Table 5. Basic analysis of variance table, regression coefficients and statistics of fit for the dependent variable extractable phosphorus[a]

Source	df	Sum of squares	F-value	R^2	CV (%)
Regression	7	477.8772	56.05****	0.434	124.7
Deviations	510	621.1792			
Total	517	1099.0564			

Source	Regression coefficient (b)	Partial sum of squares	Standard error of b	F-value
Intercept	1.5799			
Ca	0.9627	119.8916	0.0970	98.43****
Chroma	-0.3272	52.5731	0.0498	43.16****
Mn	0.0218	37.5731	0.0040	30.45****
Hue	-0.1073	25.7412	0.0233	21.13****
% Al sat.	0.0143	21.1468	0.0034	17.36***
Silt/clay	0.7115	20.9144	0.1717	17.17***
Clay	-0.0108	12.9834	0.0033	10.66**

[a]**Exceeds tabular F at significance level of 1%; ***exceeds tabular F at significance level of 0.1% and ****exceeds tabular F at significance level of 0.01%.