DISTRIBUTION OF NATIVE PHOSPHORUS AND PHOSPHORUS SORPTION CAPACITY OF SOME TROPICAL SOILS OF COLOMBIA, S. A.

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INTRODUCTION

The most important sector of the Colombian economy is its agriculture. It is important in a double sense: (a) More than two-thirds of the people live in rural areas devoted to agriculture activities, and (b) agricultural products support international trade and finances, import of many manufactured products, and equipment needed by the expanding economy of the country. However, only 2.9 million hectares (2.6% of the Colombian territory) are under cultivation; about 28.6 million hectares (23.6% of the territory) are under natural pastures and are used in extensive livestock exploitation of the land.

The "Llanos Orientales" (Eastern Plains), which lie east of the Eastern Cordillera, represent more than 60% of Colombia's total land surface. They are sparsely settled and their contribution to the Colombian economy is negligible. Most of the area is devoted to extensive grazing and only a very small area to crop farming. The Eastern Plains appear to be suited for development of an extensive crop and livestock agriculture, because they cover an immense surface area.

The Colombian government has considered it a matter of great importance to study and survey the Eastern Plains, in order to diagnose the real potentiality of natural resources there. As a consequence, the Ministry of Agriculture, with the technical assistance of the United Nations, is accomplishing an "interim survey" of the natural resources, of the northern portion of the plains. Such a survey includes the evaluation of soils, native vegetation, climate, surface and ground waters, and geology.

The program of soils study includes mapping, classification and evaluation by land capability classes, of the soil resources. As much information as possible on the chemical and physical properties of the soils and the diagnosis of the fertility status by means of laboratory, greenhouse and field experiments are being conducted.

A few preliminary works on survey and soil fertility have been made in some restricted areas. The studies indicate that these soils have a good physical condition (good drainage, moisture retention and friability), they are strongly leached, extremely acid, very low in base saturation, therefore, there is a cation and micronutrient deficiency problem. The same data suggest, however that the problems dealing with a deficiency of soil phosphorus, nitrogen and sulfur are more acute than cation deficiencies, and that the major problem is the critical deficiency of available phosphorus.

In fact, all soil test values for available phosphorus are low to very low; all greenhouse experiments carried out give response to the application of even small amounts of available phosphorus (81)[1] and the fertilizer trials with rice[2] have established that phosphorus is the most serious plant nutrient deficiency.

In order to gain a sound understanding of the phosphorus problem in these soils it was thought that a knowledge of the amount and chemical status of the native phosphorus in the whole soil profile and the phosphorus sorption capacity are part of the background data needed for

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[1] Numbers in parenthesis refer to literature cited.

[2] Personal communication of L. A. Gonzalez, Rice Institute Agronomist. Colombian Ministry of Agriculture.

further studies in soil-phosphorus-plant nutrition problems.

It is necessary to know if the deficiency of phosphorus is due to a deficiency in the phosphorus reservoir (a capacity factor) or to a low availability (intensity factor). It was believed to be imperative to learn about the reserve of phosphorus in the subsoil and in the deeper soil horizons and about the ratio of inorganic: organic forms and active forms: inactive forms of phosphorus.

The fractionation of soil phosphorus in specific chemical forms is very helpful in the study of the orgin and development of soils and in the studies of soil chemistry as such.

This report attempts to furnish some information about:

(a) The general physical and chemical characteristics of some representative soil profiles of the Eastern plains of Colombia and as a contrast of one profile of a Regosol associated with Reddish Prairie soil of Oklahoma.

(b) The total phosphorus content and the quantities of the following discrete fractions: calcium phosphate, aluminum phosphate, iron phosphate, "reductant-soluble-iron phosphate," "occluded-aluminum phosphate" and organic phosphorus, in each soil horizon.

(c) The phosphorus sorption capacity and the distribution of the phosphorus in the phosphate-saturated soils.

(d) The effect of lime and silicate treatments upon the "available phosphorus" and upon the phosphorus sorption capacity.

It is hoped that the results will be helpful in understanding the soil chemistry, fertility and pedology of some of the Eastern Plains soils of Colombia, South America.

REVIEW OF THE LITERATURE

Previous Works in the Eastern Plains

In the Eastern Plains of Colombia only preliminary and restricted studies have been made.

Goosen (38) made a reconnaissance soil survey. He established several soil series and evaluated them in land capability classes. No chemical data were reported.

In 1959, the Soil Survey Department of Colombia published a reconnaisance survey (81) which covered about 400,000 hectares. Several soil series and associations were described and mechanical and chemical analysis for many profiles were reported. Some of their findings were as follows: Many soils have good physical condition, but their fertility status is very low as revealed by chemical analysis and greenhouse assays. Soil reaction (pH) ranges from extreme to strong acidity. Cation exchange capacity is around 8 to 10 m.e./100 g. and percent base saturation is quite low, and ranges from 7 to 15%.

Available phosphorus is critically low. Phosphate and basic slag applications greatly increase yield, under greenhouse conditions five to ten times over the check treatment. The only figures for "available" phosphorus (acid soluble phosphorus) distribution in the soil profiles are based on the Truog method. In the majority of the profiles the acid soluble phosphorus decreases with depth, being about 20 Kg./hectare in the surface soil and 5 to 15 in the subsoil. There are some exceptions in which the reverse condition is true, however.

Methods of Phosphorus Fractionation

Until recently little work has been done on the distribution of various discrete chemical forms of phosphorus in soils, mainly because adequate methods of fractionation were not known.

Various methods have been developed to separate different forms of phosphorus in soils. For example, Dean (26) attempted to fractionate soil phosphorus into several forms: (a) Organic phosphorus, soluble in NaOH; (b) Inorganic phosphorus (iron and aluminum and calcium phosphates) soluble in NaOH followed by an acid extraction; and (c) Insoluble compounds. Ghani (35) tried to separate the following five soil phosphorus fractions: (a) Mono, di and tri-calcium phosphate, soluble in acetic acid; (b) Iron and aluminum-phosphates, soluble in alkali solution; (c) Organic phosphorus soluble in ammonia; (d) Apatite, soluble in sulfuric acid; and (e) Insoluble-phosphorus, considered by the author as an integral part of the clay complex. Bray and Kurtz (13) presented a method for fractionation of soil phosphorus. They attempted to distinguish (a) "adsorbed phosphorus" which is soluble in a 0.03N NH_4F in a 0.025 n HCl solution; (b) Acid soluble plus adsorbed phosphorus, soluble in 0.03N NH_4F + 0.1N HCl solution; (c) Total adsorbed phosphorus, soluble in 0.5N NH_4F;(d) Organic phosphorus determined by oxidation of organic matter with hydrogen peroxide. Chiricov and Volkova (19) distinguish five fractions of the soil phosphorus: (a) Group of compounds soluble in a CO_2 saturated water, consisting of alkali phosphates; di-phosphates of calcium and magnesium, trimagnesium phosphate and some phosphorites; (b) Group of compounds soluble in 0.5N acetic acid, which includes some apatite, phosphorite; salts of alcohol-phosphoric acids and sugar phosphoric acids;

(c) Group of compounds soluble in 0.5N HCl, which includes apatite, aluminum phosphate; iron phosphate, some of the more basic phosphates of iron and phytin; (d) A fraction soluble in 0.2N NaOH, which includes nucleins, nucleoproteins, compounds of humic acid; (e) insoluble phosphorus compounds, which are not dissolved in any of these extractants and may consist of titanium phosphate and phosphorus compounds of unweathered minerals. The groups are ranked in a decreasing order of availability to plants. Williams (102) published a method for phosphorus fractionation. He distinguished: (a) phosphorus soluble in 2.5% acetic acid with 1% 8-hydroxyquinoline; this fraction includes water soluble phosphorus, mono, di and tricalcium phosphates; hydroxy and carbonate apatite, magnesium and manganese phosphate and to some extent chloro and fluoroapatites; (b) phosphorus compounds soluble in 0.1 N NaOH, which include adsorbed phosphate, basic iron and aluminum phosphates, titanium phosphate and some organic phosphorus; (c) this group included phosphorus insoluble in the other extractants and may consist of chloro and fluoro-apatites, crystal lattice phosphate; very resistant phosphate minerals such as turquoise, monazite, amblygonite. This procedure has been modified by Bertheux (9) for routine fractionation studies in West Africa.

Bhangoo and Smith (10) studied the distribution of phosphorus of virgin soil in Kansas, and partitioned phosphorus into: (a) 0.1 N HCl soluble phosphorus fraction (calcium phosphate); (b) cold alkali soluble phosphorus after removal of acid soluble (adsorbed phosphorus); (c) hot alkali soluble phosphorus, after removal of (a) and (b), and includes iron and aluminum phosphate, and (d) Organic phosphorus. Other methods and many modifications of the procedures reviewed have been employed by many workers. Chemical fractionation has mainly involved extraction of soils with acid and alkali solutions and various complexing agents.

More recently Chang and Jackson (17) developed a systematic method for the fractionation of inorganic phosphorus in the soil. They state that inorganic phosphorus in the soil can be classified into four main groups: (a) calcium phosphate formed mainly from apatite, and small amounts of dicalcium, monocalcium and octocalcium phosphates or as transitional forms, (b) aluminum phosphate, (c) iron phosphate, and (d) reductant soluble phosphate (extractable after removal of the first three forms). Iron, aluminum and calcium phosphates also include adsorbed and surface precipitated phosphates.

The Chang and Jackson Procedure differentiate between calcium phosphate, aluminum phosphate, iron phosphate, and reductant soluble phosphate. The extraction procedure is sequential in order to obtain the complete separation of the different chemical forms of phosphorus. The method is based on the selective solubility of different phosphates in various extractants. Ammonium fluoride dissolves the aluminum phosphate and a small amount of iron phosphate. After extraction of aluminum phosphate a treatment with sodium hydroxide completely dissolves iron phosphate but not the calcium phosphate. The residual sample is extracted with sulfuric acid to dissolve the apatite and other forms of calcium phosphate. Finally after the extraction of the three forms, the "reductant-soluble iron phosphate" is dissolved by reducing the ferric iron and chelating it by a citrate-dithionite treatment. After the reduction-chelation of soil, the occluded aluminum phosphate is usually extracted with ammonium flouride. This method is an important contribution to Soil Science. It permits a complete fractionation and chemical characterization of soil phosphorus which is very helpful in studies of soil fertility because the chemical properties and especially solubility of each form of soil phosphorus is a factor in determining the total availability of this element to plants. The distribution and nature of phosphorus in the soil profile is important in pedological studies, since the presence and abundance of different phosphorus compounds are governed by the mineralogical character of the parent material, topography, drainage conditions, degree of acidity, age, and stage of weathering. Chang and Jackson (18) stated that inorganic forms of soil phosphorus provide a tool for quantitative measurement of soil chemical weathering. Changes in the soil occur as a function of soil depth, physical and chemical weathering factors, and these changes are more sensitive than those shown by the mineral colloid weathering sequence proposed by Jackson (18).

Chang and Jackson's method for fractionation of soil phosphorus has been widely used in the last few years, in the fields of chemistry, fertility and soil genesis. For example Cho and Caldwell (20) used the method in studies of phosphorus fixation. Fiskell and Rowland (31) used it for chemical studies of soil of Florida. Hsu and Jackson (47) fractionated the soil phosphorus in studies of transformation of phosphorus as influenced by pH. Khanna and Bray (58) used the method in characterizing the phosphorus of Illinois soils. Wright and Peech (108) studied the phosphate reaction products using the procedure. Yuan et al. (111) studied fixation of phosphorus by sandy soils of Florida. Chang and Chu (15) followed the fate of phosphorus applied to various soils of Taiwan, by the fractionation procedure. Pratt (75) used the fractionation method in studies of phosphorus-aluminum interaction. Mackenzie (66) fractionated the phosphorus of several soils of Canada and related his result to pH and other characteristics. Weir and Soper (100) studied adsorption and exchange of phosphorus of Manitoba's soils using the Chang and Jackson procedure.

The Chang and Jackson procedure has been applied to many fertility and phosphorus availability studies. Chang (14) investigated phosphorus availabliity and distribution in paddy soils; Hamilton and Lessard (40) determined the soil phosphorus fractions in relation to oat and clover nutrition. Mack and Barber (65) studied the effect of temperature on release of phosphorus from the several soil phosphorus fractions. Robertson and Hutton (78) studied the retention of fertilizer elements and the effect of cropping on the forms of phosphorus in soils. Laverty and McLean (63) were interested in the phosphorus uptake by different plants and its relation to the phosphorus fractions. Volk and McLean (95) studied availability of phosphorus and the products formed after application of phosphates. Bouma (12) fractioned soil phosphorus in studies of fertility for citrus, and he found that a great portion of the phosphorus in the soil studied was present as aluminum phosphate. Onken and Reed (71) studied the fate and availability of superphosphate and rock phosphate and the effect of various applications of lime. Suzuki et al. (92) determined the correlation between the phosphorus fractions and available phosphorus as measured by different extractants.

Some applications of the Chang and Jackson procedure in soil genesis problems are found in the literature. Chang and Jackson (18) investigated the chemistry and weathering stage of various Great Soil Groups (Chernozem, Brown, Gray Grown Podsolic, Latasol). Chu and Chang (22) studied the forms of phosphorus in Latosols, Alluvial soils and other soil groups. Hawkins and Kunze (43) measured the degree of weathering of some Grumosols by fractionation of inorganic phosphorus.

Some criticisms of the method of fractionation have arisen, mainly about the specificity or selectivity of the extractants to separate chemically descrete forms of phosphorus. Fife (28, 29, 30) evaluated ammonium fluoride as a selective extractant for soil aluminum phosphate. In order to obviate the problems of partial resorption of the phosphate liberated from aluminum phosphate, by free iron and to avoid release of iron phosphate and as a consequence to obtain a better selective delineation of aluminum phosphate he proposed the use of a pH 8.5 ammonium fluoride and 16 hours as an extraction period. Liaw, quoted by Chang and Chu (15), on the other hand has shown that, for soils of Taiwan, the pH of the ammonium fluoride solution in the range of 7.0-8.5 does not affect the amount of phosphorus extracted and the extension of the extraction period from one hour to 16 hours caused an increased dissolution of iron phosphate. Hsu et al. (48) reported complete dissolution of aluminum phosphate in 0.5N NH_4F in one hour over a wide range of pH, and the amounts of iron phosphate dissolved increased with time of extraction, indicating the undesirability of an extraction time in excess of one hour. These authors showed that an effective separation of aluminum phosphate from iron phosphate is obtained by extracting the soils with a pH 8.5 one-half normal NH_4F for one hour.

Khin and Leeper (59) proposed a modification of the original method of Chang and Jackson, consisting of an increase in the pH of the ammonium fluoride solution. Glenn, et al. (36) have suggested some improvements in the procedure. The proposed modifications include the extraction of aluminum-bonded phosphate with 0.5N NH_4F of pH 8.0 to 8.5 instead of pH 7.0, in order to minimize the extraction of iron phosphate, and extraction of iron phosphate with 0.1N NaOH for 9 hours instead of 17 hours. They also proposed extraction of the reductant-soluble iron-phosphate and the occluded aluminum phosphate, after the iron phosphate extraction but before the calcium phosphate solubilization. In the proposed modification the calcium phosphate is then finally extracted. The change in the sequence of extraction is based on the findings that 0.5N H_2SO_4 dissolves appreciable amounts of occluded iron and aluminum phosphates, and at the same time the dithionite-citrate treatment dissolves negligible quantities of calcium phosphate.

Distribution of Phosphorus in the Soil Profile

Many workers have fractioned the active phosphorus of surface soils and of whole profiles. The fractionation of phosphorus in soils and profiles has been studied mainly in the soils of the United States and other temperate zone soils. (2, 3, 7, 10, 37, 40, 64, 74, 90, 102, 103, 104, 106).

A few studies have been made in tropical countries. Dean (26) fractionated the phosphorus of several tropical soils of Africa and Hawaii. Almost 50% of the total phosphorus was found to be "insoluble phosphate," 5% was inorganic acid soluble, 25% organic alkali-soluble, and 20% inorganic alkali-soluble phosphorus.

Paul (73) fractionated some tropical soils of British Guiana, using Dean's procedure and he reported that these soils contained higher amounts of inorganic alkali soluble phosphorus (aluminum and iron phosphates) than inorganic-acid-soluble forms (calcium phosphate). The organic alkali soluble fraction accounted for more than 1/3 of the total phosphorus and the inert or insoluble fraction contained 36-38% of the total phosphorus.

Valente-Almeida and Brochardo (94) fractionated the soil phosphorus of several Ferralitic (tropical) soils of Angola, following the Williams procedure. They reported a similar situation to that noted by Paul (73); that is, a very low total phosphate content, and in addition a noticeable decrease with depth. Iron and aluminum phosphates constituted 7 to 34% of total phosphorus and they decreased with depth in the profile. The organic phosphorus fraction was high and reached values above 50% of the total phosphorus in the topsoil and decreased very rapidly with depth. The phosphorus dissolved by HCl (apatite) was negligible. However, the "insoluble phosphorus," measured after extraction for iron, aluminum, organic, and apatite extractions varied from 20 to 80%. These authors also studied some calcareous soils, and concluded that weathered soils have high values for iron and aluminum phosphate and organic phosphorus and were very low for calcium phosphate. On the other hand unweathered soils have a high proportion of phosphorus in the form of apatite. Ayres and Hagihara (4) studied the distribution of phosphorus in Latosols of Hawaii. They found that more than 1/3 of the phosphorus exists in organic combination. The level of phosphorus is at a maximum in the surface layer, as a result of the deposition of organic matter. Supply of available phosphorus appeared to be largely a function of degree of weathering in most tropical soils. Soils with high available phosphorus were young soils formed under moderate rainfall or were soils formed under impeded drainage. Soils low in available phosphorus were highly weathered and developed under good drainage conditions. Phosphorus content of the soil below the surface 12 inches remained extremely low in profiles of Low Humic, Humic, Hydrohumic Latosols. All of these soils demonstrated tremendous capacities for retaining applied phosphorus.

Nye and Bertheux (70) studied the distribution of phosphorus in forest and savanna soils of Ghana. They used the method of extraction of Williams,

(102) which, as noted before, is a sequential fractionation of phosphorus into acetic acid soluble, sodium hydroxide soluble, organic phosphorus, and residual phosphorus fractions. Total phosphorus was also determined by the perchloric acid digestion method. The total phosphorus of the Ghana soils was found to be low by comparison with other parts of the world; low values were attributed to some extent to a low phosphorus content in the parent rocks, but it appears more likely that this is due to their great age and the intense weathering to which they have been subjected. The forest soils contained more inorganic as well as more organic phosphorus than the savanna soils, in spite of the more intense leaching and deeper weathering of the forest soils. The preservation of the phosphorus in surface horizons of the tropical forest soils, is believed by Nye and Bertheux (70), to be due to the effect of dense forest vegetation. They believe the forest is more efficient than the savanna cover in maintaining phosphorus in circulation and thereby concentrating soluble phosphorus in the top soil. The phosphorus fractions of tropical soils were distributed similarly to that of acid soils in other parts of the world, so they concluded that there does not appear to be any special tropical peculiarity associated with the distribution of phosphorus in soil.

The mean distribution of phosphorus in 21 forest soils as reported by Nye and Bertheux (70), indicates that only 3% of the phosphorus was soluble in acetic acid (calcium phosphate); about 11% was alkali-soluble (aluminum and iron phosphate); more than 30% of the phosphorus was in the organic form and more than 56% was found to be present as insoluble or residual phosphorus (70). A similar pattern was found for the mean distribution of phosphorus in savanna soils: 4.5% of phosphorus was extracted by acetic acid; 11% extracted by sodium hydroxide; 20% was in organic combinations, and 64.5% was insoluble or residual phosphorus. The organic phosphorus was closely correlated with the organic carbon. The C/P ratio averaged 233 for forest and 247 for savanna soils. The N/P ratio averaged 21.6 for forest and 19.5 for savanna soils. These data are for surface soils. Nye and Bertheux (70) also studied the phosphorus distribution in several weathered and unweathered soil profiles. In the leached forest and savanna profiles there was evidence that the total phosphorus is greatest in the surface horizons and decreases with depth. In marked contrast to the leached profiles, the incompletely weathered profiles were distinguished by an accumulation of total phosphorus at depth. Acid soluble phosphorus both in forest and savanna soil declined rapidly to trace values below one foot depth. Both in the forest and savanna soils the inorganic alkali-soluble fraction decreased much more slowly with depth than the acid soluble fraction. The proportion of the total phosphorus in the insoluble form tended to increase with depth, corresponding to declining proportions of the acid and alkali soluble inorganic and organic phosphorus. Nye and Bertheaux (70) are of opinion that in the leached soils the insoluble phosphorus portion is in some form intimately associated with the clay mineral lattice. Organic phosphorus decreased with depth, but it declined more slowly than could be expected from the decrease in organic matter. The C/P ratio and C/N ratio decreases in the subsoil. In the surface horizon most of the inorganic phosphorus was associated with the clay fraction, though in sandy soils some phosphorus was found in the iron oxide coatings of sand grains. In the subsoil much phosphorus was associated with concretionary iron oxide gravels or pans that were present. These investigations conclude that the subsoil plays only a small part in the restoration of the available phosphorus level in the topsoil for short-term resting fallows of a few years, but is likely to be significant in long-term fallows (70).

Walker and Adams (96) reported on the distribution of the total inorganic and organic phosphorus fractions of 20 grassland soils of New Zealand. They found that the total and organic phosphorus content declined with the depth. The total phosphorus content of the soils was closely related to the phosphorus content of the parent materials and the organic phosphorus was on the average a very large fraction of the total phosphorus (74% in the 0-7 inch horizon). The carbon, nitrogen and sulfur contents were closely related to organic phosphorus. The average C:N:S: organic P = 120:10:1.3:2.7.

The same authors (97) examined the effect of more advanced weathering stages on the total and organic phosphorus content of soils formed on similar parent materials. They found a significant drop in total phosphorus with increased mineral weathering and a gradual conversion of inorganic phosphorus to organic phosphorus in the weakly weathered sequence.

Bates and Baker (6) worked on the distribution of phosphorus in a forest soil of Nigeria. Much of the phosphorus of the soil had accumulated in the surface soil. Below two inches they noted a marked decrease in total phosphorus, reflecting a large decrease in organic phosphorus. The 2 -7 inch layer contained the lowest amount of total phosphorus in the profile. They suggest that this may be due in part to removal of phosphorus by vegetation, but also to the fact that it is near the approximate lower limit of worm activity. The concentration of phosphorus was considerably higher in iron concretions than in the surrounding soil. Only the surface soil contained appreciable amounts of phosphorus soluble in acetic acid, Truog reagent, and in ammonium fluoride. Below two inches the amount of phosphorus soluble in these reagents decreased sharply. Considerable amounts of phosphorus were extracted from all soil horizons by 0.1N NaOH, of the Nigerian forest soils. The clay fraction of the topsoil contained large amounts of phosphorus soluble in NaOH.

Chang and Jackson (17, 18) in their studies of soil phosphorus fractionation included two highly weathered Latosols: Wahiawa a Low Humic Latosol from Hawaii and Catalina, a Latosol from Puerto Rico. In both soils only a very small amount of the phosphorus was present as calcium and aluminum phosphates. Most of the phosphorus was present as iron phosphate, the majority of which was occluded; also a considerable amount of occluded aluminum phosphate was found. In contrast to these tropical soils Barnes, a Cheronozem soil and Rosebud, a Dark Brown soil are very high in calcium phosphate with little iron and aluminum phosphate.

The phosphorus is fairly evenly distributed among the four forms of phosphate in accordance with the degree of weathering and because of this, Chang and Jackson (18) proposed a weathering sequence: calcium phosphate → aluminum phosphate → iron phosphate → occluded aluminum-iron phosphates as a measurement of increasing intensity of chemical weathering.

Chu and Chang (22) reported that Taiwan's Latosol soils, at least 1/3 of the phosphorus in the topsoil and 1/2 in subsoil, is present as occluded phosphorus forms, and that phosphorus in this fraction is fairly available for the flooded rice crop. They also found that iron phosphate is the dominant soil phosphorus fraction.

Chang and Chu in a recent publication (15) reported on the fractionation of phosphorus in Latosols, Alluvial and calcareous soils. In Latosols iron phosphate was the dominant phosphorus compound and the less abundant form was the aluminum phosphate and very low values were registered for calcium phosphate. In the alluvial soils aluminum phosphate was found to be the highest, followed by calcium and iron phosphates. In calcareous soils more than 75% of phosphorus was found to be present as calcium phosphate.

Hesse (46) measured the distribution of phosphorus in a swamp mud soil of Sierre Leone, by the Chang and Jackson procedure. He found that 87% of phosphorus was present in the organic form and the remaining phosphorus was distributed between calcium and iron phosphate, with very small amounts present as aluminum phosphate.

The Sorption of Phosphorus by Soil and Phosphorus Behavior in Soils

Many studies have been conducted on the mechanisms and factors affecting phosphorus retention by soils. The literature on this subject has been summarized by Dean (27), Wild (101), Kurtz (61), and Hemwall (44).

In this report the terminology proposed by Wild is used in order to be consistent:

According to Wild (101): "Phosphorus sorption" or "phosphorus retention" are used to mean the removal of phosphate from solution by soils or by soil constituents. No particular mechanism is implied. Phosphorus adsorption and phosphorus absorption are used to mean the retention of phosphate at a surface, and within a solid phase respectively. Phosphorus fixation is used to describe any change that the phosphorus undergoes in contact with the soil, which reduces the amount that plant roots can absorb. It is understood that the phosphorus is not positionally unavailable to the plant roots."

It is accepted that most of the retaining power of the soil for phosphorus lies in its finer mechanical fractions, especially clay. Retention of phosphorus by soils increases with fineness of grinding. Fine (0.2μ)

kaolinite and montmorillonite sorbed over twice as much phosphorus per gram of clay as the corresponding coarse fractions. Also it is known that the organic matter content of a soil influences the phosphorus sorption (101). The greater the ratio of phosphate to soil the greater is the retention of phosphate. Relationship between phosphate sorption and phosphorus concentration has been shown to fit the Freundlich adsorption isotherm. However, this does not necessarily imply an adsorption process, as precipitation processes also give results which conform to the Freundlich adsorption isotherm. Another factor which influences phosphorus sorption is the time of contact between the soil and the phosphate solution. Since the sorption reactions come to completion very slowly the length of time is important in determining the magnitude of the retention (101). Some investigators (61), however, have reported no difference in the amount of sorbed phosphorus after one hour and after several weeks.

The mechanism of the retention of phosphorus by the soils has been a controversial point. The main theories are isomorphic substitution, adsorption processes, and chemical precipitation.

The isomorphic substitution of phosphorus for silicon in the tetrahedral units of the mineral crystal lattice is not accepted at this time. The adsorption of phosphorus on the surfaces of clay minerals has been proposed by several workers (44, 61). It has been suggested that phosphorus is sorbed by exchange of a phosphate ion for hydroxyl ions. Hemwall (44, 45) has expressed the opinion that the data presented as evidence by the adsorption advocates can be explained on the basis of chemical precipitation and formation of iron and aluminum phosphates.

Kittrick and Jackson (60) proposed a unified theory of phosphorus "fixation." They suggest that the formation and growth of phosphate precipitates of varying composition, depends on the dominate cations of varying reactivity depending on specific surface. The mechanism of chemical-precipitation, which is controlled by the solubility product principle, provides a unified theory of phosphorus "fixation" which explains the whole range of observed facts of reactions of iron, aluminum, and calcium phosphates.

Hemwall (44, 45) reviewed many workers and concluded that phosphorus sorption in acid soils is primarily due to the formation of iron and aluminum compounds. The soil minerals containing iron and aluminum, including the clay minerals, are the sources of the iron and aluminum in soils. The formation of these compounds is governed by the solubility product principle. Under certain conditions the compounds form a precipitate, whereas under other conditions they are sorbed. Regardless whether the compounds are sorbed on the surface of a soil mineral or precipitated, the compounds formed and the mechanism of reaction seem to be essentially the same.

Fried and Shapiro (34) maintain that the two approaches to the study of soil phosphorus, that is, "mineralogical" and "adsorption" are not necessarily incompatible, but that there is a real difference in the utility of the two theories when describing the soil in relation to plant nutrition. They believed that the mineralogical characterization of soil phosphorus reflects the nature of the long term reserve supply of phosphorus in soils. They believe that it does not necessarily determine either intensity or capacity of the phosphorus supply during one season's growth of crops.

Franklin and Reisenauer (33) evaluated the chemical characteristics of soils related to phosphorus sorption and availability. Phosphorus sorption was highly correlated with exchangeable aluminum and citric acid soluble aluminum of the soils, but was not related to the mineralogical type or content of clay. Citric acid soluble aluminum was 160 times more active in phosphorus sorption than was citric acid soluble iron. They also noted that as the intensity of weathering increases the free iron and aluminum oxides, and exchangeable aluminum increase also and consequently the phosphorus sorption capacity is higher. Kanwar (56) reported on the phosphate retention capacity of some Australian soils. Surface soil had nearly two times more retention capacity than the soil of subsurface horizons. The retention of phosphorus was highly correlated with aluminum oxides.

Williams (105) and Williams et al. (107) found that the aluminum extracted by an acid-oxalate solution was highly correlated with phosphorus sorption capacity. After removal of aluminum and iron by the Tamm procedure the sorption capacity was only 10% as much as that of original soil. These authors reported a highly significant relation between phosphorus retention and carbon loss on ignition and between phosphorus retention and organic carbon, suggesting that the active iron and aluminum are closely associated with organic matter.

Rennie and McKercher (77) reported that the organic matter appeared to be equally as important as the inorganic colloids in determining the phosphorus retention capacity of Canadian soils. They reported that two soils with identical amounts of clay but with one having total nitrogen content 45% higher than the other the sorption of phosphorus by this sample was 70% larger than the low nitrogen soil.

Coleman et al. (24) studied phosphorus sorption in relation to exchangeable aluminum. A highly significant correlation was found between retained phosphorus and exchangeable aluminum, (r = 0.838). In some soils the quantities of sorbed phosphorus exceeded the exchangeable aluminum, but in others the exchange aluminum was not as active. Soils low in exchangeable aluminum but high in oxides bound considerable amounts of phosphorus by mechanisms independent of exchangeable aluminum. On the other hand some soils with large amounts of exchangeable aluminum did not bind as much phosphate as would be expected, that is, each mole of aluminum ion could bind a mole of PO_4. Removal of exchangeable aluminum by salt leaching reduced the phosphorus retention capacity. Corey and Scholten (25) studied the mechanism of phosphorus adsorption on surfaces of goethite, gibbsite, and calcite and Hsu (49) studied the sorption of phosphorus by soils. These investigators reached similar conclusions: the sorption of phosphorus by soils involves two reactions of different velocity: (a) the first reaction proceeds rapidly and is believed to be a surface reaction (adsorption) due to the native amorphous aluminum hydroxide in the soil. (b) A much slower reaction is due to the surface activity of amorphous hydroxides or oxides of aluminum and iron, developed during the first reaction process.

It is generally accepted that lime application to soil increases the availability and uptake of phosphorus by plants. Extensive reviews concerning lime application and its effect on soil characteristics and in relation to soil phosphorus chemistry are available (23, 39, 82, 93). Generally, the availability of soil phosphorus to plants appears to increase as the soil is limed to neutral pH. It is believed that the main effect of lime is the decrease of exchangeable aluminum, thereby decreasing the amount of phosphorus sorbed. No direct evidence of the reduction of phosphorus sorption capacity of soils due to application of lime or silicate has been found in any review of the literature. Sillanpaa (85) limed an acid soil, then added soluble phosphates and then extracted with acid-ammonium acetate. He reported that extracted phosphorus was a linear function of the phosphorus added. The increase of phosphorus due to phosphate application was significantly higher in limed than in unlimed samples; but liming did not significantly affect the solubility of the native phosphorus.

Several studies about the effect of silicate application on phosphorus have been made. Russell (79) reports the data of a long term experiment (1864-1900) made at Rothamsted. The application of sodium silicate increased the yield of the barley on soils deficient in phosphate. Russell reports that manuring with silicate was seriously studied in Germany and Japan. He believes that the iron and aluminum phosphates occur in many soils in the form of films, a few molecules thick, and that silicate anions will displace some of the sorbed phosphates from these films, though no implication of any particular mechanism is made. Whether it is due to an anion exchange reaction or to the formation of a silicate complex with the iron and aluminum ions has not been properly investigated. Raupach and Piper (76) examined the effect on the phosphorus economy of the addition of silicates to a Latosol with very high phosphorus sorption capacity. Laboratory studies showed that the phosphorus sorption by the tropical soil they studied was decreased in the presence of silicate. The addition of a silicate solution to the phosphate-treated soil gave a greater release of phosphorus than did the check. However pot experiments, with subterranean clover, have failed to show statistically significant effects of silicate in improving the efficiency of applied phosphate. It may be due to difficulty of obtaining an intimate reaction surface between adsorbed phosphorus and added silicate, and to the rapid inactivation of silicate by reaction with other sexquioxides.

Bauma (12) reported some results of silicate application to soil (1.5 SiO_2 ton/acre) on orange seedlings. Application of silicate alone had a small effect on growth and phosphorus uptake, but a significant response was obtained if superphosphate was also present.

MATERIALS AND METHODS

Soils

The samples for this study were secured from representative sites of terraces and alluvial plains, in the Villavicencio-Arocue area, in the Eastern Plains of Colombia and from the Reddish-Prairie soil province of Oklahoma. Some information about the environment in which the soils of the Eastern Plains have developed is pertinent.

Geomorphology and Parent Material

The Eastern Plains of Colombia consist of a series of broad smooth terraces and floodplains. Terraces are grouped in high, medium and low level terraces. Their surface is smooth, and without prominent microrelief.

Rivers have a West-East direction, and have developed floodplains of 1 to 10 kilometers wide, where alluvial soils are found. The underlying materials, of Miocene-Pliocene age, consist of a very uniform conglomerate layer at the base and a mixture of clayey and silty sands (clayey sandstones) with occasional beds of gravel.

The uppermost strata deposited over the Tertiary materials are of Pleistocene age, and came from the Eastern Cordillera, during the last interglacial age, which caused great erosion and consequent sedimentation.

The Pleistocene sediments were then eroded by the rivers resulting in the formation of the present landscape of broad terraces. The Pleistocene materials constitute the parent materials of the soils; their textures are coarse near the Cordillera and finer and finer as one moves eastward.

The parent materials are quite uniform, even between different terraces, and consist mainly of permeable silty loam and clay loam textured soils having a more sandy character near the surface. Profiles Carimagua I, Carimagua II, and soil series Upin and Guamal are representative of terrace soils and the Guayuriba soil series is a representative of a recent alluvial soil, occurring in the Guayuriba flood plain.

Climate

Climate of the Eastern Plains is warm-humid, with a mean annual temperature of 26°C; and a mean annual rainfall ranging from 6,400 mm. in the Buenavista foothills, 4,000 mm. in Villacercencio, and less than 3,000 mm. in Puerto Lopez. The geographical gradient in rainfall is very noticeable. The dominance of eastern air flow allows more precipitation near the Cordillera and less toward eastern side of the plains. Rainfall of 3,000 mm. per year, as a mean is probably characteristic for the Eastern Plains as a whole, according to scattered records from several points. Monthly precipitation distribution is characterized by a long period of rainfall, between March and the middle of December, followed by a period of severe drought extending from December through March. The mean monthly temperature and mean monthly rainfall for Villavicencio, averaged over a 30 year period are reported in Table I. These data are not quite representative for the whole Eastern Plains, because Villavicencio is located close to the Cordillera.

The temperature is almost constant throughout the year. Fluctuations are about 2.5°C, and the coolest months coincide with the high rainfall periods, while the dry months are the hottest. According to the Koeppen (81) classification this climate may be classified as Am (Monsoon Rain-forest climate) near the Eastern Cordillera, and Aw (Tropical Wet and Dry Climate of Savanna) on the plains.

TABLE I. MEAN MONTHLY TEMPERATURE AND RAINFALL OVER 20 YEARS AT VILLAVICENCIO

	Temperature in °C.	Precipitation in mm.
January	27.0	70
February	26.9	115
March	26.6	210
April	25.8	460
May	25.0	545
June	24.5	465
July	24.4	500
August	25.0	390
September	25.5	380
October	25.3	405
November	25.6	400
December	26.8	160
	Mean: 25.7°C.	Total: 4,120 mm.

Vegetation

The river and stream banks are flanked by stretches of "Gallery Forest" (38). The intervening space between these forested areas, (i.e. the terraces in between), are occupied by "savannas'" consisting of an assortment of bunch grasses with sedges and some leguminous herbs, with scattered trees or groups of trees and palms (81).

The foothills and piedmont are covered by the "Tropical Rain forest." There are many species of grasses of Genera Andropogon, Paspalum, Eragrostis, Aristida, Ctenium. Actually it is thought that the Savanna vegetation is anthropogenic (38). Every year during drought period the herbage is burned. The repeated burning has destroyed the original forest cover.

The "Chaparral tree" (Curatella americana L.) and some palms (Mauritia sp.) which occur throughout the savannas are very fire-resistant and remain alive after several fires; they are the only relics of the primary forest.

The burning practices obviously have also influenced the content of soil organic matter as well as the suite of nutrients in the soil. The burning increases the velocity of the circulating system of the nutrient elements between the surface soil and the subsoil and deeper horizons, allowing a higher concentration of nutrients in the surface soil and probably a decreasing amount of organic matter in the topsoil.

Soils

The description of soil profiles used in this work are given in the Appendix.

Classification of the Soils

There is no definite classification of the tropical soils of Colombia. Hardy (41) classified the Eastern Plain soils as "bleached earths." Lafaurie (62) included these soils in the "Lateritic group." Jenny (53), in 1947 studied many Colombian soils. In a general scheme of classification he included the soils of the Eastern Plains in the "Tropical Yellow-Brown soil group." Later, Schaufelberger (83) classified these soils as Laterite soils. Miller and Coleman (69) studied many equatorial soils in Peru and Ecuador and created the "Red Lixivium" and "Yellow Lixivium" groups in which are included many soils similar to those of the Eastern Plains. "Lixivium" refers to strong leaching and drastic weathering.

According to the system of classification developed by the Soil Survey Staff of the United States Department of Agriculture (88), the soils of the Eastern Plains of Colombia may be classified as "Entisols" that is, recent alluvium that developed into soils such as the "Guayuriba series"; and "Oxisols" for those soils that developed on the terraces; which probably fall into the class "9.41." (Ustox with a dark horizon, *Incertae Sedis*).

Laboratory Procedures

The particle size distribution was determined by the pipette method, according to Kilmer and Alexander as reported by Silva-Mojica (86), using hexameta-phosphate as a dispersant. The pH was determined, by the use of a Beckman Zeromatic pH meter with glass electrode, in suspension of soil: water ratio 1:1 and in a suspension soil: 1N KCl ratio 1:1, after 24 hours equilibration.

Cation exchange capacity was determined by the neutral 1N ammonium acetate, displacing the adsorbed ammonium with magnesium oxide.

Exchangeable sodium and potassium were determined in the ammonium acetate leachates, with a Beckman Du-flame spectrophotometer with a photomultiplier attachment, and with an oxygen-hydrogen combustion mixture. Calcium and magnesium were determined with E.D.T.A. to the USDA Salinity Laboratory as reported by Silva-Mojica (86). Pretreatment with "aqua regia" in order to eliminate organic matter and ammonium acetate was necessary for the calcium and magnesium determination. Titration of calcium with Murexide as the indicator and of calcium plus magnesium with Eriochrome black T indicator were made. Magnesium was obtained by difference. Base saturation in percent was obtained by dividing the sum of bases by the cation exchange capacity times 100.

Exchangeable aluminum was determined by the method proposed by Yuan (110).

The exchange acidity was obtained by difference, subtracting the exchangeable bases plus exchangeable aluminum from the cation exchange capacity.

Total nitrogen was determined by the Kjeldahl method. The content of organic carbon was measured by the wet combustion method of Walkley-Black as reported by Silva-Mojica (86). No recovery factor was used in calculations. The amount of organic matter in soils was calculated by multiplying the percent of organic carbon by the empirical factor 1.724.

The total phosphorus was determined by the perchloric acid digestion method as outlined by Harper (42). The amount of organic phosphorus was determined by a method developed by Metha et al. (67). "Total phosphorus" (organic plus inorganic) was extracted by successive treatments with cold and hot 0.5N NaOH. From the extract a sample was taken for "total Phosphorus" determination. The aliquot was digested with perchloric acid until all of the organic matter was oxidized. After flocculation and sedimentation of the suspended material another aliquot was taken for "inorganic phosphorus" evaluation. Differences between these two fractions was considered as the organic phosphorus in the extract.

Fractionation of Inorganic Soil Phosphorus

Fractionation of the inorganic phosphorus in soil followed the method developed by Chang and Jackson (17). It is a sequential procedure by means of which discrete forms of soil phosphorus are obtained. Two grams of soil were placed in a 100 ml. centrifuge tube and saturated with ammonium ion by adding 50 ml. neutral 1N ammonium chloride.

Aluminum Phosphate (Al-PO_4). To the NH_4-soil in the centrifuge tube 50 ml. of neutral 0.5N NH_4F was added and the suspension shaken for one hour. The suspension was centrifuged and the clear supernatant was decanted for determination of Al-PO_4. Phosphorus was determined by chloromolybdic acid and stannous chloride in the presence of boric acid, which is used to complex the fluoride ion.

Iron Phosphate (Fe-PO_4). The soil sample saved after the extraction of Al-PO_4 was washed twice with 25 ml. portions of saturated sodium chloride solution. Then it was extracted with 50 ml. of 0.1N NaOH on a shaking machine for 17 hours. The soil suspension was centrifuged and the clear solution was decanted into another centrifuge tube. In order to remove the dissolved organic matter sulfuric acid was added until organic colloids floculated. The suspension was centrifuged and the clear solution collected. An aliquot was used for phosphorus determination with sulfomolybdic acid and stannous chloride.

Calcium Phosphate (Ca-PO_4). The sample saved after extraction of iron phosphate was washed again with two portions of 25 ml. of saturated sodium chloride solution. Then it was extracted with 50 ml. of 0.5N sulfuric acid for one hour on a shaking machine. The suspension was centrifuged and supernatant solution collected. The sample was saved for extraction of reductant soluble iron phosphate. Phosphorus was determined colorimetrically, with sulfomolybdic acid and stannous chloride.

Reductant Iron Phosphate (RFe-PO_4). After extraction of Ca-PO_4 the sample was washed two times with 25 ml. of saturated sodium chloride solution. It was then suspended in 40 ml. of 0.3M sodium citrate solution and one gram of solid sodium dithionite ($Na_2S_2O_4$) was added. The suspension was heated in a water bath at 80-90°C with constant stirring for 15 minutes. The supernatant solution, after centrifugation was collected in a 100 ml. volumetric flask. The soil was washed two times with 25 ml. portions of saturated sodium chloride. The washings were combined with the extract in the 100 ml. flask. An aliquot was taken for phosphorus determination.

According to this procedure the aliquot extract is oxidized by adding 5 to 10 ml. of hydrogen peroxide (H_2O_2), but at this point a modification of the Chang and Jackson method was introduced. Perchloric acid was used as an oxidant instead of hydrogen peroxide, because it was not possible to remove the preservative phosphoric acid from the hydrogen peroxide, even though seven shakings with colloidal Kaolin were used, according to the recommendations of Chang and Jackson (16). The determination of RFe-PO_4 was made by the same method as for Fe-PO_4, outlined above.

Occluded Aluminum Phosphate (OAl-PO_4). The soil residue saved from the former extractions was extracted with 50 ml. of neutral normal ammonium fluoride for one hour to remove occluded aluminum phosphate. The phosphorus in solution was determined in the same way as Al-PO_4.

Extractable Iron. Iron dissolved during the extraction of the RFe-PO_4 (extraction with sodium citrate and sodium dithionite) was determined by the method of Aguilera and Jackson (1). An aliquot of the extract was treated with one drop of hydrogen peroxide, acidified with 6N HCl. Then iron was colorimetrically evaluated by adding potassium thiocyanate (KSCN).

Available Phosphorus. The available phosphorus was determined by the Bray and Kurtz method "1" as described by Jackson (52). The extractant solution is 0.03N NH_4F in 0.025N HCl. The ratio soil: extractant was kept at 1:7 (2.85 grams of soil and 20 ml. of extractant solution). The shaking time was one minute. The determination was the routine colorimetric procedure with chloromolybdic acid and stannous chloride.

Phosphorus Sorption Capacity

The phosphorus sorption capacity was measured following the two procedures given by Bass and Sieling (5).

Procedure number one: Five grams of soil was weighed into a 100 ml.

centrifuge tube and 50 ml. 0.5M KH_2PO_4, buffered at pH 3.4 with phosphoric acid, were added. The suspension was digested on a water bath for four hours and then centrifuged to clarify the solution. The supernatant liquid was poured off and 40 ml. of hot one percent sodium chloride was then added. The tubes were then heated, shaken and centrifuged. Then a second and third washing with hot sodium chloride were made. After three washings the soil was then leached with ethanol containing two percent sodium chloride. The retained phosphate was displaced by digesting the sample in a hot water bath for one hour with 0.5M citric acid. The suspension was filtered, cooled and made to volume. An aliquot was taken for oxidation with a mixture of perchloric and nitric acids and then the colorimetric phosphorus determination was carried out with sulfomolybdic acid and stannous chloride.

Procedure number two: The second procedure presented by Bass and Sieling (5) was used in order to compare results with the first procedure. Iron and aluminum were extracted from the soil with a 0.5M citric acid solution. Twenty grams of soil and 75 ml. of 0.5M citric acid were digested on a hot water bath for one hour. The suspension was filtered and washed with hot water and diluted to volume. An aliquot of the filtrate was taken for oxidation with nitric and perchloric acids. The iron and aluminum were precipitated as phosphates, by adding 0.03M KH_2PO_4, and adjusting the pH of the solution to 3.5 with NaOH and HCl with methyl orange as the indicator and digesting on the hot plate for 30 minutes. The precipitate was then washed several times with a hot one percent, pH 3.4 sodium chloride solution and then was dissolved with a hot 0.2N sulfuric acid solution. The dissolved phosphate was made to volume and an aliquot was taken for colorimetric analysis of the phosphorus with sulfomolybdic acid. The number of millimols of phosphorus per 100 grams of soil constitutes the "phosphate exchange capacity" which is equivalent to the millimols of iron and aluminum extracted from the soil by the citric acid solution.

Phosphorus fractionation of phosphate saturated soils was measured as follows: To 10 grams of soil were added 50 ml. of 0.5M KH_2PO_4. The samples were shaken and digested for six hours in a hot water bath. The excess of phosphate was removed by shaking the soil with a hot one percent sodium chloride solution and centrifuging and extracting again. Then five washings with ethanol containing two percent sodium chloride in a Buchner funnel were made. The soil samples were then air dried and ground. One gram was taken for phosphorus fractionation into ammonium chloride soluble phosphate; (Saloid-bounded phosphate); Al-PO_4, Fe-PO_4 and Ca-PO_4, according to the Chang and Jackson procedure (17).

Effect of Lime and Silicate Applications on the Phosphorus Sorption Capacity of Soils

200 grams of each soil and subsoil, of the five profiles, received the following treatments:

A. None.

B. Calcium carbonate to reach 40% base saturation.

C. Calcium carbonate to reach 80% base saturation.

D. Sodium silicate in amount equivalent to 1000 Kg./hectare.

E. Sodium silicate in amount equivalent to 2000 Kg./hectare.

F. Sodium silicate in amount equivalent to 4000 Kg./hectare.

Calcium carbonate was mixed with soils and then enough water was added to attain field capacity. An equilibrium period of one month was allowed, after that pH was taken on a 1:1 suspension. The silicate treated soils were kept at field capacity moisture level. The reaction period was two days; after which the pH was measured. After the equilibration period the samples were air dried for 12 hours and the samples crushed. From each treatment four portions of 10 grams of soil were weighed into 100 ml. beakers, and increasing quantities of KH_2PO_4 solution containing 500 p.p.m. of phosphorus were added in order to obtain a final concentration of 100, 200, 400 and 800 p.p.m. of phosphorus in the soil. Then the necessary amount of water was added in order to have a soil:liquid ratio of 1:1. The suspension was mixed and permitted to stand for 24 hours, after this period the samples were air dried for 12 hours, crushed and a one gram sample was taken for extraction of the non-sorbed phosphorus, by the Bray and Kurtz method "1", (13) but with a soil extractant solution ratio of 1:50, (87). The top soil and subsoil of Carimagua II profile received a double phosphorus dose, so the final concentration was 200, 400, 800 and 1,600 p.p.m. of phosphorus in this soil. These amounts were added because of the very high phosphorus sorption capacity of this soil.

Statistical analysis. In order to establish relations among soil characteristics and phosphorus status some simple and multiple correlation and regression analyses were worked out, following the instructions of Steel and Torrie (89).

RESULTS AND DISCUSSION

Particle Size Distribution

Particle size distribution for all profiles are reported in Table II. The values for silt are apparently too high, probably due to an incomplete dispersion of the clay particles. The resistance of the clays of tropical soils to dispersion is quite characteristic. The uniformity of the soil material of the soils of the Eastern Plains is quite noticeable. This is an outstanding feature of many tropical soils. Russell (79), cites many references in which a very uniform distribution of clays has been shown to occur down the soil profile. Some workers (99) use the fine silt:clay ratio as a relative measurement of degree of weathering of tropical soils. The Minco soil of Southwestern Oklahoma exhibits the highest values for that ratio, which means a low degree of weathering, in comparison with the Colombian soils. For these Colombian soils there is not a very definite trend in the silt:clay ratio values, however, this may be due to the incomplete dispersion of clays.

Chemical Characteristics

The chemical characteristics of the soils used in this work are presented for each profile in Tables III to VIII.

The reaction of the soils ranges from extremely acid to strongly acid, with one exception: the first horizon of the alluvial Guayuriba soil has a slightly acid reaction. As a contrast the Minco soil of Oklahoma has a slightly acid reaction in the topsoil and neutral to

TABLE II. PARTICLE SIZE DISTRIBUTION OF THE SOILS IN PERCENT
(Diameter is Given in Microns)

Sample Number	Dept. cm	<2u	2-20u	20-50u	50-100u	100-250u	250-500u	500-1000u	1000-2000u	Textural Class	Fine Silt: Loam
					SOIL CARIMAGUA I						
1	0-6	29.68	28.24	33.46	7.73	0.58	0.17	0.14	0.00	Si.CL.	0.95
2	6-15	31.47	25.86	34.17	7.57	0.67	0.22	0.04	0.00	Si.CL.	0.82
3	15-40	30.33	29.30	31.45	8.21	0.51	0.20	0.00	0.00	Si.CL.	0.97
4	40-70	32.61	28.78	30.20	7.78	0.38	0.24	0.00	0.00	Si.CL.	0.88
5	70-100	28.02	14.06	50.05	7.26	0.38	0.12	0.00	0.00	Si.CL.	0.50
6	100-150	24.01	29.26	38.34	7.71	0.48	0.20	0.00	0.00	Si.C.	
					SOIL CARIMAGUA II						
7	0-30	34.53	37.20	22.60	5.40	0.22	0.03	0.01	0.00	Si.CL.	1.08
8	30-70	33.07	20.72	35.43	10.42	0.27	0.09	0.00	0.00	Si.CL.	0.63
9	70-100	32.38	23.50	29.76	13.49	0.49	0.22	0.16	0.00	Si.CL.	0.73
					UPIN SERIES						
10	0-3	28.02	32.97	16.44	12.12	8.18	2.20	0.07	0.00	C.L.	1.18
11	3-10	28.14	33.70	16.16	11.86	7.47	2.42	0.27	0.00	C.L.	I.20
12	10-55	24.84	34.11	25.59	9.76	4.95	0.68	0.05	0.00	Si.L.	1.37
13	55-105	15.32	37.02	18.08	17.54	10.88	1.18	0.02	0.00	Si.L.	2.42

TABLE II. (Continued)

Sample Number	Dept. cm	<2u	2-20u	20-50u	50-100u	100-250u	250-500u	500-1000u	1000-2000u	Textural Class	Fine Silt Loam
					GUAYURIBA SERIES						
14	0-2	--	--	--	--	--	--	--	--	--	--
15	2-6	10.31	11.98	4.97	15.23	25.25	24.11	8.15	0.00	S.L.	1.16
16	6-12	15.34	11.77	8.50	16.56	21.21	20.23	6.38	0.00	S.L.	0.77
17	12-34	8.62	14.25	5.80	15.81	22.62	27.40	5.50	0.00	S.L.	1.65
18	34-75	21.87	0.62	3.51	11.20	23.26	32.02	7.52	0.00	S.C.L.	0.03
19	75-120	28.58	14.23	3.91	8.18	15.33	23.59	6.18	0.00	S.C.L.	0.50
20	120-150	6.31	31.50	1.98	15.66	18.90	19.11	6.64	0.00	S.L.	4.99
					GUAMAL SERIES						
21	0-4	29.91	29.98	7.34	10.34	17.34	4.53	0.65	0.00	C.L.	1.00
22	4-8	21.37	28.65	120.1	15.38	15.44	5.90	1.25	0.00	L.	1.34
23	8-50	33.90	35.04	1.00	13.69	13.56	2.44	0.37	0.00	C.L.	1.03
24	50-110	35.29	21.86	6.44	9.79	13.47	10.31	2.84	0.00	C.L.	0.62
25	110-150	11.53	9.47	2.58	24.37	48.59	3.35	0.10	0.00	S.L.	0.82
					MINCO SERIES (OKLAHOMA)						
26	0-25	6.00	33.50*		60.50**					S.L.	5.58***
27	25-44	11.75	29.50		59.25					S.L.	2.51
28	44-87	10.00	27.50		63.00					S.L.	2.75
29	87-140	13.00	37.25		49.75					L.	2.87

*These figures include the fine and coarse silt.
**These figures include all range of sand size from very fine to very coarse sand.
***These values represent the ratio of total silt:clay.

TABLE III. CHEMICAL CHARACTERISTICS OF THE CARIMAGUA I SOIL

		Horizons					
Determination	Depth cm.	0-6	6-15	15-40	40-70	70-100	100-150
	Sample No.	1	2	3	4	5	6
pH in H_2O (1:1)		4.55	4.62	4.63	4.89	5.15	5.10
pH in 1N KCl (1:1)		3.68	3.74	3.83	4.01	4.20	4.22
Cation Exchange Capacity*		11.15	10.48	8.15	5.74	5.67	4.85
Exchangeable bases*		0.84	0.70	10.1	0.89	1.67	0.85
Calcium*		0.42	0.51	0.42	0.51	0.68	0.63
Magnesium*		0.25	0.08	0.50	0.25	0.80	0.12
Potassium*		0.09	0.06	0.06	0.05	0.09	0.04
Sodium*		0.08	0.05	0.09	0.08	0.10	0.10
Exchangeable Aluminum*		2.93	3.29	2.36	1.42	0.74	0.66
Exchangeable Hydrogen*		7.38	6.49	4.72	3.43	3.26	3.67
Percent Base Saturation		7.53	6.68	13.13	15.50	29.45	21.09
Percent Calcium Saturation		3.77	4.87	5.15	8.89	11.90	12.99
Percent Aluminum Saturation		26.28	31.39	28.96	24.74	13.05	15.64
Percent Organic Carbon		2.26	1.84	1.13	0.53	0.43	0.24
Percent Organic Matter		3.90	3.17	1.95	0.91	0.74	0.41
Percent Total Nitrogen		0.18	0.15	0.11	0.06	0.05	0.03
Carbon:Nitrogen Ratio		12.56	12.27	10.27	8.83	8.60	8.00
Available Phosphorus PPM**		0.7	1.1	1.4	0.4	0.0	0.7

* Milliequivalents per 100 grams of soil (m.e/100 g. soil).

**Parts per Million of Phosphorus.

TABLE IV. CHEMICAL CHARACTERISTICS OF THE *CARIMAGUA* II SOIL

Determination	Horizons		
Depth of Horizon cm.	0-30	30-70	70-100
Sample No.	7	8	9
pH in H_2O (1:1)	4.68	4.60	4.91
pH in 1N KCl (1:1)	4.20	3.79	3.83
Cation Exchange Capacity*	22.89	5.72	5.60
Exchangeable Bases*	1.15	1.03	1.08
Calcium*	0.49	0.69	0.64
Magnesium*	0.50	0.19	0.33
Potassium*	0.11	0.04	0.03
Sodium*	0.05	0.11	0.08
Exchangeable Aluminum*	2.68	2.28	2.00
Exchangeable Hydrogen*	19.16	2.41	2.52
Percent Base Saturation	5.02	18.00	19.29
Percent Calcium Saturation	2.14	12.06	11.43
Percent Aluminum Saturation	11.71	39.86	35.71
Percent Organic Carbon	3.09	0.26	0.26
Percent Organic Matter	.533	0.45	0.45
Percent Total Nitrogen	0.57	0.04	0.04
Carbon:Nitrogen Ratio	5.42	6.50	6.50
Available Phosphorus PPM**	3.2	1.8	0.0

*m.e./100 g. Soil.

**Parts per Million of Phosphorus.

TABLE V. CHEMICAL CHARACTERISTICS OF THE UPIN SOIL SERIES

Determination	Horizons			
Depth of Horizon cm.	0-3	3-10	10-55	55-105
Sample No.	10	11	12	13
pH in H_2O (1:1)	5.06	4.82	4.85	5.08
pH in 1N KCl (1:1)	4.11	3.92	3.86	3.88
Cation Exchange Capacity*	12.36	9.07	5.80	3.79
Exchangeable Bases*	3.73	1.50	0.78	0.72
Calcium*	2.10	0.75	0.21	0.37
Magnesium*	0.92	0.39	0.28	0.07
Potassium*	0.64	0.27	0.24	0.23
Sodium*	0.07	0.09	0.05	0.05
Exchangeable Aluminum*	0.88	1.83	2.08	1.73
Exchangeable Hydrogen*	7.75	5.74	2.91	1.34
Percent Base Saturation	30.18	16.53	13.45	19.30
Percent Calcium Saturation	16.99	8.27	3.62	9.76
Percent Aluminum Saturation	7.12	20.18	35.86	45.64
Percent Organic Carbon	2.96	1.50	0.42	0.12
Percent Organic Matter	5.10	2.59	0.72	0.21
Percent Total Nitrogen	0.39	0.28	0.12	0.06
Carbon: Nitrogen Ratio	7.59	5.36	3.50	2.00
Available Phosphorus, P.P.M.**	28.1	12.3	7.0	3.5

*m.e./100 g. soil.

**Parts per Million of Phosphorus.

TABLE VI. CHEMICAL CHARACTERISTICS OF THE GUAYURIBA SOIL SERIES

Determination	Horizons						
Depth of Horizon cm.	0-2	2-6	6-12	12-34	34-75	75-120	120-150
Sample No.	14	15	16	17	18	19	20
pH in H_2O (1:1)	6.32	5.20	4.65	4.69	4.68	4.32	4.48
pH in1 N KCl (1:1)	5.48	4.15	3.78	3.82	3.72	3.52	3.55
Cation Exchange Capacity*	15.73	3.61	4.01	1.88	1.83	6.17	0.15
Exchangeable Bases*	12.48	1.98	0.93	0.44	0.63	0.60	0.67
Calcium*	6.28	0.54	0.26	0.13	0.19	0.15	0.19
Magnesium*	5.40	0.95	0.18	0.10	0.15	0.21	0.17
Potassium*	0.76	0.37	0.36	0.17	0.18	0.20	0.15
Sodium*	0.04	0.12	0.13	0.04	0.11	0.04	0.16
Exchangeable Aluminum*	0.00	0.36	1.54	0.97	1.14	3.61	2.17
Exchangeable Hydrogen*	3.25	1.27	1.55	0.47	0.06	1.96	1.23
Percent Base Saturation	79.34	54.84	23.12	23.40	34.43	9.72	16.46
Percent Calcium Saturation	39.92	14.96	6.48	6.91	10.38	2.43	4.67
Percent Aluminum Saturation	0.00	9.97	38.31	51.60	62.30	58.51	53.32
Percent Organic Carbon	3.85	0.77	0.64	0.25	0.08	0.18	0.08
Percent Organic Matter	6.64	1.32	1.10	0.43	0.14	0.31	0.14
Percent Total Nitrogen	0.35	0.09	0.07	0.03	0.03	0.04	0.02
Carbon:Nitrogen Ratio	11.00	8.56	9.14	8.33	2.67	4.50	4.00
Available Phosphorus**	36.0	24.6	7.0	5.3	0.0	0.7	1.8

*m.e./100 g. of soil.

**Parts per Million of Phosphorus.

TABLE VII. CHEMICAL CHARACTERISTICS OF THE GUAMAL SOIL SERIES

Determination	Horizons				
Depth of Horizon cm.	0-4	4-8	8-50	50-110	110-150
Sample No.	21	22	23	24	25
pH in H_2O (1:1)	4.15	4.61	4.15	4.28	4.62
pH in 1N KCl (1:1)	3.48	3.81	3.48	3.57	3.82
Cation Exchange Capacity*	12.06	9.48	9.47	8.97	2.00
Exchangeable Bases*	1.35	0.65	0.81	0.82	0.49
Calcium*	0.54	0.16	0.31	0.13	0.14
Magnesium*	0.42	0.18	0.22	0.44	0.13
Potassium*	0.32	0.20	0.23	0.21	0.12
Sodium*	0.07	0.11	0.05	0.04	0.10
Exchangeable Aluminum*	3.71	3.20	3.84	4.30	1.34
Exchangeable Hydrogen*	7.00	5.63	4.82	3.85	0.17
Percent Base Saturation	11.19	6.86	8.55	9.14	24.50
Percent Calcium Saturation	4.78	1.69	3.27	1.45	7.00
Percent Aluminum Saturation	30.76	33.76	40.55	47.94	67.00
Percent Organic Carbon	2.66	1.34	1.36	0.64	0.04
Percent Organic Matter	4.59	2.31	2.34	1.10	0.07
Percent Total Nitrogen	0.28	0.14	0.19	0.10	0.01
Carbon:Nitrogen Ratio	9.50	9.57	7.16	6.40	4.00
Available Phosphorus, PPM*	9.1	0.7	8.8	1.8	10.5

*m.e./100 g. soil.

**Parts per Million of Phosphorus.

TABLE VIII. CHEMICAL CHARACTERISTICS OF THE MINCO SOIL SERIES (OKLAHOMA)

Determination	Horizons			
Depth of Horizon cm.	0-25	25-44	44-87	87-110
Sample No.	26	27	28	29
pH in H_2O (1:1)	6.12	6.71	7.17	7.45
pH in 1 N KCl (1:1)	5.60	5.72	6.05	6.42
Cation Exchange Capacity*	10.36	11.43	12.80	13.89
Exchangeable Bases*	10.14	11.73	13.43	14.68
Calcium*	6.30	6.90	7.83	8.25
Magnesium*	3.00	4.00	5.00	5.90
Potassium*	0.69	0.59	0.37	0.34
Sodium*	0.15	0.24	0.23	0.19
Exchangeable Aluminum*	0.20	0.00	0.00	0.00
Exchangeable Hydrogen*	0.02	0.00	0.00	0.00
Percent Base Saturation	97.87	100.00	100.00	100.00
Percent Calcium Saturation	60.81	60.37	61.17	59.37
Percent Alumimum Saturation	1.93	0.00	0.00	0.00
Percent Organic Carbon	0.89	0.83	0.53	0.42
Percent Organic Matter	1.53	1.43	0.91	0.72
Percent Total Nitrogen	0.07	0.06	0.03	0.04
Carbon:Nitrogen Ratio	12.71	13.83	17.66	10.50
Available Phosphorus**	3.1	2.3	2.2	2.3

*m.e./100 g. of soil.
**Parts per Million of Phosphorus.

mildly alkaline in the subsoil and deeper horizons. The pH values measured in 1N. KCl are in all cases, lower than the pH measured in water.

The cation exchange capacity decreases with depth in tropical soils; in contrast, it increases in the Minco soil. The decline of the cation exchange capacity with depth of these tropical soils is due to a decrease in the content of organic matter. A highly significant coefficient of correlation ($r = 0.919$) was found between cation exchange capacity and percent of organic carbon for these Colombian soils. A highly significant correlation ($r = 0.619$) was also found between cation exchange capacity and clay content. In order to know the contribution of clay and organic matter to the cation exchange capacity the multiple linear regression equation was calculated:

$$\text{C.E.C.} = 0.479 + 0.133\, x_1 + 3.839 x_2$$

where C.E.C. = cation exchange capacity in m.e./100 g. x_1 = percent of clay and x_2 = percent of organic carbon. The values of the equation indicate that for these soils, the clay has a mean cation exchange capacity of about 13 m.e. per 100 grams of clay and the organic carbon has a mean cation exchange capacity of 384 m.e. per 100 grams of organic carbon.

A direct determination by Schulz (84) was made for plains soils of Venezuela, and he obtained a mean value of 20 m.e./100 grams, for the clay fraction and a series of values between 240-256 m.e./100 grams for organic carbon.

The value obtained by the linear function, for cation exchange capacity of the clay agrees very well with the nature of the clay minerals; Kaolinite and hydrated oxides, as reported by Schaufelberger (83) are the clay minerals found in the Colombian tropical Savanna soils. A single sample of the

Eastern Plain soils (terrace soil) has been analysed by X-ray methods, at the North Carolina State University[1]. The results indicated the clay contained 50-60% Kaolinite; 20-30% interstratified chlorite-vermiculite; 10% Goethite; 10% talc and traces of quartz.

The cation exchange capacity of the organic matter has been determined in a wide variety of soils. The recorded values vary from 60 to 280 m.e./100 g. of organic carbon (55). A recent report (32) estimates that the cation exchange capacity of organic matter to be as high as 1,200 m.e./100 grams of organic carbon.

Since the cation exchange capacity of the mineral fraction in tropical soils is small, it appears that the organic fraction makes an important contribution to the exchange properties of these soils and should be the most important factor affecting the "potential fertility" of these soils.

The exchangeable cations are very low and the degree of saturation is also quite low, which indicates that these soils have been strongly leached; only the top horizons of the alluvial Guayuriba soil shows saturations over 50% while the values for the other soils fall between 6 and 29.5%. There is some relationship, however, between pH and degrees of base saturation. In Carimagua I and Carimagua II soils the base saturation increases with depth. In Upin and Guayuriba soils the degree of base saturation decreases with depth. The degree of "aluminum saturation" shows definite changes with depth in these profiles. It declines in the Carimagua I profile as a function of depth, but increases in all other profiles.

The organic fraction and the total nitrogen are high at the surface and subsurface horizon and then they diminish very rapidly with depth.

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[1] Personal communication, indebted to Dr. Alfredo Leon.

The distribution of organic matter is very important in relation to the amounts of phosphorus in these profiles as will be noted later. The mean value of the carbon:nitrogen ratio is 7.3. The ratio becomes more and more narrow with depth. With the exception of the Carimagua II, the highest values of C/N correspond to top soil; the narrowing of the C/N with depth is very definite, and values as low as two and three are found in the deep horizons. Numerous studies and reports have reported substantial narrowing of C/N ratio with depth, in many soil profiles. Recently, this fact has been experimentally explained (91, 109). Two factors, at least, seem to be responsible: (a) increase in relative amount of nitrogen fixed as NH_4 (mineral nitrogen) with depth, in the profile and (b) the presence of relatively greater amounts of nitrogen rich non-proteinaceous constituents of the fulvic acid fraction in subsoil organic matter. Better data on the C/N may be obtained by using organic carbon:organic nitrogen ratio.

Soil Phosphorus Fractionation

The data obtained from the analysis of the soils for phosphorus fractions are reported in Tables IX and X. The inorganic phosphorus is grouped into active forms and inactive forms. The active inorganic phosphorus refers to the summation of aluminum phosphate, iron phosphate and calcium phosphate fraction extracted by ammonium fluoride, sodium hydroxide and sulfuric acid solutions respectively. These fractions are chemically more active than the occluded or "insoluble" or "residual" forms. The inactive fraction consists of the reductant soluble iron phosphate and the occluded aluminum phosphate, which are extractable only after removal of iron oxide coatings by a strong reduction-chelation procedure. These fractions are considered chemically inactive.

The total phosphorus in the soil may vary over a wide range depending

TABLE IX. DISTRIBUTION OF THE SEVERAL FRACTIONS OF SOIL PHOSPHORUS IN FIVE COLOMBIAN AND ONE OKLAHOMA SOIL PROFILE

Sample Number	Horizon Depth cm.	Total P (P.P.M.)	Organic P (P.P.M.)	Inorganic Phosphorus Fractions					Added Total P (P.P.M.)	Active P% of Total P
				Active Fractions			Inactive Fractions			
				Ca-PO4 (P.P.M.)	Al-PO4 (P.P.M.)	Fe-PO4 (P.P.M.)	RFe-PO4* (P.P.M.)	OAl-PO4** (P.P.M.)		
				SOIL CARIMAGUA I						
1	0-6	185	138	1.6	1.4	18.9	16.5	2.3	178.7	12.3
2	6-15	151	104	0.8	1.3	15.1	15.7	1.5	138.4	12.4
3	15-40	126	92	0.9	1.5	8.4	21.5	1.7	126.0	8.6
4	40-70	114	60	0.9	1.4	7.7	36.9	1.6	108.5	9.2
5	70-100	90	43	0.5	0.9	8.1	38.0	1.0	91.5	10.4
6	100-150	84	27	0.5	0.9	3.3	41.0	3.3	76.0	6.2
				SOIL CARIMAGUA II						
7	0-30	464	330	17.3	63.9	13.0	24.5	2.2	450.9	20.8
8	30-70	78	33	2.4	6.3	3.5	16.5	0.2	61.9	19.7
9	70-100	60	30	0.5	2.3	1.2	21.7	0.2	55.9	7.2
				UPIN SOIL SERIES						
10	0-3	610	364	16.4	22.5	158.5	37.0	2.8	601.2	32.8
11	3-10	448	207	26.0	14.1	169.6	45.2	3.2	465.1	45.1
12	10-55	328	184	22.0	5.2	78.6	44.9	3.4	338.1	31.3
13	55-105	226	87	18.2	4.1	51.5	43.7	2.3	206.7	35.7

Table IX (Continued)

Sample Number	Horozon Depth cm.	Total P (P.P.M.)	Organic P (P.P.M.)	Inorganic Phosphorus Fractions					Added Total P (P.P.M.)	Active P% of Total P
				Active Fractions			Inactive Fractions			
				Ca-PO4 (P.P.M.)	Al-PO4 (P.P.M.)	Fe-PO4 (P.P.M.)	RFe-PO4* (P.P.M.)	OAl-PO4** (P.P.M.)		
				GUAYURIBA SOIL SERIES						
14	0-2	452	280	54.3	53.1	52.9	5.5	0.4	446.2	35.9
15	2-6	195	101	0.5	18.0	47.0	17.3	0.2	184.4	35.6
16	6-12	153	80	0.5	4.4	27.5	22.0	0.0	134.4	24.1
17	12-34	81	40	0.5	5.6	15.1	15.3	0.0	76.5	27.7
18	34-75	73	30	1.7	7.7	8.9	21.0	0.0	69.3	26.4
19	75-120	99	45	0.5	4.9	5.6	25.3	0.0	81.3	13.5
20	120-150	173	18	21.4	77.4	27.1	25.5	0.0	169.4	74.3
				GUAMAL SOIL SERIES						
21	0.4	472	248	9.4	11.4	90.3	94.8	4.2	158.2	24.3
22	4-8	365	161	13.2	10.6	89.2	69.9	6.4	350.3	32.3
23	8-50	383	185	2.8	4.4	70.5	95.7	11.7	370.1	21.0
24	50-110	180	119	1.3	7.9	9.8	30.6	6.9	175.5	10.8
25	110-150	160	12	7.6	12.0	54.3	66.5	1.0	153.4	48.2
				MINCO SOIL SERIES (OKLAHOMA						
26	0-25	275	129	115	5.8	5.3	10.0	0.2	265.3	47.5
27	25-44	274	120	105	4.4	4.9	19.5	1.5	255.3	44.8
28	44-87	307	117	133	2.4	4.0	19.0	0.6	276.1	50.5
29	87-140	322	109	151	3.2	3.6	20.5	0.8	288.1	54.8

*RFe-PO4 = Reductant Soluble Iron Phosphate.

**OAl-PO4 = Occluded Aluminum Phosphate.

TABLE X. FRACTIONS OF THE SOIL PHOSPHORUS AS PERCENT OF THE TOTAL PHOSPHORUS

Sample Number	Inorganic Phosphorus Fractions					Inorganic P Fractions	Organic P
	Active Fractions			Inactive Fractions			
	Ca-PO4 %	Al-PO4 %	Fe-PO4 %	RFe-PO4 %	OAl-PO4 %	%	%
SOIL CARIMAGUA I							
1	0.89	0.81	10.55	9.23	1.29	22.78	77.22
2	0.58	0.91	10.93	11.34	1.08	24.86	75.14
3	0.71	1.21	6.64	17.06	1.35	26.98	73.02
4	0.83	1.33	7.06	34.00	1.47	44.70	55.30
5	0.55	0.98	8.85	41.53	1.09	53.01	46.99
6	0.66	1.18	4.34	53.95	4.34	64.47	35.53
SOIL CARIMAGUA II							
7	3.86	14.10	2.98	5.45	0.48	26.78	73.22
8	3.88	10.18	5.65	26.66	0.32	46.49	53.31
9	0.89	4.19	2.08	38.81	0.36	46.34	53.66
UPIN SOIL SERIES							
10	2.73	3.74	26.37	6.15	0.47	39.46	60.54
11	3.59	3.00	36.46	9.73	0.69	55.47	46.53
12	6.15	1.54	23.24	13.29	1.00	45.58	54.42
13	8.81	2.00	24.90	21.14	1.11	57.96	42.04
GUAYURIBA SOIL SERIES							
14	12.17	11.90	11.86	1.23	0.10	37.25	65.75
15	0.27	9.78	25.54	9.41	0.11	45.02	54.89
16	0.37	3.28	20.45	16.37	0.00	40.48	59.52
17	0.65	7.29	19.76	20.00	0.00	47.71	52.29
18	2.45	11.17	12.78	30.30	0.00	56.71	43.29
19	0.62	6.01	6.83	31.15	0.00	44.70	55.40
20	12.63	45.69	16.01	15.04	0.00	89.38	10.62
GUAMAL SOIL SERIES							
21	2.05	2.49	19.70	20.70	0.92	45.86	54.14
22	3.77	3.37	25.12	19.95	1.83	54.04	45.96
23	0.76	1.32	18.91	25.86	3.16	50.01	49.99
24	0.74	4.46	5.57	17.42	3.93	32.19	67.81
25	4.95	7.80	34.44	43.34	0.65	92.18	7.82
MINCO SOIL SERIES (OKLAHOMA)							
26	43.35	2.17	2.37	3.77	0.10	51.38	48.62
27	41.13	1.72	1.91	7.64	0.59	53.00	47.00
28	48.20	0.97	1.46	6.88	0.10	57.60	42.40
29	52.41	1.12	1.24	7.11	0.28	62.17	37.83

on the parent material, organic matter content and degree of weathering (61). The amount of total phosphorus in the soil is a measure of the reservoir and potential adequacy for future plant nutrition and in some cases, as Aldrich and Buchanan (2) have shown, a direct measurement of phosphorus availability.

The total amount of phosphorus in the Eastern Plain top soils of Colombia varies from 185 P.P.M. to 610 P.P.M. The lowest values recorded correspond to the deeper horizons, 84, 60, 73 P.P.M. of phosphorus. This fact indicates that the parent materials of these soils have a very low total phosphorus content.

The total phosphorus varies between and within profiles. Within profiles in every profile the total phosphorus decreases with depth. In profiles Carimagua I, Upin, and Guamal the decrease in the amount of total phosphorus down the profile is gradual and relatively smooth, but in Carimagua II and Guayuriba soil the decline of phosphorus content from the first to the second horizon is very sharp. A highly significant negative correlation ($r = -0.574$) was found between the total phosphorus and the depth in centimeters. The regression equation was also computed:

$$Y = 287.58 - 1.916X$$

where Y is the total phosphorus in parts per million and X the depth in centimeters. On the mean, the total phosphorus is equal to 285 P.P.M. at the surface. The total phosphorus in the Minco profile increases with depth, as a contrast with these tropical soils.

There is a very definite influence of the organic matter on total phosphorus in the profile. The surface accumulation of total phosphorus is attributed to the action of vegetation in transferring phosphorus from the root zone to the surface layer. This enrichment of the surface horizons by the removal of phosphorus from the subsoil by plants has been reported for tropical soils by various workers including Nye and Berthex (70) for Ghanian soils, Middleton (68) for Sudanese soils and Bates and Baker (6) for Nigerian soils. The total phosphorus follows the same pattern of distribution through the profile as the organic matter. A very highly significant correlation coefficient $r = 0.749$ was found between the total phosphorus in P.P.M. and percent of organic carbon. The corresponding linear regression equation was computed to have the form,

$$Y = 108.96 + 110.19X$$

where Y accounts for total phosphorus in P.P.M. and X for organic carbon in percent.

Organic phosphorus. The organic phosphorus accounts for 54 to 77% of the total phosphorus in the surface soil horizon. With few exceptions, the organic fraction is higher than any other fraction. This is a different situation than that reported by Chang and Jackson (17) for a Latosol (Catalina) from Puerto Rico, in which the organic phosphorus accounts for only a 3% of the total phosphorus and the major proportion of inorganic phosphorus (about 73%) is present as reductant soluble phosphorus. In some New Zealand soils, Walker, Adams and Thapa (98) found that the organic phosphorus content was, on the average a very high proportion of the total phosphorus, that is, between 74 and 90% in the top 10 centimeters. For the Eastern Plain soils, it is reasonable to believe that the organic phosphorus ia agriculturally important because its mineralization, (at the same rate as the organic matter), permits the replenishment of the phosphorus taken by the vegetation. The amounts of organic phosphorus are fairly well related with the amounts of nitrogen and organic carbon. The data showing the ratios C:N, C:P, N:P: C:N:P by weight are reported in Table XI. The

TABLE XI. CARBON, NITROGEN AND ORGANIC PHOSPHORUS RATIOS IN THE COLOMBIAN IN THE COLOMBIAN EASTERN PLAIN SOILS

Sample Number	Horizon Depth cm.	C:N Ratios	C:P Ratios	N:P Ratios	C:N:P Ratios	C:N:P Molar Ratios
		SOIL CARIMAGUA I				
1	0-6	12.6	163.8	13.0	164:13:1	419:29:1
2	6-15	12.3	176.9	14.4	177:14:1	451:32:1
3	15-40	10.3	122.8	12.0	123:12:1	314:26:1
4	40-70	8.8	88.3	10.0	88:10:1	228:23:1
5	70-100	8.6	100.0	11.6	100:12:1	256:26:1
6	100-150	8.0	88.9	11.1	89:11:1	230:24:1
		SOIL CARIMAGUA II				
7	0-30	5.4	93.6	17.3	94:17:1	243:38:1
8	30-70	6.5	78.8	12.1	79:12:1	196:26:1
9	70-100	6.5	86.7	13.3	87:13:1	216:28:1
		UPIN SOIL SERIES				
10	0-3	7.6	81.3	10.7	81:11:1	210:24:1
11	3-10	5.4	72.5	13.5	72:14:1	157:30:1
12	10-55	3.4	22.8	6.5	22.6:1	59:15:1
13	55-105	2.0	13.9	6.9	14:7:1	36:15:1
		QUAYURIBA SOIL SERIES				
14	0-2	11.0	135.7	12.5	138:12:1	356"28:1
15	2-6	3.6	76.2	8.9	76:9:1	196:19:1
16	6-12	9.1	80.0	8.8	80:9:1	202:19:1
17	12-34	8.3	62.5	7.5	63:7:1	160:16:1
18	34-75	2.7	26.7	10.0	27:10:1	67:21:1
19	75-120	4.5	40.0	8.9	40:9:1	100:19:1
20	120-150	4.0	44.0	11.1	44:11:1	111:24:1
		GUAMAL SOIL SERIES				
21	0-4	9.5	107.3	11.3	107:11:1	227:25:1
22	4-8	9.6	112.6	11.8	113:12:1	294:26:1
23	8-50	7.2	86.5	11.8	84:12:1	218:26:1
24	50-110	6.4	34.6	5.4	35:5:1	89:12:1
25	110-150	4.0	33.3	8.3	33:8:1	82:17:1

C:N:P molar ratio is also included. A general trend in all profiles is noticed;the C:N:P are wide in the surface soils and narrow in the subsoil and deeper horizons. Nye and Bertheux (70) reported a sharp drop in the C:P in most profile studies from Ghana. The same was found for soils in Nigeria (6).

The carbon:organic phosphorus is highly variable, from 177 down to 13, a difference of almost 13 times. On the other hand, the nitrogen: organic phosphorus ratio is fairly constant between and within profiles. A little speculation may suggest that the nitrogen and organic phosphorus are combined in the organic matter as a compounds with a definite molecular constitution. Taking all values, a mean ratio equal to 81:10:1 is found. Black and Goring (11) calculated a ratio from all available data, for many soils in the world and they found a mean value of 110:9:1. Karim and Khan (57) reported a ratio 122:12:1 for east Pakistan soils. Nye and Bertheux (70) found much higher ratios for forest and savanna soils of Ghana. The mean values reported were 233:22:1, and 247:20:1 respectively. Some tropical soils of Ceylon (quoted by Nye and Bertheux (70) have a mean carbon organic phosphorus ratio 83:1, very close to that of these Colombian soils.

The contribution of calcium phosphate to total phosphorus content is low and ranges from 0.2 to 8.8%. Only in the alluvial Guayuriba soil does the calcium phosphate reach an appreciable level, that is 12% in the first 2 cm. horizon and at the very bottom of the profile. The unweathered Minco, a Regosol of Reddish Prairie soil area, on the other hand has almost one half of the total phosphorus in the form of calcium phosphate, and it increases with depth. In the tropical soils no noticeable trend is observed, in the distribution within each profile.

The aluminum phosphate content of the soils studied is a little higher than the calcium phosphate. The range is from 0.8% to 14%. The lowest values correspond to Carimagua I soil and the highest to the Carimagua II soil. In the lowest horizon of the Guayuriba soil there is an unusually high percentage of aluminum phosphate. This horizon seems to be an accumulation layer influenced perhaps by the water table.

The iron phosphate makes a more important contribution to the total phosphorus than calcium and aluminum phosphate, excepting in the Carimagua II profile, where the aluminum bonded phosphorus is dominant. The proportion of iron phosphate in Carimagua I soil decreases with depth from about 11% down to 4%. In Carimagua II the proportion varies from 2 to 6%. In the Upin series the iron phosphate is important and forms from 25% to 35% of the total phosphorus. The aluminum and iron phosphates are low in the Minco soil series and are present in equal proportions. Both decrease with depth from about 2% to about 1%. In tropical soils a tendency is noted for a relation between the calcium phosphate and pH of the surface horizons. For the other forms of phosphorus this relation is not observed.

The reductant soluble iron phosphate is not important in Minco soils, where it varies from 5 to 7%, but it is a very important fraction in the tropical soils. In the Carimagua I profile a very sharp increase in reductant soluble iron phosphate with depth is found. It is only 9% of the total phosphorus in the surface horizon and reaches 54% in the lowest horizon. In the Carimagua II the same distribution occurs. This phosphorus fraction varies from 5% in the first horizon to 39% in the last. In the Upin soil series the increase is from 6% in the topsoil to 21% in the subsoil. The Guayuriba surface horizon has a very small proportion of reductant soluble iron phosphate, that is, only about 1% of the total phosphorus. In the second horizon it is 9%. The maximum value of 31% is reported in the 6th horizon. In the last horizon the percent decreases to 15%. In the Guamal soil this form of phosphorus is important; the distribution through the profile is quite similar to the former profiles. The lowest proportion is found in surface horizon, 21% and the highest in the lowest horizon of the profile 43%. In the Minco soil the reductant soluble iron phosphate accounts for only 4% to 8% of the total phosphorus. It is at a minimum in the topsoil and a maximum in the subsoil.

The occluded aluminum phosphate is only a minor portion of the total phosphorus in all soils. Summarizing the facts about the phosphorus fractions in these soils it is found that the organic phosphorus as a whole, is the most important fraction of the total phosphorus in tropical soils. In the Regosol of Reddish Prairie soil area of Oklahoma the most important fraction is the calcium phosphate. The second most important phosphorus fraction, by its magnitude, is the reductant soluble iron phosphate for tropical soils and the organic phosphorus for the temperate zone soil. The third most abundant fraction is the iron phosphate. The fourth fraction in magnitude is the aluminum phosphate and the less abundant fraction is calcium phosphate. For the Minco soil the phosphorus fractions in decreasing concentrations are calcium phosphate, organic phosphorus, reductant soluble iron phosphate, iron phosphate and aluminum phosphate.

Chang and Jackson (17, 18), Chang and Chu (15), and Chu and Chang (22) reported only small amounts of phosphorus were present as calcium phosphate and aluminum phosphate in tropical soils. Most of the phosphorus in these soils was present in the form of iron phosphate, the majority of which was occluded.

The phosphorus of some Chernozen and Brown soils has been fractionated

(18). For example the Rosebud series, a Brown soil, shows in the B_2 horizon a dominance of calcium phosphate and relatively low quantities of aluminum and iron phosphate, quite similar in distribution of forms of phosphorus to that of the Minco soil.

It appears to be somewhat abnormal that the Minco soil contains some reductant soluble iron phosphate. But it is probably correct since the iron extracted by the reduction-chelation treatment is high enough, which by the way, is against the current belief that neutral and calcarous soils have only small amounts or no iron and aluminum phosphates. Similar results have been found by the Indian soil chemists and other workers (47, 72).

Chang and Jackson (18) have stated that the distribution of inorganic phosphorus is related to the degree of soil chemical weathering during soil development in the sequence shown below:

$$\text{Ca-PO}_4 \rightarrow \text{Al-PO}_4 \rightarrow \text{Fe-PO}_4 \rightarrow \text{Occluded P.}$$

Bauwin and Tyner also, (8) have suggested that "synthesis" of reductant soluble iron phosphate and occluded phosphate occurs during soil development. These forms of soil phosphorus are associated with pedological processes, so their relative proportions should increase with increasing maturity.

The main factors controlling the distribution of soil phosphorus are the cation activities of the hydroxides, pH, mineralogical nature of the soil and parent material, topography and drainage conditions (47). The conclusion reached by Chang and Jackson (18) after fractionation of a wide variety of soils was: the formation of various discrete chemical forms of phosphate in soils is apparently related to soil factors such as pH, activities of various cations, solubility products of the various phosphates, degree of chemical weathering and fertilizer practice. At the initial stage of weathering and also right after the application of phosphate fertilizers, calcium phosphate and aluminum phosphate are more likely to be formed than iron phosphate. This is attributed to the relatively higher activities in the soil of calcium and aluminum ions than iron ions, which are controlled by the activities of the respective cations, of calcium carbonate, alumino-silicates and gibbsite, and iron oxides. During the soil development, aluminum phosphate at first increases more than iron phosphate. However, with time the calcium and aluminum phosphates change gradually into iron phosphate which is the least soluble among them. The activity of the iron associated with iron oxide increases with a decrease in pH and with increasing amounts of iron oxides in the soil. The inference drawn from the Latosol analysis is that iron phosphate and also portions of aluminum phosphate and aluminum-iron phosphate (barrandite-like) finally becomes occluded by an iron-oxide coating, formed first as a gel in the course of chemical weathering. Since the soil is a heterogeneous particulate system, the change from one phosphate form to another requires a long period of time. The occluded phosphate is the most resistant form to further weathering and accumulates during the several centuries of time these soils have developed. Thus the formation and transformation of the various phosphate species according to the chemical principle of solubility product, following the order of calcium, aluminum, iron and occluded phosphate, corresponds to increasing stages in a weathering sequence, due to their different stabilities(18).

For determining the degree of weathering by employing the inorganic phosphorus fractions index, the calcium, aluminum, iron phosphates and occluded iron and aluminum phosphates(summation of reductant iron phosphate and occluded aluminum) were totaled for each horizon. Then each phosphorus fraction was calculated as a percent of the inorganic phosphorus. The results are reported in Table XII. In the Carimagua I soil the proportion of calcium phosphate decreases a little with depth, and the same pattern is followed by the aluminum phosphate. The iron bonded phosphorus decreases very rapidly. In the topsoil it is about 7 times higher than in the deepest horizon. The occluded phosphorus increases with depth. From this distribution of the phosphorus fraction it is concluded that the degree of weathering is lower at the surface and higher in the subsoil, with the maximum weathering in the lowest horizon. In the Carimagua II soil the same distribution is found, so the degree of weathering increases with depth. Comparing Carimagua I with Carimagua II soil it appears that the first profile has suffered more weathering than the second. This may be due to the drainage conditions. The Carimagua II profile is located in a depression (small basin) and has imperfect drainage, while the Carimagua I profile is located on a high terrace and is well drained. The Upin profile shows an increase of calcium phosphate with depth. Aluminum and iron phosphates decrease with depth, with a corresponding increase in the occluded fraction and as pointed out previously the occluded phosphates increase with depth. The Guayuriba soil shows some erratic distribution through the profile of the calcium, aluminum and iron phosphate, reflecting its alluvial origin, However, the occluded phosphorus increases consistently with depth, from 35% to 68%; however, an exception is noted in the last horizon of this profile. Gúamal soil also exhibits some erratic distribution in inorganic phosphorus fractions. The occluded phosphate increases and then in the last horizon, it decreases. Taking into account the iron phosphate plus the occluded phosphate as well as the other fractions it appears that the terrace soils Upin, Carimagua I, Guamal,

TABLE XII. DISTRIBUTION OF THE INORGANIC SOIL PHOSPHORUS FRACTIONS AS PERCENT OF THE TOTAL INORGANIC PHOSPHORUS

Sample Number	Horizon Depth cm.	Ca-PO4 %	Al-PO4 %	Fe-PO4 %	RFe-PO4* OAl-PO4 %	Inorganic P P.P.M.
SOIL CARIMAGUA I						
1	0-6	3.93	3.54	46.33	46.19	40.7
2	5-15	2.32	3.66	44.00	50.00	34.4
3	15-40	2.65	4.50	24.62	68.23	34.0
4	40-70	1.85	2.97	15.79	79.38	48.5
5	70-100	1.03	1.85	16.70	80.40	48.5
6	100-150	1.02	1.84	6.73	90.41	49.0
SOIL CARIMAGUA II						
7	0-30	14.33	52.93	10.77	21.97	120.7
8	30-70	8.30	21.80	12.11	57.79	28.9
9	70-100	1.93	9.03	4.48	84.56	25.9
UPIN SOIL SERIES						
10	0-3	6.91	9.49	66.82	16.78	237.2
11	3-10	10.07	5.47	65.69	18.77	258.1
12	10-55	14.27	3.39	50.98	31.36	154.1
13	55-105	15.19	3.46	42.96	38.39	119.9
GUAYURIBA SOIL SERIES						
14	0-2	32-67	31.95	31.83	3.55	166.2
15	2-6	0.60	21.68	56.61	21.10	83.0
16	6-12	0.92	8.10	50.53	40.44	54.4
17	12-34	1.37	15.29	41.42	41.91	36.5
18	34-75	4.33	19.69	22.54	53.43	39.3
19	75-100	1.38	13.64	15.29	67.70	36.3
20	120-150	14.13	51.12	17.90	16.84	151.4
GUAMAL SOIL SERIES						
21	0-4	4.41	6.77	42.35	46.47	213.1
22	4-8	6.97	5.61	47.11	40.30	189.3
23	8-50	1.51	2.38	38.07	58.04	185.2
24	50-110	2.30	14.02	17.32	66.26	56.5
25	110-150	5.38	8.47	38.44	47.72	141.4
MINCO SOIL SERIES						
26	0-25	84.37	4.23	3.92	7.48	136.3
27	25-44	77.60	3.26	3.61	15.52	135.3
28	44-87	83.61	1.50	2.54	12.32	159.1
29	87-141	84.31	1.81	1.99	11.89	179.1

*RFe-PO4 = Reductant soluble iron phosphate.
OAl-PO4 = Occluded aluminum phosphate. Both fractions constitute the "occluded phosphorus."

as well as the alluvial Guayuriba are in the same stage of weathering. It appears, at least in the surface horizons, that the weathering is not as advanced as the chemical properties indicated and what would be expected from the climatic condition. The top soil of Carimagua II profile appears less weathered, but the subsoil is quite strongly weathered.

Guayuriba soil has developed from recent alluvium, however, it shows a degree of weathering similar to that of all terrace soils. This is probably due to weathering of these parent materials before they were sedimented in the present environment.

Two conclusions are reasonably drawn here, that is: the Eastern Plains, with the exception of topsoil of Carimagua II which has an impeded drainage, are in a similar stage of weathering and the degree of weathering increases with the depth. In order to establish if the degree of weathering is not extreme, as the phosphorus fractions index suggest, mineralogical analyses are needed.

The Minco soil presents a striking contrast with these tropical soils. More than 4/5 of the inorganic phosphorus is contributed by the calcium phosphate, and 1/5 by the other forms of phosphate Weathering curves for surface and subsurface horizons of the profiles based on phosphorus fractions are presented in figures 1 and 2. The data for these curves were obtained by the summation of the mean amounts of inorganic fractions of phosphorus, in percent. The summation percents were plotted against data representing compounds of the chemical weathering sequence: Ca-PO_4, Al-PO_4, Fe-PO_4 Occluded phosphorus. For the first point the percent of calcium phosphate was plotted. For the second point (Al-PO_4) the summation percent of calcium phosphate plus aluminum phosphate was plotted; for the third the summation of calcium plus aluminum plus iron phosphate

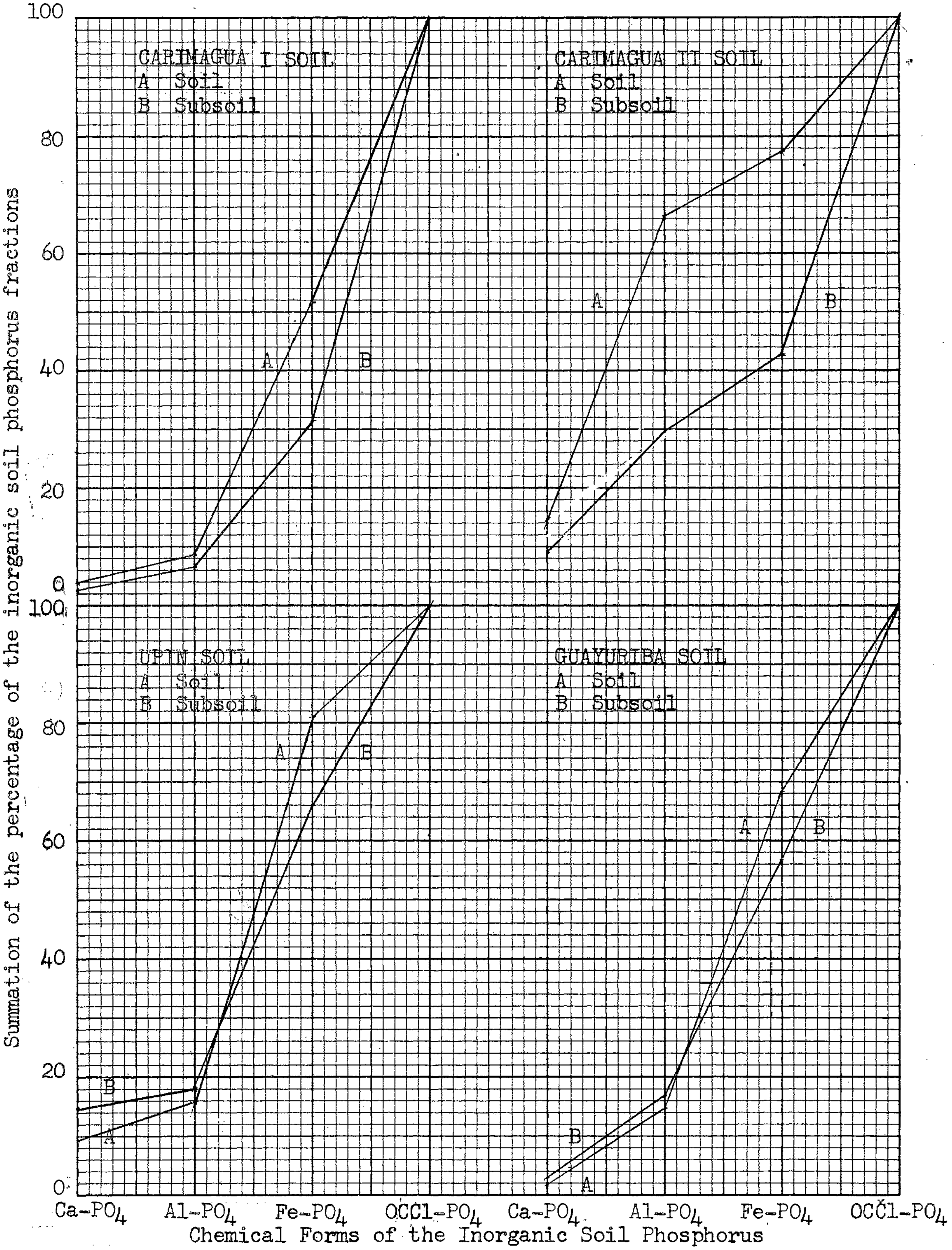

Figure 1. Weathering sequence curves obtained from the fractionation of inorganic soil phosphorus of tropical soils of Colombia. The summation percent of inorganic phosphorus fractions plotted against the discrete chemical forms.

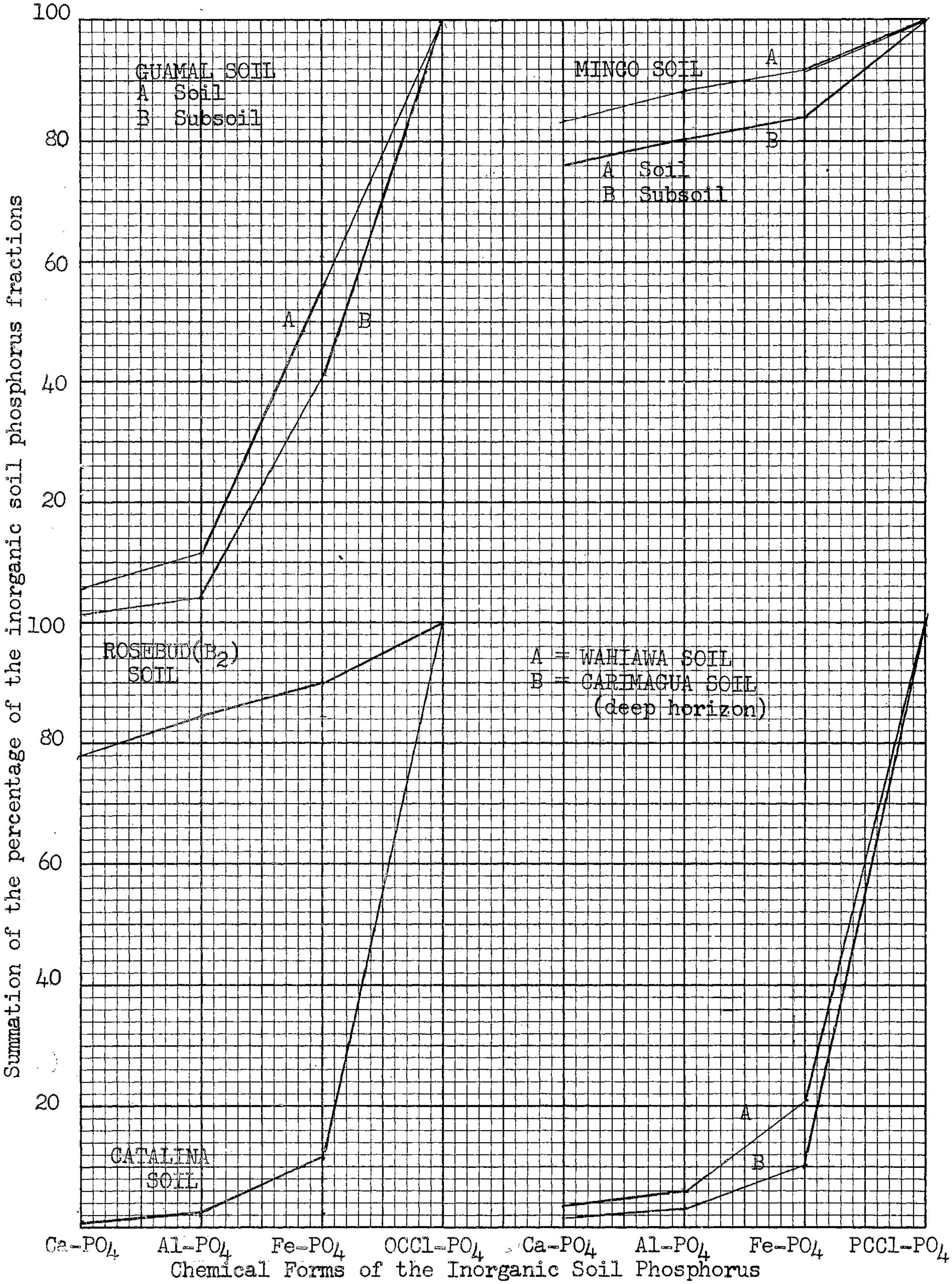

Figure 2. Weathering sequence obtained from the fractions of the inorganic phosphorus of various soils. The summation percent of the inorganic phosphorus fractions plotted against the discrete chemical forms.

was taken and for the last point (occluded phosphorus) the 100% level or the sumation of all inorganic phosphorus forms was plotted. Three soils analyzed by Chang and Jackson (18) are included in the weathering curves. They are the Catalina and Wahiawa Latosols and the Rosebud Brown soils. The striking similarity of the weathering curves of the Minco and Rosebud soil is quite noticeable. Even more striking is the comparison among the Catalina and Wahiawa Latosols and the deep horizon of the Carimagua I profile. It appears that this type of presentation may be useful in comparing the weathering stages of different soils.

The "available" phosphorus was determined for all horizons in each profile by the Bray and Kurtz #1 method with a soil: extractant of 1:7. The Bray and Kurtz method #1 is the method that gives a good correlation with plant response, in greenhouse conditions, for some soils of Colombia[1]. Because of these results this method was selected as the best method for predicting plant response to extractable phosphorus.

Correlation coefficients were calculated between the Bray "available" phosphorus and each one of the phosphorus fractions. The results are presented in Table XIII. The lack of correlation between the aluminum phosphate and available phosphorus is surprising. In view that the same solvent, NH_4F, is used for aluminum phosphate and Bray phosphorus some correlation was expected. However, Jackson (52) has pointed out that aluminum phosphate removed by the 0.5N NH_4F solution includes much phosphorus that is only very slowly available to crops and therefore the results are not highly correlated with yield responses, as one would expect with the dilute acid-fluoride extraction. A high correlation between calcium phosphate

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[1] Unpublished data.

and available phosphorus was obtained. There is also a very good relationship between Bray available phosphorus and the organic phosphorus fraction. A highly significant correlation was obtained between Bray phosphorus and organic phosphorus in the study reported here.

TABLE XIII. CORRELATION ANALYSIS BETWEEN AVAILABLE PHOSPHORUS BRAY NO. 1, AND SOIL PHOSPHORUS FRACTIONS

Soil Phosphorus Fraction	Correlation Coefficient (r)
Calcium Phosphate	0.655**
Aluminum Phosphate	0.360 N.S.
Iron Phosphate	0.582**
Calcium PO_4 + Aluminum PO_4	0.522**
Active Phosphorus fraction ($Ca\ PO_4 + Al\ PO_4 + Fe\ PO_4$)	0.669**
Inorganic Phosphorus	0.550*
Organic Phosphorus	0.955**
Total Phosphorus	0.620**

*Significant at the 5% level of confidence.
**Significant at 1% level of confidence.
M.S. Not significant.

A significant correlation does not necessarily mean a cause-effect relationship in the complex system of the soil where some soil properties influence many other properties. The high relationship between the organic and available phosphorus in these tropical soils emphasizes the importance of the organic matter and nothing more. Cho and Caldwell (20) found highly significant correlations between the Bray #1 phosphorus and aluminum and iron phosphate but a negative and non-significant response between the Bray #1 phosphorus and calcium phosphate.

Other results have been reported concerning the availability of different forms of soil phosphorus. Chang and Jackson (18) pointed out that the calcium, aluminum and iron phosphates are all available to plants if their specific surface area is sufficiently large. The reductant soluble iron phosphate is not available to the plants, except in a strongly reducing condition, for example, under poor drainage conditions as in the flooded rice crop (18, 22). Robertson and Hutton (78) found that cropping tends to decrease the aluminum phosphate level leaving the iron phosphate constant. Laverty and McLean (63) found a positive correlation between phosphorus uptake by plants and aluminum and iron phosphates, and the suggestion is made that the aluminum phosphate is more available than iron phosphate. Other workers (92) found that iron phosphate and organic phosphorus did not contribute to the phosphorus removed by plants.

The active phosphorus in the Eastern Plain soils with the exception of profile Carimagua II, consists, on the average, of 60-80% iron phosphate, 10-30% aluminum phosphate and 2-10% calcium phosphate. This distribution may be responsible for the deficiency of available phosphorus in these soils since the largest fraction is very low in availability to plants.

Phosphorus Sorption Capacity

The phosphorus sorption capacity of these soils was also determined. The results are reported in Table XIV, which also includes data on the amount of extractable iron. All data are given in milli-mols/100 grams of soil. The sorption was determined by two methods developed by Bass and Sealing (5); (method #1 and method #2).

Method #1 is the counterpart of the cation exchange capacity method. The soil is saturated with phosphate, the excess is leached out and the retained phosphate is displaced and measured. In method #2 the active

TABLE XIV. PHOSPHORUS SORPTION CAPACITY OF FIVE COLOMBIAN SOILS AND ONE OKLAHOMA SOIL IN MILLIMOLS OF PHOSPHORUS PER 100 GRAMS OF SOIL

SOIL CARIMAGUA I

Horizon Depth cm. Sample Number	0-6 1	6-15 2	15-40 3	40-70 4	70-100 5	100-150 6
P Sorption Capacity						
Method 1	29.16	30.06	28.26	23.48	23.74	23.61
Method 2	32.77	30.06	33.80	27.87	28.64	27.87
Extractable Iron mmols/100 g.	27.57	30.79	36.35	43.50	51.57	51.39

SOIL CARIMAGUA II

Horizon Depth cm. Sample Number	0-30 7	30-70 8	70-100 9
P Sorption Capacity			
Method 1	81.94	28.64	28.38
Method 2	82.06	25.67	31.06
Extractable Iron mmol/100 g.	6.44	2.24	13.79

UPIN SOIL SERIES

Horizon Depth cm. Sample Number	0-3 10	3-10 11	10-55 12	55-105 13
P. Sorption Capacity				
Method 1	38.71	38.19	37.29	25.29
Method 2	42.58	37.42	40.00	26.19
Extractable Iron mmol/100 g.	22.92	23.10	26.14	21.31

GUAYURIBA SOIL SERIES

Horizon Depth cm. Sample Number	0-2 14	2-6 14	6-12 16	12-34 17	34-75 18	75-120 19	120-150 20
P Sorption Capacity							
Method 1	6.01	7.02	11.12	3.97	3.95	13.13	10.18
Method 2	5.57	7.15	10.19	4.33	2.16	12.88	9.13
Extractable Iron mmol/100g.	0.25	1.11	1.29	0.28	0.24	0.45	0.21

TABLE XIV (Continued)

GUAMAL SOIL SERIES

Horizon Depth cm.	0-4	4-8	8-50	50-110	110-150
Sample Number	21	22	23	24	25
P Sorption Capacity					
Method 1	21.80	21.62	21.55	42.32	7.22
Method 2	22.19	21.61	20.52	35.48	6.58
Extractable Iron mmol/100 g.	18.26	20.23	30.26	21.31	10.56

MINCO SOIL SERIES (OKLAHOMA)

Horizon Depth cm.	0-25	25-44	44-87	87-140
Sample Number	26	27	28	29
P Sorption Capacity				
Method L	8.15	8.50	10.68	12.64
Method 2	7.48	8.65	10.58	12.58
Extractable Iron mmol/100 g.	8.24	9.85	10.56	10.21

components of the soil responsible for phosphorus sorption are extracted and determined directly, by precipitation as phosphates. The active components of phosphorus retention by soils are mainly iron and aluminum compounds, so method #2 gives a measure of citric-acid-extractable aluminum and iron. With few exceptions, method #2 gave higher values for sorbed phosphorus, than method #1.

The alluvial Guayuriba soil has low phosphorus retention capacity. The other soils retain relatively large amounts of phosphorus, varying from 22 to 82 millimols/100 grams of soil. Similar values were obtained by Jenny and coworkers for tropical soils of Colombia (54).

The topsoil of the soil profile Carimagua II has an unusually high phosphorus sorption capacity. Clay content, extractable iron and exchangeable aluminum are normal for these soils. The amount of organic matter, however, is somewhat higher than for other soils. There is no apparent cause of the high power of phosphorus retention. This soil, as noted, has a poor drainage condition; this is the only fact that is unusual with respect to the other soils. There is no explanation why this soil with similar characteristics of the other soils should have an unusually high phosphorus sorption capacity

The high values for sorption capacity have some practical implications, since it is a major factor governing the magnitudes and interrelations of readily soluble phosphorus values measured by conventional dilute extractants (107). Sorption capacity has a definite influence on the uptake of the phosphorus by plants. The phosphorus uptake by plants has been related with the reciprocal of the sorption capacity of soils (80). Jenny et al. (54) also found an inverse relation between sorption capacity and plant growth for several tropical soils of Colombia.

Islam (50) and Islam and Rahman (51) have called attention to the importance of the "degree of phosphorus saturation" in the fertility status of a soil. These authors have demonstrated that the yield of lettuce increases with an increase in the percent of phosphorus saturation, but only to a certain extent, and a higher degree of saturation has no significant effect. They defined the required level of saturation as "sensitivity value." The degree of saturation should not be below this value in order to obtain satisfactory yields. For lettuce the sensitivy is between 4 and 6% of phosphate saturation.

In order to bring the phosphorus saturation up to 5% in the Eastern Plain soils it would be necessary to apply about 5000 Kg./hectare of treble superphosphate (45% P_2O_5) to the Carimagua I soil; 12,000 Kg./hectare to Carimagua II soil, 8000 to the Upin soil, 3000 to Guamal soil and 500 to the Guayuriba soil. These estimations agree with results obtained by Jenny et al. (54) for other tropical soils of Colombia, in which a satisfactory yield of lettuce was reached only when more than five tons of superphosphate (45% P_2O_5) were applied.

Some of the soil characteristics which are associated with the phosphorus sorption were studied statistically, by means of multiple linear regression analysis. There was a highly significant correlation between the phosphorus sorbed and the clay content ($r = 0.730$). Also there were highly significant correlations between phosphorus sorption capacity with organic carbon ($r = 0.535$); and with the extractable iron ($r = 0.537$). No significant correlations were found between exchangeable aluminum and phosphorus retention ($r = 0.199$). Other workers, however, have reported a close relation between phosphate retention and exchangeable aluminum (24, 33).

The corresponding single regression equations were as follows:

Y = Stands for phosphorus sorption capacity in millimols per 100 grams of soil

$Y = 19.37 + 4.537X_1$

where X_1 = exchangeable aluminum in millimols per 100 grams.

$Y = 15.45 + 0.375X_2$

where X_2 = extractable iron in millimols per 100 grams

$Y = 0.25 + 0.914X_3$

where X_3 = % of clay in soil

$Y = 16.67 + 6,762X_4$

where X_4 = % of organic carbon in soil

The multiple regression linear equation gave the following values:

$Y = 12.16 + 4.656X_1 + 0.376X_2$ and $Y = 2.01 + 0.714X_3 + 3.599X_4$

In these equations Y, X_1, X_2, X_3 X_4 have the same value as above.

The multiple correlation coefficients were highly significant:

$R_{Y}. X_1X_2 = 0.575$; $R_{Y}. X_3X_4 = 0.730$

$R_{Y}. X_1X_2$ is the multiple correlation coefficient; it measures the closeness of association between the phosphorus sorption capacity in millimols per 100 grams of soil (Y) and the exchangeable aluminum in millimols per 100 grams of soil (X_1) and extractable iron in millimols per 100 grams of soil (X_2) when both independent variables (X_1 and X_2) as considered together and their combined effect on Y is estimated (89). $R_{Y}. X_3X_4$ is the multiple correlation coefficient, which estimates the combined effect of the percent of clay (X_3) and the percent of organic carbon (X_4) on the phosphorus sorption capacity.

The partial correlation coefficient measures the closeness of association between the observed phosphorus sorption capacity Y and the exchangeable aluminum (X_1), for example, when the free iron (X_2) is held constant. It is represented $rYX_{1.}X_{2.}$

The values for partial correlation coefficients calculated for phosphorus sorption capacity and the soil characteristics are as follows:

$rYX_{1.}X_2 = 0.238$ n.s.[1/] $rYX_{3.}X_4 = 0.656$**[3/]

$rYX_{2.}X_1 = 0.546$*[2/] $rYX_{4.}X_3 = 0.616$**

The partial correlation coefficients indicate close relationships between phosphorus sorption capacity and free iron (X_2) when the exchangeable aluminum (X_1) is kept constant; the same is true for the correlation between phosphorus sorption capacity and the clay content (X_3), when the value for organic carbon is maintained constant and for the correlation between phosphorus sorption capacity and the organic carbon content (X_4) when the clay content is kept constant. But no relationship exists between phosphorus sorption capacity and exchangeable aluminum (X_1) when the value of free iron (X_2) is permitted to remain constant.

The main factor in determining the phosphorus sorption capacity is the clay content, which consists of kaolinite, a source of exchange

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[1/] Y = Phosphorus sorption capacity (mmols/100 g. soil). n.s. = nonsignificant
X_1 = Exchangeable aluminum (mmols/100 g. soil). *Significant at 5% level of confidence.

[2/] X_2 = Free iron (mmols/100 g. soil). **Significant at 5% level of confidence.

[3/] X_3 = Clay content in percent. **Significant at 1% level of confidence.
X_4 = Organic carbon content in percent. **Significant at 1% level of confidence.

aluminum, as well as the oxides and hydroxides of iron and aluminum. The organic matter appeared to be as important as the mineral colloids in determining the retention capacity of phosphorus by these soils. This finding is in agreement with those of other workers (77, 107). The relationship between the organic matter and phosphorus retention is probably due to presence of considerable proportions of active aluminum and possibly iron which occur in intimate association with the organic matter (105). The extractable iron correlates significantly with phosphorus retained by soil. In some cases the iron exceeds the value of phosphorus sorbed. Not all of the free iron, however, combines with phosphate. It is known that some iron and aluminum form stable complexes with some of the organic matter fractions and the ions so complexed are not available for reaction with phosphate (56), but the reduction-chelation treatment possibly dissolves such complexes. The aluminum oxides were not analyzed separately, because an estimation of the iron plus aluminum oxides is obtained by the Bass and Sieling (5) method #2. If this is true, obviously the extractable aluminum must be significantly correlated with the phosphorus sorption capacity. The lack of correlation between the retained phosphorus and exchangeable aluminum has no explanation, perhaps a refinement of the method of aluminum determination is needed.

Samples of all profile horizons were saturated with potassium phosphate, the excess removed and then the retained phosphorus was fractionated according to the Chang and Jackson procedure. The results are reported in Table XV. Values are reported in millimols per 100 grams of soil and as percent of the total phosphorus extracted with different solvents.

Some of the phosphorus was retained as "saloid-bound phosphate" (NH_4Cl soluble). The amount of phosphate retained as calcium phosphate is

TABLE XV. PHOSPHORUS FRACTIONATION OF PHOSPHATE SATURATED SOILS OF COLOMBIA AND OKLAHOMA

Sample Number	Horizon Depth cm.	NH_4Cl mmol/100g.	Soluble P* %	$Ca-PO_4$ mmol/100g.	$Ca-PO_4$ %	$Al-PO_4$ mmol/100g.	$Al-PO_4$ %	$Fe-PO_4$ mmol/100g.	$Fe-PO_4$ %	Σ of P Fractions mmol/100g.
					SOIL CARIMAGUA I					
1	0-6	4.19	10.93	0.37	0.97	27.11	70.71	6.67	17.40	38.34
2	6-15	4.43	12.16	0.30	0.82	25.40	69.74	6.29	17.27	36.42
3	15-40	3.74	9.40	0.31	0.78	30.52	76.74	5.20	13.06	39.77
4	40-70	3.39	9.85	0.25	0.73	27.14	78.83	3.65	10.60	34.43
5	70-100	3.35	10.02	0.33	0.99	26.11	78.10	3.64	10.89	33.43
6	100-150	2.97	10.03	0.29	0.98	22.70	76.69	3.69	12.30	29.60
					SOIL CARIMAGUA II					
7	0-30	10.13	10.99	0.27	0.29	79.19	85.95	2.55	2.77	92.14
8	30-70	2.06	5.50	0.15	0.40	34.27	91.56	0.95	2.54	37.43
9	70-100	2.32	5.52	0.20	0.45	39.80	89.48	2.16	4.86	44.48
					UPIN SOIL SERIES					
10	0-3	0.42	1.12	0.38	1.02	21.77	58.18	14.85	39.68	37.42
11	3-10	0.39	1.01	0.37	0.96	21.77	56.59	15.94	41.43	38.47
12	10-55	2.64	6.91	0.38	1.00	21.21	55.55	13.95	36.54	38.18
13	55-105	1.13	3.73	0.28	0.92	17.14	56.59	11.74	38.76	30.29

TABLE XV. (Continued)

Sample Number	Horizon Depth cm.	NH_4Cl mmol/100g.	Soluble P* %	$Ca-PO_4$ mmol/100g.	%	$Al-PO_4$ mmol/100g.	%	$Fe-PO_4$ mmol/100g.	%	Σ of P Fractions mmol/100g.
				GUAYURIBA SOIL SERIES						
14	0-2	1.34	24.19	0.07	1.26	3.79	68.41	0.34	6.14	5.54
15	2-6	1.40	16.79	0.08	0.96	5.16	61.87	1.70	20.38	8.34
16	6-12	1.57	15.18	0.09	0.87	6.16	59.57	2.52	24.37	10.34
17	12-34	0.61	12.92	0.04	0.85	3.50	74.15	0.57	12.08	4.72
18	34-75	0.51	11.46	0.05	1.12	3.47	77.98	0.42	9.44	4.45
19	75-120	1.01	7.03	0.08	0.56	12.62	87.88	0.56	4.53	14.36
20	120-150	0.53	4.49	0.06	0.51	10.97	92.89	0.25	2.12	11.81
				GUAMAL SOIL SERIES						
21	0-4	3.10	13.00	0.20	0.84	14.11	59.16	6.44	27.00	23.85
22	4-8	2.97	12.02	0.24	0.97	13.55	54.84	7.95	32.17	24.71
23	8-50	3.18	13.45	0.22	0.93	14.71	62.20	5.54	23.42	23.65
24	50-110	5.39	10.14	0.24	0.45	44.35	83.40	3.20	6.02	53.18
25	110-150	0.87	10.97	0.08	1.01	5.73	72.17	1.26	15.87	7.94
				MINCO SOIL SERIES (OKLAHOMA)						
26	0-25	1.53	16.12	0.56	5.90	6.45	67.97	0.95	10.01	9.49
27	25-44	1.55	16.33	0.51	5.37	6.61	69.65	0.82	8.64	9.49
28	44-87	1.76	17.81	0.60	6.07	6.77	68.52	0.75	7.59	9.88
29	87-140	1.81	16.87	0.79	7.36	6.81	63.47	1.32	12.30	10.73

*Phosphate soluble in iN ammonium chloride.

very low; in almost all samples it was less than one percent. In the Minco soil it reaches six to seven percent of the total phosphorus sorbed; this value is low, however, if compared with the quantity of exchangeable calcium and magnesium. This fact is in agreement with that reported by Chang and Chu (15) who found that little calcium phosphate is formed, by addition of soluble phosphate, even to calcareous soils. A great proportion of the phosphate is recovered as aluminum phosphate. Between 55 and 93% of the total retained phosphorus was found as aluminum phosphate on all soils studied. The iron phosphate represents from 2 up to 41% of the sorption capacity. The higher proportions of iron phosphate are found in the Upin soil and the lowest values correspond to the Guayuriba soil. The added values of the calcium, aluminum and iron phosphates are generally higher than the phosphorus sorption capacity.

The fractionation of the phosphorus saturated soil clearly shows that after short periods of soil-phosphorus contact the phosphate is mainly combined as aluminum phosphate, followed by iron phosphate and saloid-bound phosphate, or soluble phosphate, and only to a minor extent as calcium phosphate. This distribution is in agreement with findings reported by several workers (14, 15, 21, 58, 71, 95, 111).

Saloid-bound phosphate decreases with time and amount of iron phosphate increases and the aluminum phosphate decreases accordingly, therefore, the applied phosphorus becomes less and less available.

An experiment was carried out in order to observe the effect of lime and silicate treatments on the release of phosphorus on the retention of phosphorus by the soil and subsoil of each profile. The pH values after the equilibration period were taken in soil paste are given in Table XVI. In general there was a good correspondence between the pH

TABLE XVI. pH VALUES OF THE SOILS TREATED WITH CALCIUM CARBONATE AND SODIUM SILICATE TAKEN AT SOIL PASTE AFTER EQUILIBRATION PERIOD

Soil	Sample Number	Treatments A*	B*	C*	D*	E*	F*
Carimagua I							
Soil	1	4.50	5.58	6.18	5.50	5.87	6.11
Subsoil	2	4.52	5.63	6.22	5.50	5.92	6.38
Carimagua II							
Soil	7	4.68	6.15	6.69	5.77	6.02	6.42
Subsoil	8	4.62	5.62	6.68	5.75	6.05	7.45
Upin							
Soil	10	5.05	5.95	6.55	6.42	6.71	7.08
Subsoil	11	4.81	6.15	6.65	6.30	6.62	7.00
Guayuriba							
Soil	15	5.20	--	5.80	6.92	7.48	8.40
Subsoil	16	4.40	5.12	6.50	6.20	6.72	7.58
Guamal							
Soil	21	4.15	4.90	5.15	5.70	6.01	6.46
Subsoil	22	4.15	5.30	6.05	5.70	5.85	6.52

*Treatments: A check
B = $CaCO_3$ added to obtain 40% base saturation
C = $CaCO_3$ added to obtain 80% base saturation
D = Sodium silicate added at the rate of 1000 Kg. Si02/hectare
E = Sodium silicate added at the rate of 2000 Kg. Si02/hectate
F = Sodium silicate added at the rate of 4000 Kg. Si02/hectare

TABLE XVII. PHOSPHORUS RELEASED BY SOILS TREATED WITH CALCIUM CARBONATE AND SODIUM SILICATE

Soil	Carimagua I		Carimagua II		Upin		Guayuriba		Guamal	
Treatment	Soil	Subsoil	Soil	Subsoil	Soil	Subsoil	Soil	Subsoil	Soil	Subsoil
	P (PPM)	P (PPM)	P (PPM)	P (PPM)	P (PPM)	P (PPM)	P (PPM)	P (PPM)	P (PPM)	P (PPM)
A = Check	2.1	0.5	30.2	2.1	53.1	24.4	35.1	12.6	32.0	18.2
B = $CaCO_3$ to 40% base Sat.	1.8	0.5	30.6	2.1	49.5	24.8	--	12.2	32.0	18.0
C = $CaCO_3$ to 80% base Sat.	2.1	0.4	30.9	8.6	54.5	24.5	36.4	11.2	30.7	18.2
D = Sodium Silicate, 1000 Kg SiO_2/hectare	3.6	1.9	38.3	3.6	56.7	29.1	32.4	12.4	30.7	18.3
E = Sodium Silicate, 2000 Kg SiO_2/hectare	3.9	2.1	35.1	3.0	59.0	27.4	30.6	14.7	30.2	18.0
F = Sodium Silicate, 4000 Kg SiO_2/hectare	4.1	2.1	37.6	5.4	59.0	27.5	33.0	18.9	28.8	18.5

and the level of base saturation.

The data on the effect of the lime and silicate treatments on solubilization of native phosphorus is given in Table XVII. The two levels of calcium carbonate do not produce any liberation of phosphorus, but rather a decline in soluble phosphorus is observed in some cases. It has been found that lime applications to tropical soils does not increase neither the amount of available nor the uptake of phosphorus by plants, but the combined application of lime and phosphate fertilizer is usually beneficial, because a better utilization of the applied phosphorus is obtained (54).

With two exceptions, (Guayuriba and Guamal soils) the silicate treatments increased the amounts of available phosphorus; in some cases to a considerable extent. The different rates of applied silica seem to have no significant effect upon the phosphorus liberation. Some beneficial effect of the application of silica in the field would be expected in view of the present results; but the application of silicates under field conditions is impracticable because of the high cost of the soluble silica product. The use of silica phosphates, such as Rhenania phosphates, silica-magnesium-phosphates and basic slags may be recommended in order to use the apparent desirable fertility effects of the silicate.

A final experiment was devised for estimating the effects of calcium carbonate and sodium silicate upon the retention of applied phosphorus to the soil. Rates of 100, 200, 400 and 800 parts per million of phosphorus were applied to all soils except Carimagua II, which received 200, 400, 800 and 1600 parts per million of phosphorus. The amounts of phosphorus recovered, in parts per million and the amount retained in percent, for the first rate of phosphorus, i.e. (200 P.P.M. for Carimagua II and 100 P.P.M. for other soils) are reported in Table XVIII. The data for

TABLE XVIII. RECOVERY OF ADDED PHOSPHORUS IN P.P.M. FROM SOILS TREATED WITH CALCIUM CARBONATE AND SODIUM SILICATE AND AMOUNT SORBED, AS PERCENT OF THE QUANTITY OF PHOSPHORUS ADDED

Sample No.	Soils	Treatments P Added PPM	A* P(PPM)	A* %	B* P(PPM)	B* %	C* P(PPM)	C* %	D* P(PPM)	D* %	E* P(PPM)	E* %	F* P(PPM)	F* %
	Carimagua I													
1	Soil	100	49.9	50.1	50.4	49.6	50.8	49.8	48.4	51.6	48.5	51.5	48.6	51.4
2	Subsoil	100	52.3	47.7	52.4	47.6	52.7	47.3	51.3	48.7	50.3	49.7	49.9	50.1
	Carimagua II													
7	Soil	200	77.8	61.1	81.4	59.3	82.1	58.9	69.2	65.4	80.6	59.7	72.1	50.4
8	Subsoil	200	94.6	52.7	95.2	52.4	95.8	52.1	95.4	52.3	99.2	50.4	83.4	58.3
	Upin													
10	Soil	100	58.9	41.1	62.5	37.5	59.8	40.2	51.8	48.2	56.7	43.3	50.7	49.3
11	Subsoil	100	52.6	47.4	52.2	47.8	55.2	44.8	47.4	52.6	57.8	42.2	51.0	49.0
	Guayuriba													
15	Soil	100	71.6	28.4	--	--	76.7	23.3	75.1	24.9	80.6	19.4	80.5	19.5
16	Subsoil	100	77.9	22.1	80.5	19.5	84.3	15.7	77.0	23.0	77.0	23.0	70.8	29.2
	Guamal													
21	Soil	100	67.5	32.5	72.0	28.0	76.5	23.5	67.8	32.2	70.5	29.5	75.7	24.5
22	Subsoil	100	55.8	44.2	58.2	41.8	62.8	37.2	58.7	41.3	60.5	39.5	57.7	42.3

*Soil Treatments:
A = Check
B = $CaCO_3$ added to obtain 40% base saturation
C = $CaCO_3$ added to obtain 80% base saturation
D = Sodium Silicate added at the rate of 1000 SiO_2 Kg./hectare
E = Sodium Silicate added at the rate of 2000 SiO_2 Kg./hectare
F = Sodium Silicate added at the rate of 4000 SiO_2 Kg./hectare

the other rates are given in Tables XX and XXI in the appendix. The Carimagua I soil retained about one half of the applied phosphate. The Carimagua II soil retained about 60% of the applied phosphorus in the topsoil and 52% in subsoil. This soil exhibits the highest power of retention, which is in agreement with its high phosphorus sorption capacity. The Upin soil retained more phosphorus in the subsoil (47%) than in the surface soil (40%). The Guayuriba soil retained only about 26% of the applied phosphorus. The Guamal soil sorbed about 30% of 100 P.P.M. of phosphorus applied in topsoil and about 40% in subsoil. Ranking the soils according to increasing amounts of phosphorus retained in this experiment and comparing with the phosphorus sorption capacity, some relations are noted in Table XIX.

TABLE XIX. RELATION BETWEEN PHOSPHORUS SORPTION CAPACITY AND PHOSPHORUS RETAINED BY THE SOILS IN PERCENT OF THE QUANTITY APPLIED

Soil	Rank	P Retained % (Treatment)	Rank	P Sorption Capacity
Guayuriba soil	1	28	1	7 m mol/100g.
Guamal soil	2	32	2	21 m mol/100g.
Upin soil	3	41	4	38 m mol/100g.
Carimagua I soil	4	50	3	29 m mol/100g.
Carimagua II soil	5	61	5	81 m mol/100g.

No clear effect of lime on the retention of phosphorus is noticed from the data of Tables XVIII and XX, in spite of the considerable effect of the treatments in raising the pH. In some cases there is an increase in the amount of phosphorus released, but in other cases the lime induced a decrease in the recovery of applied phosphorus.

Raising the pH due to application of lime, permits the precipitation of aluminum (79). It was thought that by decreasing the exchangeable aluminum content a decline in the phosphorus sorption power of soils would be obtained. But this effect was not noticeable in the experiments reported here. The failure of the lime to decrease the sorption of the phosphorus may be due to an inherent dependence or no relation between exchangeable aluminum and phosphorus sorption capacity or it may be that the freshly precipitated hydrated aluminum oxides are as active as exchangeable aluminum in the retention of phosphorus.

The silicate ion seems to have a little or no effective action in decreasing the sorption of phosphorus by soil. In some cases conspicuous differences between the check soil and the treated soils are shown. Unfortunately it was not possible to establish the statistical significance of these differences among treatments due to lack of replications. There were some cases in which silicate decreased the amount of phosphorus recovered, in relation to the check treatment. However, it seems safe to conclude that the lime and heavy doses of silicates do not reduce to a "practical" extent the phosphorus sorption power of these tropical soils.

SUMMARY AND CONCLUSIONS

Five representative profiles of the tropical soils of the Eastern Plains of Colombia and one profile of a Regosol associated with Reddish Prairie Soils of Oklahoma were selected for this study. Analysis of particle size distribution, pH, cation exchange capacity, exchangeable ions, total nitrogen, total phosphorus and organic matter were made.

The native phosphorus of each horizon was fractionated into organic and inorganic fractions. The inorganic phosphorus was partitioned into calcium phosphate, aluminum phosphate, iron phosphate, reductant soluble iron phosphate and occluded aluminum phosphate using a sequential extraction procedure developed by Chang and Jackson. The available phosphorus was determined by the Bray and Kurtz method #1. Correlation analyses were made between available phosphorus and each of the determined fractions.

The phosphorus sorption capacity was determined in each horizon. Multiple regression analyses were carried out relating the phosphorus sorption capacity with extractable iron, exchangeable aluminum, clay and organic carbon content. Samples were saturated with phosphate and then fractioned into calcium, aluminum and iron phosphates.

Samples were treated with calcium carbonate to obtain 40% and 80% base saturation, and with sodium silicate at rates of 1000, 2000, and 4000 Kg. SiO_2/hectate. After an incubation period, (one month for limed soils and 48 hours for silicate treatment soils), pH was taken; and phosphorus was extracted with Bray and Kurtz 1 extractant. Samples of each treated soil received 100, 200, 400, 800 P.P.M. of phosphorus from a solution of KH_2PO_4; mixed, kept for 24 hours, dried. Samples were taken and phosphorus extracted with Bray and Kurtz extraction solution 1, and sorbed phosphorus was determined.

From the results obtained in this study the following conclusions seem to be justifiable:

1. The Eastern Plains soils of Colombia, studied in this work are extreme to strongly acid, low in exchangeable bases and high in exchangeable hydrogen and aluminum. Cation exchange capacity has a higher correlation with organic carbon than with clay content. The organic carbon and total nitrogen are high at the surface and decrease very rapidly with depth.
2. Total phosphorus is highest in the surface and lowest in the last horizon. Parent material is low in phosphorus. There is a highly significant correlation between total phosphorus and organic carbon.
3. Organic phosphorus constitutes the largest fraction (54-77%) of the total phosphorus. The mean C:N: organic P ratio is 81:10:1.
4. Reductant soluble iron phosphate is the dominant form of the inorganic phosphorus fractions followed by iron phosphate, aluminum phosphate and a small amount of calcium phosphate. In the Minco soil calcium phosphate is responsible for about ½ of the total phosphorus, followed by organic phosphorus and reductant iron phosphate , iron phosphate and aluminum phosphate. There was a highly significant relation between available phosphorus of the Colombian soil and each of the phosphorous fractions, except the aluminum phosphate. The active phosphorus fractions consisted of 60-80% iron phosphate; 10-30%

aluminum phosphate; 2-10% calcium phosphate. This distribution is probably responsible for deficiency of available phosphorus for plant growth since the largest portion is unavailable or very low in available phosphorus to plants.

5. Phosphorus sorption capacity is high (22-82 m mol P/100 g. soil) in terrace soils and low in alluvial soils of the Eastern Plains. There was a highly significant correlation between phosphorus sorption capacity and clay content, organic carbon, extractable iron, and a non-significant correlation with exchangeable aluminum. Organic matter has a very important role in the retention of phosphorus.
6. Phosphate saturated samples retain phosphorus mainly as aluminum phosphate (55-93%) and iron phosphate (2-41%). Somewhat lower amounts of phosphorus (5-10%) is extractable by ammonium chloride and only a small quantity ($<$ 1%) is found as calcium phosphate, in Colombian soils; in the Minco soil calcium phosphate is higher (50%).
7. Lime applications have little effect upon the release of native phosphorus while silicate treatments increase the extractable phosphorus.
8. No "practical" effect of lime and silicate treatments is noticed on the reduction of the phosphorus sorption power of tropical soils.

Suggestions for Further Work

1. To establish the availability of the different phosphorus fractions, measuring phosphorus uptake, yield and phosphorus responses in pot and field experiments.
2. To determine the real effect of silicate on the availability of phosphorus.
3. To elucidate the detailed mineralogy of soil phosphorus by studying crystallization rates.

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APPENDIX

PROFILE DESCRIPTIONS

The descriptions of the soil profiles used in this work are given in the following paragraphs.

Profile 1. Soil Carimagua I

Location: Shown in photo-mosaic L-16-NW

Slope: 0-1%

Flood Hazard: Rare

Runoff: Moderately slow

Internal Drainage: Medium

Natural Drainage: Moderately well drained

Erosion: None

Vegetation: Savanna vegetation, gramineous and ciperaceous plants

Use: Range livestock

1.	0.00-0.06 m.	Silty clay loam; very dark gray brown (10YR 3/2 moist); granular; friable; medium to low organic matter content; pH 4.55.
2.	0.06-0.15 m.	Silty clay loam; dark brown (10YR 3/3 moist); subangular blocky; friable; low organic matter content;pH 4.62.
3.	0.15-0.40 m.	Silty clay loam; dark yellowish brown (10YR 4/4 moist); subangular blocky, friable; very low organic matter content; pH 4.63.
4.	0.40-0.70 m.	Silty clay loam, yellowish brown (10YR 5/6 moist); subangular blocky, friable; very low organic matter content; pH 4.89.
5.	0.70-1.00 m.	Silty clay loam, yellowish brown (10YR 5/6 moist) subangular blocky; no organic matter; pH 5.15.
6.	1.00-1.50 m.	Silt loam; yellowish brown (10YR 5/8 moist); subangular blocky; very friable; presence of iron concretions no organic matter; pH 5.10.

Remarks: In the fourth horizon there are mottlings of red color (2.5YR 4/6). In the fifth and sixth horizons the mottlings are abundant in the red colors (2.5YR 4/8).

Profile 2. Soil Carimagua II

Location: Shown in photo-mosaic L-16-NW

Slope: 0-1%

Runoff: Very slow

Internal Drainage: Slow

Natural Drainage: Imperfectly drained

Erosion: None

Vegetation: Grasses of wet lands

7.	0.00-030 m.	Silty clay loam; black (N 2/0 moist); subangular blocky; friable; high content of organic matter; pH 4.68.
8.	0.30-0.70 m.	Silty clay loam; light brownish gray (10YR 6/2 moist); some mottling yellowish brown (10YR 5/6 moist); subangular blocky; very friable low content of organic matter; pH 4.60.
9.	0.70-1.00 m.	Silty clay loam; light brownish gray (10YR 6/2 moist); abundant yellowish red (5YR 5/8 moist) mottlings; columar structure which breaks into subangular blocky; there are some iron and manganese concretions; low content of organic matter; pH 4.91.

Profile 3. Upin Soil Series

Location: "Territario Espinal" farm, Restrepo-Cumaral road; shown in photo-mosaic L-12-NW

Slope: 0-1%

Flood Hazard: Rare and by short periods

Runoff: Very slow

Internal Drainage: Slow to medium

Natural Drainage: Well drained

Erosion: None

Vegetation: Tall bunch grasses

Use: Livestock

10.	0.00-0.03 m.	Clay loam; reddish brown (5YR 4/3 dry); dark reddish brown (5YR 3/3 moist); weak subangular blocky; firm and slightly plastic and sticky; clear and smooth limit; pH 5.06.
11.	0.03-0.10 m.	Clay loam; reddish brown (5YR 4/4 moist) with a few yellowish red (5YR 5/8) mottlings; moderate blocky; slightly plastic and sticky; clear and smooth limit; pH 4.82.
12.	0.10-0.55 m.	Silt loam; reddish brown (2YR 4/4 moist); Medium moderate subangular blocky; slightly plastic and sticky; diffuse and smooth limit; pH 4.85.
13.	0.55-1.05 m.	Silty loam; reddish brown (2.5YR 4/4 moist); weak medium angular blocky; very friable; slightly plastic and sticky; abrupt and smooth limit; presence of rounded stones; pH 5.08.

Profile 4. Guayuriba Soil Series

Location: Shown in photo-mosaic L-12-NW

Slope: 0-2%

Flood Hazard: Frequent and regular

Runoff: Slow

Internal Drainage: Slow

Natural Drainage: Imperfectly drained

Erosion: None

Vegetation: Grasses (Hyparrenia Rufa)

Use: Range livestock

14.	0.00-0.02 m.	Sandy loam, very dark brown (10YR 2/2 moist); weak fine crumb; very friable; clear and smooth limit; pH 6.32.

15.	0.02-0.26 m	Sandy loam; dark brown (7.5YR 4/4 moist) and grayish brown (10YR 5/2 moist); granular; friable pH 5.20.
16.	0.06-0.12 m.	Sandy loam; yellowish brown (10YR 5/4 moist); moderate medium blocky; friable; slightly plastic and sticky; clear and smooth limit; pH 4.65.
17.	0.12-0.24 m.	Sandy loam; dark grayish brown (10YR 4/2 moist); weak medium blocks; friable; slightly plastic and sticky gradual and smooth limit; pH 4.69.
18.	0.34-0.75 m.	Sandy clay loam; grayish brown (10YR 5/2 moist); strong brown mottlings (7.5 YR 5/8 moist); very weak subangular blocky; friable; slightly sticky; diffuse and smooth limit; pH 4.68.
19.	0.75-1.50 m.	Sandy clay loam; gray (5YR 5/1 moist) with strong brown (7.5YR 5/8 moist) mottlings; moderate medium blocky; friable; plastic and sticky; clear and smooth limits; pH 4.30.
20.	1.50-1.80 + m.	Sandy loam; light gray (10YR 7/1 moist); with prominent strong brown (7.5YR 5/8 moist) mottling. It is very hard and strongly cemented when dry; plastic and sticky when wet. It appears as an accumulation layer; pH 4.45.

Profile 5. Guamal Soil Series

Location: Shown in mosaic L-16-NW

Slope: 1-2%

Flood Hazard: Rare

Runoff: Low

Internal Drainage: Low

Natural Drainage: Well drained

Erosion: None

Vegetation: Tall grasses

Use: Range livestock

21.	0.00-0.04 m.	Clay loam; dark grayish brown (10YR 4/2 moist) moderate fine crumb; friable; slightly plastic and sticky; clear and smooth limit; pH 4.15.
22.	0.04-0.08 m.	Loam; dark gray 10YR 4/1 moist) yellowish red (5YR 4/6 moist) mottlings moderate medium blocks; friable slightly plastic and sticky; clear and broken; pH 4.61.
23.	0.08-0.50 m.	Clay loam; strong brown (7.5YR 5/6 moist); moderate and medium blocks; friable; slightly plastic and sticky; diffuse and smooth limit; pH 4.15.
24.	0.50-1.10 m.	Clay loam; yellowish brown (10YR 5/8 moist); moderate medium blocks; friable; plastic and sticky; clear and smooth limit; pH 4.28.
25.	1.10-1.30 + m.	Sandy loam; reddish yellow (7.5YR 6/6) massive; very friable; slightly plastic and sticky; pH 4.62.

Profile 6. Minco Soil Series

Location: Hydro, Caddo County, Central Oklahoma

Slope: 2%

Flood Hazard: None

Runoff: Medium

Internal Drainage: Rapid

Natural Drainage: Somewhat excessively drained

Erosion: None

Vegetation: Grasses

Use: Livestock

26.	0.00-0.25 m.	Sandy loam; very dark brown (10YR 2/2 moist), dark brown (7.5YR 4/2 dry); weak medium granular; soft; very friable; clear and smooth limit; pH 6.12.
27.	0.25-0.44 m.	Sandy loam; very dark brown (10YR 3/3 moist); dark brown (7.5YR 3/2 dry); very weak granular; very friable; slightly hard; gradual and smooth limit; pH 6.71.

28.	0.44-0.87 m.	Sandy loam; brown (7.5YR 4/2 moist); reddish brown (5YR 4/3 dry); porous massive; friable; slightly hard; gradual limit; pH 7.17.
29.	0.87-1.40 m.	Loam; dark reddish brown (5YR 4/2 moist); reddish brown (5YR 4/4 dry); porous massive; friable; slightly hard; pH 7.41.

TABLE XX. RECOVERY OF ADDED PHOSPHORUS FROM SOILS TREATED WITH CALCIUM CARBONATE AND SODIUM SILICATE, IN PARTS PER MILLION

Soil Treatment Amounts of Phosphorus Added to Soils	A*		B*		C*		D*		E*		F*	
	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub - soil
SOIL CARIMAGUA I												
200 P.P.M.	101.9	110.7	102.2	110.7	105.1	111.6	103.1	107.8	104.6	108.1	102.6	105.4
400 P.P.M.	129.1	243.5	244.7	243.5	247.9	247.1	240.4	240.1	242.6	242.9	243.4	230.9
800 P.P.M.	496.9	505.5	495.4	505.5	497.9	514.7	448.	522.1	505.1	521.9	480.9	500.9
SOIL CARIMAGUA II												
400 P.P.M.	122.3	187.9	119.9	194.9	135.1	215.4	120.7	186.4	125.9	196.0	154.9	191.6
800 P.P.M.	341.8	369.4	339.9	372.9	345.6	387.9	342.7	374.9	354.9	382.0	322.8	376.0
1600 P.P.M.	632.3	632.9	641.9	637.9	654.1	686.4	624.2	646.4	644.9	672.5	6.9.9	6.2.1
UPIN SOIL SERIES												
200 P.P.M.	99.4	93.6	103.0	94.2	108.5	99.0	113.8	100.9	113.0	105.1	86.0	99.5
400 P.P.M.	227.4	249.1	230.5	250.7	228.0	253.5	216.3	244.4	225.5	248.1	221.5	239.5
800 P.P.M.	427.9	446.6	413.5	456.2	433.5	461.5	424.3	456.9	425.0	460.6	422.0	456.5
GUAYURIBA SOIL SERIES												
200 P.P.M.	136.9	153.9	--	156.3	169.6	157.8	175.6	155.1	179.9	153.8	180.5	136.1
400 P.P.M.	274.4	292.4	--	292.8	279.1	296.3	308.6	296.6	314.9	316.3	328.0	290.6
800 P.P.M.	594.9	592.3	--	601.6	672.6	620.6	604.6	597.9	660.4	599.3	658.0	560.8

TABLE XX (Continued)

Soil Treatment Amounts of Phosphorus Added to Soils	A*		B*		C*		D*		E*		F*	
	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil
						GUAMAL SOIL SERIES						
200 P.M.	134.5	127.8	133.0	128.0	137.8	133.8	135.3	129.7	138.3	132.5	132.7	135.3
400 P.P.M.	269.5	209.3	281.0	209.0	286.8	239.8	269.8	237.3	292.8	237.5	262.7	196.5
800 P.P.M.	563.5	511.3	556.5	504.3	568.9	516.7	561.3	504.0	569.3	512.0	577.9	520.0

*Soil treatments A = Check
B = $CaCO_3$ added to obtain 40% base saturation
C = $CaCO_3$ added to obtain 80% base saturation
D = Sodium silicate added at the rate of 1000 SiO_2 Kg./hectare
E = Sodium silicate added at the rate of 2000 SiO_2 Kg./hectare
F = Sodium silicate added at the rate of 4000 SiO_2 Kg./hectate

TABLE XXI. SORPBED PHOSPHORUS BY SOILS TREATED WITH CALCIUM CARBONATE AND SODIUM SILICATE, AS PERCENT OF THE PHOSPHORUS ADDED

Soil Treatment	A*		B*		C*		D*		E*		F*	
Amounts of Phosphorus Added to Soils	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil
CARIMAGUA I SOIL												
200 P.P.M.	49	45	49	45	47	44	48	46	48	46	49	47
400 P.P.M.	40	39	39	39	38	38	40	40	39	39	39	42
800 P.P.M.	38	37	38	37	38	36	44	35	37	35	40	38
CARIMAGUA II SOIL												
400 P.P.M.	69	53	70	51	66	46	70	53	68	51	61	52
800 P.P.M.	57	54	57	53	57	53	57	53	56	52	60	53
1600 P.P.M.	60	60	60	60	59	57	61	60	60	58	61	62
UPIN SOIL												
200 P.P.M.	50	53	48	53	46	50	43	49	43	47	57	50
400 P.P.M.	43	38	42	37	43	37	46	39	44	38	45	40
800 P.P.M.	46	44	46	43	46	42	47	43	47	43	47	43

TABLE XXI. (Continued)

Soil Treatment	A*		B*		C*		D*		E*		F*	
Amounts of Phosphorus Added to Soils	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil	Soil	Sub-soil
GUAYURIBA SOIL												
200 P.P.M.	32	23	--	22	15	21	12	22	10	23	10	32
400 P.P.MP	31	27	--	27	30	26	23	27	21	21	18	27
800 P.P.M.	32	23	--	25	16	22	24	25	17	25	18	30
GUAMAL SOIL												
200 P.P.M.	33	36	33	36	31	33	32	35	31	34	34	32
400 P.P.M.	33	48	30	48	28	40	33	41	27	41	34	51
800 P.P.M.	30	36	30	37	29	35	30	37	29	36	28	35

*Soil treatments A = Check
B = $CaCO_3$ added to obtain 40% base saturation
C = $CaCO_3$ added to obtain 80% base saturation
D = Sodium silicate added at the rate of 1000 SiO_2 Kg./hectare
E = Sodium silicate added at the rate of 2000 SiO_2 Kg./hectare
F = Sodium silicate added at the rate of 4000 SiO_2 Kg./hectare

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