# SOIL PHOSPHORUS FRACTIONATION
# AND PLANT GROWTH RELATIONSHIPS

by

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# II. INTRODUCTION

The measurement of phosphorus which is available to plants, is a problem closely related to the forms and amounts of phosphorus present in soils. Many of the methods, which are utilized in the measurement of available phosphorus, arenot well correlated with plant growth. Among the most probable causes of the low correlation coefficients between yield of plants and amounts of available forms, are the soil chemical properties and strength of the extracting solutions utilized to measure the amount of phosphorus which may be available to plants. In some cases, a particular extracting solution dissolves one or several chemical forms of phosphorus present in soils, some of which are taken up very slowly by plants or are insoluble in natural conditions. Therefore the extraction and determination of these quantities of soil phosphorus cause serious error in the estimation of the rates of phosphorus fertilizers that should be applied to soils to assure high yields of plants.

The fractionation of soil phosphorus, based on a series of extractions, is a procedure that has been utilized by many investigators. It is a reliable approach to determine the content of the various chemical forms of phosphorus in soils.

In the present study, this scheme was utilized in an attempt to improve and evaluate the effectiveness of some methods employed in the measurement of available phosphorus to plants. This was done in order to estimate more accurately the amounts of phosphorus fertilizer that should be applied to soils in order to increase the yield of plants. The present study had the following specific objectives:

1. To compare the relationships between inorganic forms of soil-bound phosphates determined by the procedure stated by Chang and Jackson (1957), and the yield of plants, grown in soils fertilized at various rates of phosphorus.

2. To compare two relationships: (a) between yield of plants and the amounts of that form of soil phosphate that appears to be the most available to plants and (b) between yield of plants and the amounts of $HCl$-$H_2SO_4$-extractable phosphorus of soils fertilized at various levels of phosphorus.

3. To study the effects of soils of different texture and fertilized with various rates of phosphorus, on the yield and uptake of phosphorus by plants.

# III. LITERATURE REVIEW

## Classification of the Soil Phosphorus Fractions

Phosphorus exists in soils in several forms and the chemical nature of each of these compounds determines its relative efficiency as a plant nutrient (Patel and Metha, 1961). Consequently the study of the soil factors that affect the availability of each soil phosphorus fraction may give some information as to the amount and the source of phosphorus that should be present in soils in order to obtain good crop yields.

Russell (1932) grouped the phosphorus compounds occurring in soils into:

(a) Inorganic phosphorus in neutral soils; probably a calcium phosphate: hydroxyapatite.

(b) Inorganic phosphorus in acid soils; presumably combinations with iron and aluminum oxides.

(c) Organic phosphorus compounds; presumably of value only after they have been decomposed by micro-organisms and their phosphorus converted into inorganic phosphates.

Based on this classification, Dean (1938) attempted to fractionate the soil phosphorus as a means to reproduce conditions somewhat analogous to the processes which are believed to proceed near the roots of plants. By extracting the soil phosphorus with sodium hydroxide, followed by acid solutions, he found that the amount of soil phosphorus soluble in sodium hydroxide was affected by the active calcium. He observed that sodium saturated soils need to be used when studying the alkali-soluble phosphorus. The acid-soluble phosphorous remaining in the soil appeared to be similar to the apatites.

Truog (1930) suggested that the designation of readily available phosphorus be used rather than available and unavailable in regard to phosphorus availability to plants. He reasoned that plants secure some phosphorus from even the most difficultly available forms. He classified the soil phosphorus compounds into two groups having widely different degrees of solubility and availability:

(a) The readily available phosphorus which dissolves rather quickly in a weak solvent.

(b) The difficultly available group which dissolves slowly in the same extracting solution.

Ghani (1943a) made a critical examination of the method employed by Dean (1938) with special reference to removal of exchangeable bases before extraction of the different forms of phosphorus. The pretreating agent should effect complete removal of the exchangeable bases without dissolving organic or inorganic phosphorus. For this purpose, hydrochloric acid did not prove to be satisfactory, since it dissolves appreciable amounts of iron phosphate and in some cases, organic phosphorus. On the other hand, dilute acetic acid dissolves the readily available phosphorus and removes exchangeable bases. The soil phosphorus extracted with 0.5<u>N</u> acetic acid was identified as monocalcium, dicalcium and tricalcium phosphate. Although the last form was found to be slightly less soluble, these compounds probably constitute the fraction that is highly available to plants. Further investigations of Chani and Aleem (1943b) indicate that the solubility of aluminum and iron phosphate in 0.5N acetic acid is extremely low. However, iron phosphate was found to be highly soluble in sodium hydroxide, but aluminum phosphate less soluble. The solubility of apatite remained unaffected by the previous acetic acid extraction, but it was dissolved in 2N sulphuric acid. Although this procedure of phosphorus extraction may be the basis of the soil phosphorus fractionation is not complete because aluminum phosphate can not be separated thoroughly from iron phosphate by using sodium hydroxide as the extractant.

Chang and Jackson (1957) studied the solubility properties of the soil phosphorus compounds in different extracting solutions and classified them into:

(a) Loosely bound phosphorus, soluble in 1N ammonium chloride

(b) Aluminum phosphate, soluble in 0.5N neutral ammonium fluoride

(c) Iron phosphate, soluble in 0.1N sodium hydroxide

(d) Calcium phosphate, soluble in 0.5N sulphuric acid

(e) Reductant-soluble or occluded phosphate. These forms of phosphorus are constituted mainly by coated aluminum and iron phosphate which remains insoluble in the ammonium fluoride and sodium hydroxide

(f) Organic phosphorus. This form of phosphorus is unavailable to plants and may be defined as the difference between total soil phosphorus and the sum of inorganic phosphorus.

The formation and distribution of these various forms of phosphorus in soils apparently is related to such soil factors as pH, activity of various cations, solubility products of the various forms of soil phosphorus, age and degree of chemical weathering, drainage and mineralogical nature of the soil. (Chang and Jackson, 1958).

According to Chu and Chang (1960) the distribution patterns of the inorganic phosphorus are greatly influenced by the age of the soil and the nature of the parent materials. Thus, for example, iron phosphates are most abundant in Latosols and Lateritic soils; and both the iron phosphate and aluminum phosphate are abundant in acid sandstone, shale, and alluvial soils.

## The Status of the Methods of Available Phosphorus Determination

Dickman and Bray (1941) proposed, as a soil phosphorus extractant, 0.1N ammonium fluoride, since it was found that complete recovery of the phosphate added was obtained by shaking 1 g. of kaolinite with 50 ml. of 0.1N ammonium fluoride for one minute. Swenson, Cole and Sieling (1949) indicated that neutral ammonium fluoride reacts with $Al(OH)_3$ gels to form $(NH_4)_3AlF_6$ and the phosphate adsorbed by these gels is more or less completely released by the action of fluoride. On the other hand, $Fe(OH)_3$ gels at neutral pH are apparently not attacked by the fluoride ion. Turner (1952) concluded that the efficiency of neutral $NH_4F$ as an extractant of phosphate adsorbed by $Al(OH)_3$ is explained by the stability of $(NH_4)_3AlF_6$ in neutral and alkaline solutions.

Thompson and Pratt (1954) compared 0.025N HCl + 0.03N $NH_4F$, or Bray No. 1 (Bray and Kurtz, 1945), and 0.1N HCl + 0.03N $NH_4F$, or Bray No. 2, with plant yield. Bray No. 1 correlated better with yield than Bray No. 2. Similar results were obtained by Pratt, et al. (1955a). This may be due to the fact that Bray No. 2 gives a serious overestimation of the plant available phosphorus in soils that have large amounts of acid-soluble phosphates.

Olsen and Cole (1954) proposed 0.5M $NaHCO_3$ at pH 8.5 as an extractant for calcareous soils. This solution increases the extractable phosphate as a result of lowering the calcium activity in solutions and because of its alkaline reaction also dissolves phosphorus from iron and aluminum complexes. The Soil Test Work Group (Soil Tests, 1956) compared many extracting solutions for the determination of available phosphorus in relation to the Neubauer test. In 13 soil types of different characteristics, 0.025N HCl + 0.025N $H_2SO_4$ showed the highest correlation coefficient ($0.87^{**}$) of all solutions. Welch, et al. (1957) compared this $HCl$-$H_2SO_4$ solution, 0.5M $NaHCO_3$ (pH 8.5) and Bray No. 1 in order to estimate the availability of phosphorus to

Ladino clover. All solutions proved to be statistically similar and tended to give high correlation coefficient for the Eutaw and Cecil series and rather low correlation coefficients in the Norfolk series. Similar results were obtained by Bhangov and Smith (1957). The 0.5M $NaHCO_3$ was compared to Bray No. 1 in wheat experiments.

Fife (1959a) showed that $NH_4F$ is more efficient extractant of phosphorus than $NH_4Cl$. In a second experiment (Fife, 1959b) the solubility of phosphate in 0.5M $NH_4F$ was studied in a number of New Zealand soils, using a range of pH values. The results obtained showed that the most selective delineation of aluminum-bound soil phosphate from iron-bound phosphate by this extractant is likely to be attained at approximately pH 8.5.

Breland and Sierra (1962) comparing various soil phosphorus extracting solutions, found that 0.025M HCl + 0.03M $NH_4F$ and 0.05M HCl + 0.025M $H_2SO_4$ removed the largest amount of soil phosphorus. However, the fact that the concentration of phosphorus measured by each extracting solution was not correlated with plant growth, renders their studies useless.

Chang and Juo (1963) compared seven extractants for the determination of available phosphorus in soils previously classified according to their predominant form of inorganic phosphate.

| Method No. | Extracting Solution | Author |
|---|---|---|
| 1 | 0.002N $H_2SO_4$ | Truog |
| 2 | 0.05N HCl + 0.025N $H_2SO_4$ | Soil Test (N.C.St.) |
| 3 | 1N NaOAc + 1N HAc | Peech |

| Method No. | Extracting Solution | Author |
|---|---|---|
| 4 | 0.5M $NaHCO_3$ | Olsen |
| 5 | 0.025N HCl + 0.03N $NH_4F$ (No. 1) | Bray |
| 6 | 0.1N N HCl + 0.3N $NH_4F$ (No. 2) | Bray |
| 7 | 0.1N HCl + 0.5N $NH_4F$ (No. 4) | Bray |

The 26 soils utilized were classified as high in calcium phosphate, high in iron phosphate, or high in aluminum phosphate. The dilute acid (Method No. 1), extracted more available phosphorus because of dissolution of calcium phosphate. Method No. 3 extracted more calcium phosphate but little aluminum phosphate. Method No. 3 showed no differences between forms of phosphorus. Method No. 4 dissolved more iron phosphate. Methods No. 5, No. 6, and No. 7 appeared to be similar. However, Method No. 7 extracted more aluminum phosphate. Method No. 7 extracted equal amounts of aluminum, iron and calcium phosphate. Consequently, if aluminum phosphate is the main source of phosphorus, fluoride extractions are more reliable. For soils high in iron phosphate, alkaline extractants are more useful. For soils high in calcium phosphate, the acid extractants are preferable. Although this approach is realistic, it is difficult to decide how high in aluminum, iron and/or calcium a soil should be, before any extracting solution is selected for the determination of available phosphorus.

## Transformation of Phosphorus Fertilizer in Soils

It has been clearly demonstrated that soluble phosphorus fertilizers, when applied to soils, immediately react with cations present in the soil solution or held on the surface of the soil colloids (Davis, 1943). In order to understand whether phosphorus is held by the coarse and fine fraction of kaolinite and montmorillonite, both free iron and aluminum oxides should be removed. Coleman (1944), after a series of experiments, arrived at the conclusion that mica, quartz, kaolinite and montmorillonite, when deprived of their free aluminum and iron oxides, are unable to react appreciably with phosphorus.

Ghani and Islam (1946) incubated mixtures of soils and phosphatic fertilizers at the optimum moisture content to obtain information regarding the nature of phosphates formed in soils during the reaction period. The samples were fractionated at periodic intervals. They found that as the amount of phosphorus added increased, the available phosphorus also increased but not in the same proportion. This amount tended to decrease after 2 weeks and then remain constant. More than 90% of the reacted phosphorus was recovered as aluminum and iron phosphate, showing that chemical precipitation of the compounds was the principal nature of the reaction. Similar results were obtained by Haseman, Brown and Whitt (1950).

Cole and Jackson (1950) identified the chemical composition of the aluminum and iron phosphate formed in acid soils through addition of phosphorus. The minerals formed were identified as $Al(OH)_2HPO_4$ (variscite) and $Fe(OH)_2HPO_4$ (strengite). The pK values were determined to be 29 and 35 respectively. These constants relate the equilibrium concentration (availability) of phosphorus directly to the aluminum and iron activities of the soil. Hemwall (1957) found that the rate of formation of variscite dependent upon the rate at which the clay replenishes the solution with soluble aluminum, and that this reaction is very fast in the presence of exchangeable aluminum. In calcareous soils, Cole and Olsen (1959a) demonstrated that the chemistry of phosphorus is mutually interdependent on the pH, $Ca^{++}$, $H_2PO_4^-$ and $HPO_4^{--}$ concentrations. The concentration of phosphorus in equilibrated soil solutions being inversely related to the calcium concentration and indirectly to the pH as it affects the dissociation of phosphoric acid and the ratio of the $H_2PO_4^-$ and $HPO_4^{--}$ ions. The validity of this observation is based on the fact that the ionic product $aCa^{++} \times aHPO_4^{--}$ in various solutions in equilibrium with a given soil, remains constant over a range of values of pH and calcium concentration. Further studies of Cole and Olsen (1959b) in calcareous soils, have indicated that when a given amount of phosphorus fertilizer is added to a series of soils of the same phosphorus solubility and in a range of textural properties, the solubility of phosphorus in the sandy loam textures increases more than in the clay textures under the same treatments. The results show that phosphorus solubility in calcareous soils is directly related to the amount of surface area and to the percentage of phosphorus saturation on these surfaces. This provides a means of calculating the amounts of phosphorus additions required to bring a group of soils to the same level of soluble phosphorus.

Lindsay, Lehr, and Stephenson (1959) investigated the nature of the reactions of monocalcium phosphate (the major component of superphosphate) in the immediate vicinity of a band placement of this substance in the soil to characterize the movement of moisture into the fertilizer band, to determine the composition of the solution leaving the band and to observe changes in this solution as it moves away from the band to form a wetted zone in the surrounding soil. Their results indicate that the solution sampled at the fertilizer band approximate very closely the composition of the metastable triple point solution in which phosphorus is 3.98*M*, calcium is 1.44 *M* and pH is 1.48. This highly concentrated solution moves slowly away from the fertilizer band into the partially dried soil dissolving aluminum, iron, magnesium and other constituents from the soil. In this complex chemical matrix, many different phosphate compounds of aluminum, iron, calcium and magnesium precipitate as the solution reacts with more soil and the pH rises gradually to that of the surrounding soil. Hsu and Jackson (1960) found that within a soil pH range from 6 to 7, the aluminum and iron phosphate thus formed remained stable. Above this range, the calcium phosphate is more stable.

Regardless of the soil pH, Cheng and Chu (1961) clearly showed that over comparatively short periods and in a relatively dry soil, the first step of the reaction of added soluble phosphate and the soil colloids is the formation of variscite followed by strengite and then by the hydroxy apatities. When time of contact is prolonged, the amount of variscite and hydroxy apatite decreases and the amounts of strengite increases. Their results suggest that since phosphoric acid is added to the clays, the content of aluminum in solution is much higher than that of either iron or calcium. Therefore, the added phosphate is most likely to be transformed into variscite.

Similar results were obtained by Chu, Moschler and Thomas (1962). When rock phosphate was applied to acid soils, it apparently was decomposed by the acid into monocalcium phosphate which ionized to calcium and $H_2PO_4^-$ and finally into aluminum phosphate.

That aluminum-bound phosphate is the first product of the reaction of added phosphorus and the soil, has been demonstrated by Baker and Dunbar[1] (1963). Radioactive phosphorus was equilibrated with the soils for certain lengths of time. The radioactivity of the phosphorus in the aluminum and iron fractions was measured and compared to that of phosphorus at equilibrium. In all cases, the percentage of radioactive phosphorus was much higher in aluminum phosphate than in iron phosphate. The results clearly show that $Al(OH)_2HPO_4$ is the first product of the reaction of phosphorus. The lapse between the formation of aluminum and iron phosphate depends upon weathering and probably upon the relative content of aluminum and iron of the soil.

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[1]Baker, D. E. and Dunbar, A. D. Pennsylvania State University. Unpublished Research. 1963.

## The Supply Pattern of Phosphorus for Plant Growth

The relationships between plant uptake of phosphorus and the phosphorus supply of soils is neither well defined or well understood. The main difficulty is in both the measurement and understanding of the ever changing supply of phosphorus to the plant (Fried and Shapiro, 1956). At any instant during the growth of plants in soils, there is a given supply of phosphorus to the plant if the plant feeds only from the soil solution. This instantaneous supply is the amount _factor_. However, if the plant takes phosphorus from solution only, then the phosphorus in the soil solution would have to be renewed many times per day to give the total uptake of phosphorus absorbed by plants. The phosphorus from which the solution phosphorus comes may be considered as the _capacity factor_, analogous to total acid present in the hydrogen system. By means of continuous soil leaching of a soil with water or a weak extracting solution, the renewal rate of phosphorus may be determined and if soils showing similar pattern of phosphate release are compared, the initial water extract is a relatively better measurement of plant available phosphorus.

Olsen and Watanabe (1963) estimated theoretical values of phosphorus renewal rate for different textures since, in most instances, these values can not be measured practically, especially when the time required for phosphorus to diffuse from the soil colloid to the soil solution is nearly zero. The results indicate that the diffusion coefficient of phosphorus, $D_p$, expressed in $cm^2/sec$ measures its renewal rate and this coefficient increases as the percentage of clay increases. This is due to the fact that in the 3 layer clays, the distance traveled by phosphorus from one surface to the nearest one, is much smaller than that of the coarser textures.

The relation between phosphorus in solution (or the intensity factor) and the ability of the soil to provide this phosphorus (or capacity factor-probably aluminum phosphate), is given by the regression coefficient, b, of these variables. According to Olsen and Watanabe (1963) the uptake of phosphorus by plants is given by the expression $\sqrt{bD_p}$. Consequently, it is expected that as the percentage of clay increases, the uptake of phosphorus by plants will always be higher in clays than in sandy textures. By comparing the actual relative uptake of phosphorus by plants with those values predicted by the expression $\sqrt{bD_p}$, it would be possible to predict the phosphorus requirements for a good plant yield.

# IV. MATERIALS AND METHODS

## Soils Selected for the Investigation

During the fall of 1962 and the summer and the fall of 1963, soil samples were taken from Virginia to provide a rather wide range of soil properties. The location of the samples are given in Figure 1. The mechanical analysis and the chemical characteristics of each soil sampled are given in Table 1 and 1a.

## Preparation of Soil Samples

For this investigation, the soil samples were dried and sieved through a 4 mesh screen. Lime was added as $CaCO_3$ to about ph 6.0, except for the Westmoreland s.c.l. and Huntington l. soils. These two soils had pH values of 7.4 and 6.5, respectively. Nitrogen was supplied as $NH_4NO_3$ and potassium as KCl to prevent deficiencies of these nutrients in the plants studied. Phosphorus was applied as $Ca(H_2PO_4)\ H_2O$ in solution to each pot.

## Plant Growth Experiments

<u>Greenhouse Experiment with Ladino Clover</u>.

During the fall of 1962, a four (soils) x four (phosphorus rates) x three (replications) factorial experiment was designed for greenhouse conditions to study the relation between the yield of Ladino clover and the soil phosphorus fractions of a Sassafras s.l., Nason s.l., Davidson c. and Westmoreland si.c.l. Phosphorus was applied to each two kilograms of dried soil at the rate of 0.0, 25.0, 50.0 and

Figure 1.- Location of the soils selected for the investigation.

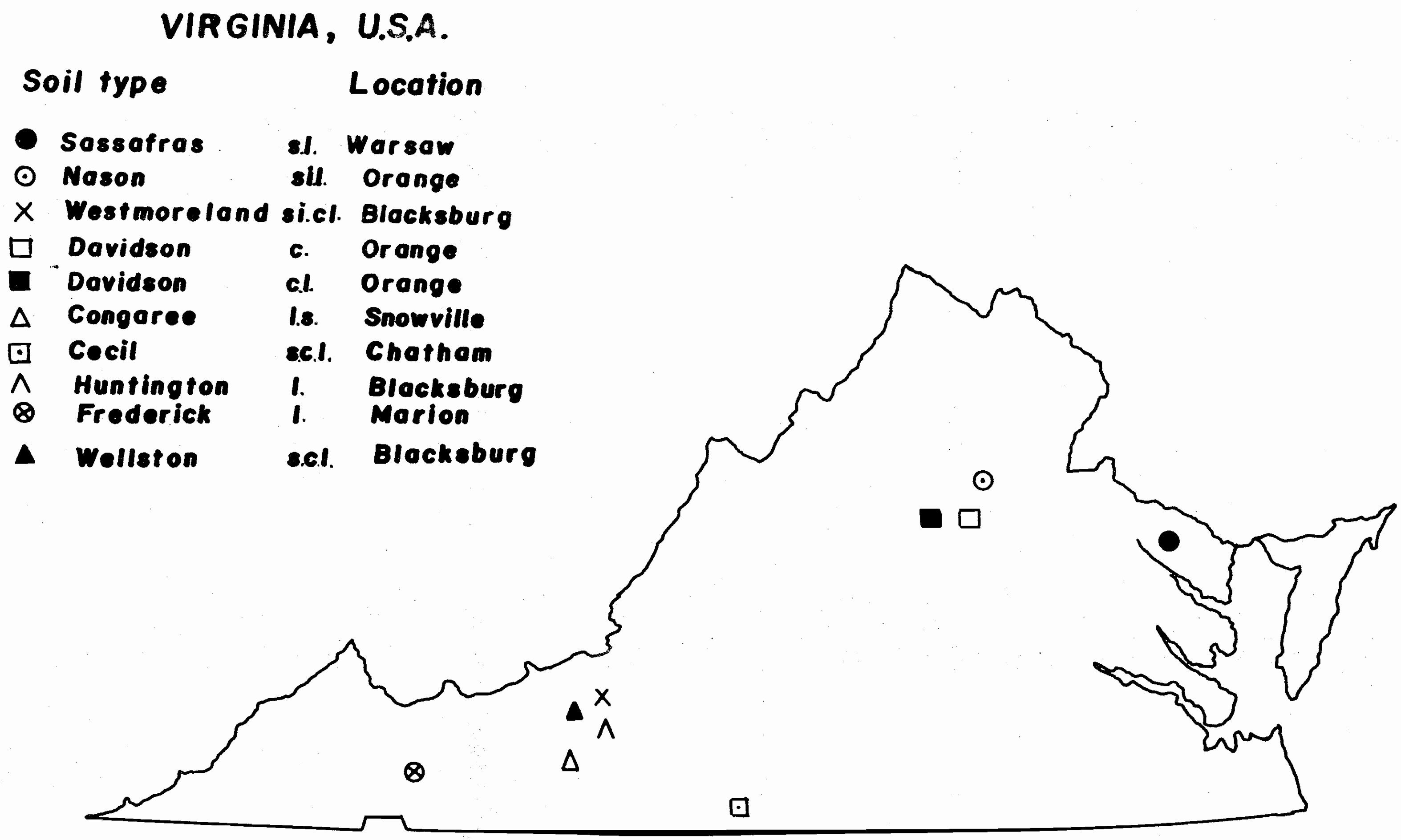
VIRGINIA, U.S.A.
Soil type
Location
Sassafras s.l. Warsaw
Nason sil. Orange
Westmoreland si.cl. Blacksburg
Davidson c. Orange
Davidson c.l. Orange
Congaree l.s. Snowville
Cecil s.c.l. Chatham
Huntington l. Blacksburg
Frederick l. Marion
Wellston s.c.l. Blacksburg

Table 1.- Mechanical analysis and chemical characteristics of the surface soils sampled for the investigation.

| Soil Type | Mechanical Analysis | | | Soil Test | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Sand | Silt | Clay | pH | Organic Matter | Ca | Mg | K | P |
| | % | | | | % | ppm | | | |
| Sassafras s.l. | 72.0 | 17.0 | 11.0 | 4.9 | 2.8 | 229 | 49 | 47 | 5.9 |
| Mason si.l. | 19.0 | 61.0 | 20.0 | 5.2 | 2.8 | 128 | 34 | 16 | 4.0 |
| Westmoreland si.c.l. | 19.0 | 47.0 | 34.0 | 7.4 | 2.8 | 2250 | 283 | 168 | 4.0 |
| Davidson c. | 18.0 | 20.0 | 62.0 | 5.4 | 3.1 | 113 | 178 | 168 | 1.6 |
| Davidson c.l. | 21.0 | 30.0 | 49.0 | 5.8 | 2.5 | 2187 | 227 | 24 | 2.3 |
| Congaree l.s. | 82.0 | 8.0 | 10.0 | 5.3 | 10.0 | 40 | 76 | 89 | 15.0 |
| Cecil s.c.l. | 59.6 | 20.4 | 20.4 | 5.0 | 2.8 | 350 | 109 | 98 | 5.1 |
| Huntington l. | 41.0 | 37.0 | 22.0 | 6.5 | 2.9 | 1500 | 183 | 37 | 2.2 |
| Frederick l. | 29.2 | 47.6 | 23.2 | 5.3 | 2.8 | 259 | 138 | 97 | 1.8 |
| Wallston s.c.l. | 49.2 | 22.0 | 22.8 | 5.7 | 2.4 | 613 | 109 | 99 | 2.2 |

Table Ia.— Chemical characteristics of a Davidson c.l. fertilized yearly since 1952 with two levels of phosphorus.

| | | Soil Test | | | | | |
|---|---|---|---|---|---|---|---|
| Plot No. | Added | pH | Organic Matter | Ca | Mg | K | P |
| | ppm | | % | ---- | ---- | ppm | ---- |
| 1 | 6.0 | 5.9 | 2.5 | 2250 | 224 | 28 | 2.2 |
| 2 | 6.0 | 5.7 | 2.8 | 2250 | 224 | 21 | 2.2 |
| 3 | 6.0 | 6.1 | 2.4 | 2250 | 233 | 21 | 1.8 |
| 4 | 6.0 | 5.6 | 2.4 | 2250 | 228 | 21 | 1.8 |
| 5 | 12.0 | 5.7 | 2.4 | 2250 | 224 | 23 | 2.2 |
| 6 | 12.0 | 5.8 | 2.5 | 1750 | 220 | 30 | 3.5 |
| 7 | 12.0 | 5.9 | 2.3 | 2250 | 233 | 23 | 2.2 |
| 8 | 12.0 | 5.9 | 2.5 | 2250 | 233 | 23 | 2.7 |

100 ppm. Each pot was planted with 75 seeds of Ladino clover. After germination, the seedlings were thinned to 50 healthy plants. When appreciable differences in the rate of growth of Ladino clover were observed, the plants were clipped back to one half inch above the soil surface. The plants were oven-dried at 100° C. Three cuttings were made and the yields from each pot were added.

Greenhouse Experiment with Corn.

During the summer of 1963, a two (soils) x three (phosphorus rates) x four (replications) factorial experiment was designed for greenhouse condit ons to study the effect of phosphorus additions to a Davidson c.l. on the yield and uptake of phosphorus by corn. Since 1952, this soil has been fertilized yearly with two levels of phosphorus (6.0 and 12.0 ppm) in field conditions. The field and greenhouse treatments were as follows:

| P previously added | P added |
|---|---|
| ppm | |
| 6.0 | 0.0 |
| 6.0 | 10.0 |
| 6.0 | 40.0 |
| 12.0 | 0.0 |
| 12.0 | 10.0 |
| 12.0 | 40.0 |

The phosphorus added to Davidson c.l. under greenhouse conditions, was mixed with each one kilogram of dried soil. Each pot was planted with eight seeds of corn. After germination, the seedlings were thinned to five healthy plants. After four weeks, the plants were harvested and oven-dried at 100° C. Each pot was planted again with the same number of seeds and the seedlings were thinned to five healthy plants. After four weeks, the plants were harvested and oven-dried at 100° C. The yield of both crops of corn from each pot was added.

Greenhouse Experiment with Oats.

During the winter of 1963, a six (soils) x four (phosphorus rates) x three (replications) experiment was designed for greenhouse conditions to study the effect of phosphorus additions to a Congaree l.s., Davidson c., Wellston s.c.l., Cecil s.c.l., Huntington l., and Frederick l., on the yield and uptake of phosphorus of the semi-winter variety of oats. Phosphorus was applied to each 1.5 kilograms of dried soil at the rate of 0.0, 10.0, 20.0 and 40.0 ppm. As an attempt to obtain larger plant responses, two extra treatments, 80.0 and 160.0 ppm of phosphorus, were applied to Cecil s.c.l., Huntington l., and Frederick l. One extra treatment of 80 ppm of phosphorus was applied to Wellston s.c.l. Each pot was planted with 20 seeds of oats and after germination, the seedlings were thinned to ten healthy plants. After four weeks, the plants were harvested and oven-dried at 100° C. Each pot was planted again with 30 seeds of oats and after germination, the seedlings were thinned to 20 healthy plants. After four weeks, the plants were harvested and oven-dried at 100° C. The yield of both crops of oats of each pot was added.

Growth Chamber Experiment with Snap Beans.

During the winter of 1963, a three (soils) x six (phosphorus rates) x three (replications) factorial experiment was designed for growth chamber conditions to study the effect of a rather wide range of phosphorus additions to a Congaree l.s., Davidson c. and Wellston s.c.l., on the yield and uptake of phosphorus by snap beans. Phosphorus was applied to each 1.5 kilograms of dried soil at the rate of 0.0, 20.0, 40.0, 80.0, 160.0, and 320.0 ppm. The water content of each soil was kept at field capacity. The "day" temperature of the growth chamber was maintained at 25° C. and the "night" temperature at 15° C. The surrounding relative humidity varied from 70% up to 100%. The light intensity was maintained at 1500 foot candles during 14 hours each day. Each soil was planted with eight rizhobium inoculated seeds. After germination, the seedlings were thinned to five healthy plants. After four weeks, the plants were harvested and oven-dried at 100° C.

## Soil Experiments

Measurement of Phosphorus in Solution as Related to Successive Increments of leaching.

This experiment was designed in order to measure the changes in the concentration of phosphorus in the soil solution as related to successive increments of leachings. For this purpose, 100 grams of soil, one sample unfertilized and the other fertilized with 320 ppm of phosphorus, of Congaree l.s., Davidson c., and Wellston s.c.l., were placed separately in glass columns. A 0.02N $CaCl_2$ solution was poured on top of each column and the leachates collected in 50 ml. volumetric flasks until from 12 to 20 fractions were obtained to draw the

? elution curve.

Measurement of Phosphorus in Solution as Related to Rate of Leaching.

This experiment was designed as an attempt to measure the time that soil phosphorus requires to reach the soil solution. For this purpose, 100 grams of unfertilized Congaree l.s. was placed in duplicates in glass columns. A 0.02N $CaCl_2$ solution was poured on top of each column and the rate of leaching was adjusted by inserting a clamp in the lower part of the column. In the first column, 40 drops per minute were obtained and 15 drops per minute in the second column. The leachates were collected in 50 ml. volumetric flasks until from 12 to 20 fractions were obtained to draw the elution curve.

Measurement of Phosphorus in Solution as Related to Phosphorus Fertilization.

This experiment was designed as an attempt to compare the effect phosphorus in the soil solution and the content of aluminum phosphate on the uptake of phosphorus by snap beans. For this purpose, the soil samples of the plant growth experiment with snap beans treated with 0.0, 20.0, 40.0, 80.0, 160,0 and 320.0 ppm of phosphorus, were utilized Each 50 grams of dried soil were mixed with 50 ml of 0.02N $CaCl_2$. The samples were shaken for 1 hour, centrifugated and filtered in order to eliminate the undecomposed organic matter and to determine the concentration of phosphorus in solution.

## Chemical Analysis

The available soil phosphorus was determined by means of the Soil Phosphorus Test ($0.05\underline{N}$ HCl + $0.025\underline{N}$ $H_2SO_4$) developed by Mehlich[2] (1953) and adapted to soils of Virginia by Rich (1955).

The inorganic soil phosphorus fractions were determined according to the procedure stated by Chang and Jackson (1957).

The phosphorus in the soil solution was determined according to the modified procedure stated by Lueck and Boltz (1956).

The soil pH, organic matter, calcium, magnesium, potassium and phosphorus status of each soil utilized in the present investigation were determined by means of the Rapid Soil Testing Procedure used at Virginia Polytechnic Institute adapted by Rich (1955).

The phosphorus uptake by plants was determined according to the procedure stated by Jackson (1958).

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[2] Mehlich, A. Determination of P, Ca, Mg, K, Na, and $NH_4$ by the North Carolina Soil Testing Laboratory. Mimeo. 1953.

# V. RESULTS AND DISCUSSION

## Plant Response to Phosphorus Fertilization

The results of each experiment are reported in the Appendix. Only mean values are reported in this portion of the thesis.

<u>Greenhouse Experiment with Ladino Clover</u>.

The yield of three cuttings of Ladino clover grown in four soils contained in pots, are given in Table 2. Clover in all soils responded to a level of 25.0 ppm of phosphorus. Yields of clover were very low from these soils when no phosphorus was applied, but response to applications higher than 25 ppm was somewhat enatic. In the case of Westmoreland sl.c.l., the maximum yield of Ladino clover, occurred at 50.0 ppm of added phosphorus.

Apparently, the levels of added phosphorus to Sassafras s.l., Mason sl.l. and Davidson c., were not high enough to indicate the amount of phosphorus fertilizer required for maximum yields of Ladino clover. For this reason, further experiments were designed to study the effect of various levels of added phosphorus to soils of different characteristics, on the yield of plants.

The uptake of phosphorus by Ladino clover (Table 3) showed an increase with increasing phosphorus fertilization, although in the case of Davidson c. and Westmoreland sl.c.l., a great amount of variability was observed. In the four soils studied, the maximum uptake of phosphorus did not occur at the levels of added phosphorus.

Table 2.– Yield of three cuttings of Ladino clover as affected by phosphorus fertilization of four soils (Avg. of three replications).

| P Added | Sassafras s.l. | Davidson c. | Westmoreland si.c.l. | Mason si.l. |
|---|---|---|---|---|
| ppm | | g/pot | | |
| 0 | 1.39 | 4.24 | 2.09 | 4.85 |
| 25 | 6.75 | 6.82 | 6.34 | 7.46 |
| 50 | 6.50 | 6.50 | 9.28 | -- |
| 100 | 7.39 | 6.16 | 8.44 | 9.17 |

Table 3.- Uptake of phosphorus by three cuttings of Ladino clover as affected by phosphorus fertilization of four soils. (Avg. of three replications).

| P Added | Sassafras s.l. | Davidson c. | Westmoreland si.c.l. | Nason si.l. |
|---|---|---|---|---|
| ppm | | mg/pot | | |
| 0 | 3.04 | 7.28 | 3.77 | 9.06 |
| 25 | 15.88 | 16.40 | 15.93 | 18.99 |
| 50 | 17.45 | 15.37 | 23.95 | -- |
| 100 | 25.39 | 18.21 | 25.90 | 30.75 |

Greenhouse Experiment with Corn

Davidson c.l., taken from plots of the fertilizer distribution study at Orange, was fertilized and planted to corn. Soils from one plot had received a total of approximately 6.0 ppm of phosphorus, whereas the other plot had received about 12.0 ppm of phosphorus during a 10-year period. Additional phosphorus was added to this soil, contained in pots, to determine the effects of past fertilization on the response curve of corn. Yield and uptake of phosphorus by corn are shown in Table 4. It is apparent that the yield of corn was enhanced by past fertilization with phosphorus. At 10 and 40 ppm rate of added phosphorus to Davidson c., the maximum yield of corn did not occur.

The uptake of phosphorus by corn grown in Davidson c.l., previously fertilized with 6.0 ppm of phosphorus increased with increasing the rate of added phosphorus. The uptake of phosphorus by corn grown in Davidson c.l., previously fertilized with 12.0 ppm of phosphorus, did not show a marked increase with increasing rate of added phosphorus. Apparently, this low response in the uptake of phosphorus may be related to more insoluble products formed when 40.0 ppm of phosphorus was added to a Davidson c.l. previously fertilized with 12.0 ppm of phosphorus.

Greenhouse Experiment with Oats

The yields of two crops of oats grown in six soils, contained in pots, are given in Table 5. The yields of oats increased with increas-

Table 4.- Yield and uptake of phosphorus by corn as affected by phosphorus fertilization of a Davidson c.l. (Avg. of four replications).

| | P previously added = 6.0ppm | | P previously added = 12.0ppm | |
|---|---|---|---|---|
| Added | Yield | P uptake | Yield | P uptake |
| ppm | g/pot | mg/pot | g/pot | mg/pot |
| 0 | 3.41 | 1.83 | 3.72 | 2.11 |
| 10 | 3.57 | 1.93 | 3.73 | 2.41 |
| 40 | 4.08 | 3.48 | 4.38 | 2.67 |

Table 5.- Yield of two crops of oats as affected by phosphorus fertilization of six soils (Avg. of three replications).

| P Added | Congaree l.s. | Davidson c. | Wellston s.c.l. | Cecil s.c.l. | Huntington l. | Frederick l. |
|---|---|---|---|---|---|---|
| ppm | | | g/pot | | | |
| 0 | 1.94 | 1.55 | 1.77 | 2.15 | 1.72 | 2.06 |
| 10 | 2.64 | 1.63 | 2.06 | 2.39 | 1.93 | 2.30 |
| 20 | 2.83 | 2.01 | 2.55 | 3.03 | 2.28 | 2.03 |
| 40 | 2.93 | 2.29 | 2.86 | 3.51 | 2.28 | 2.37 |
| 80 | -- | -- | 2.79 | 3.84 | 3.52 | 2.89 |
| 160 | -- | -- | -- | 4.55 | 3.74 | 3.20 |

ing rate of added phosphorus to Congaree l.s., Davidson c., Cecil s.c.l., Huntington l., and Frederick l. At the various levels of added phosphorus, Cecils c.l. gave the largest response and Davidson c. gave the lowest response. This may be attributed to the fact that when a small quantity of phosphorus is added to Davidson c., phosphorus forms insoluble products which are less available to plants, whereas when the same quantity of phosphorus is added to Cecil s.c.l., phosphorus forms more soluble products which are more available to plants.

The uptake of phosphorus by two crops of oats, showed an increase with increasing rate of added phosphorus (Table 6). At the various levels of added phosphorus, the uptake of phosphorus by oats grown in Cecil s.c.l. was the highest of the six soils studied. The uptake of phosphorus by oats grown in Davidson c., was the lowest of the six soils studied.

<u>Growth Chamber Experiment with Snap Beans</u>

Snap beans were grown in pots in a growth chamber. The yields are given in Table 7. Snap beans responded to the various rates of added phosphorus in the three soils studied. However, snap beans grown in Davidson c., responded only to 80.0, 160.0, and 320.0 ppm of added phosphorus.

Of the three soils studied, Wellston s.c.l. gave the largest response. The maximum yield of oats grown in this soil was obtained at about 160.0 ppm of added phosphorus. Congaree l.s. gave intermediate response. The maximum yield of oats grown in this soil was

Table 6.- Uptake of phosphorus by two crops of oats as affected by phosphorus fertilization of six soils (Avg. of three replications).

| P Added | Congaree l.s. | Davidson c. | Wellston s.c.l. | Cecil s.c.l. | Huntington l. | Frederick l. |
|---|---|---|---|---|---|---|
| ppm | -------------------------- | ------------ | mg/pot | ------------ | ------------ | -------------------------- |
| 0 | 2.77 | 1.52 | 1.91 | 2.81 | 1.60 | 1.81 |
| 10 | 4.17 | 1.79 | 2.72 | 3.47 | 2.10 | 2.69 |
| 20 | 4.52 | 1.64 | 3.29 | 5.25 | 3.11 | 2.00 |
| 40 | 6.92 | 3.39 | 4.79 | 6.56 | 5.28 | 3.01 |
| 80 | -- | -- | 5.75 | 9.06 | 7.51 | 4.31 |
| 160 | -- | -- | -- | 13.82 | 9.35 | 6.15 |

Table 7.- Yield of snap beans as affected by phosphorus fertilization of three soils (Avg. of three replications).

| P Added | Congaree l.s. | Davidson c. | Wellston s.c.l. |
|---|---|---|---|
| ppm | | g/pot | |
| 0 | 3.79 | 4.77 | 4.46 |
| 20 | 4.68 | 4.00 | 5.72 |
| 40 | 5.55 | 4.52 | 6.51 |
| 80 | 6.43 | 5.57 | 7.63 |
| 160 | 6.01 | 6.42 | 8.82 |
| 320 | 7.09 | 7.14 | 9.14 |

obtained in about 80.0 ppm of added phosphorus. Davidson c. gave the lowest response. The maximum yield of oats grown in this soil was obtained at about 200.0 ppm of added phosphorus.

The uptake of phosphorus by snap beans is given in Table 8. In general, the uptake of phosphorus by snap beans grown in Davidson c., Congaree l.s. and Wellston s.c.l., showed an increase with increasing rates of added phosphorus. At the various levels of added phosphorus, Davidson c. gave the largest response. Congaree gave intermediate response and Wellston s.c.l. gave the lowest response.

From the results of the Ladino clover, corn, oats and snap beans plant-growth experiments, it is concluded that in order to insure proper phosphorus nutrition of plants, heavy-textured soils should receive more phosphate fertilizer than light-textured soils.

## Rationalization of Yields in Pot Experiments

### Aluminum Phosphate-P vs. Iron and Calcium Phosphate-P

The regression of yields of Ladino clover and the phosphorus extracted by $NH_4F$, $NaOH$ and $H_2SO_4$ gave correlation coefficients of 0.43, 0.38, and 0.29, respectively. Previous work by Chu (1962) showed that iron phosphate-P is usually high in the case of red clay soils and rather low in sandy soils. This also was the case in the present study. Davidson c., contained 134 ppm of iron phosphate-P before fertilization whereas Sassafras s.l. contained only 44 ppm of iron phosphate-P.

Table 8.- Uptake of phosphorus by snap beans as affected by phosphorus fertilization of three soils. (Avg. of three replications).

| P Added | Congaree l.s. | Davidson c. | Wellston s.c.l. |
|---|---|---|---|
| ppm | | mg/pot | |
| 0 | 3.73 | 5.85 | 6.00 |
| 20 | 7.00 | 10.24 | 5.63 |
| 40 | 11.25 | 15.73 | 8.52 |
| 80 | 17.13 | 22.94 | 12.83 |
| 160 | 26.09 | 37.90 | 21.79 |
| 320 | 45.36 | 56.83 | 37.89 |

These large differences tend to smear out the iron phosphate-P regression. The amount of calcium phosphate-P was exceedingly variable in all soils, but was significantly higher in Westmoreland s.c.l., a calcareous soil.

Aluminum phosphate-P not only gave a better regression with plant yield, but also appeared to be better related to the phosphorus applied, even in the calcareous soil, Westmoreland si.c.l. This agrees with the observations of Lindsay et al. (1959) and Chang and Juo (1963), who observed that aluminum phosphate was the first product of superphosphate reaction with soils. Complete data are given in the Appendix in Tables 1 through 4.

Aluminum Phosphate-P vs. $HCl-H_2SO_4$ - Extractable Phosphorus.

The $HCl-H_2SO_4$ - extractable phosphorus test was developed by Mehlich[2] in 1953 in North Carolina in an effort to approximate the extractability of the Bray test, but at the same time to use only one solution for extraction of cations and phosphorus. This test presently is used in the states of Maryland, Virginia, North Carolina, South Carolina, Georgia and Alabama.

General experience has shown that this test gives low results when used on heavy red soils. In North Carolina and Georgia, this is partially compensated for by the expedient of changing the levels, low, medium and high, to one-half the value used for lighter soils. This moves

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[2]Mehlich, A. Determination of P, Ca, Mg, K, Na, and $NH_4$ by the North Carolina Soil Testing Laboratory. Mimeo. 1953.

in the right direction, but the effect is not large enough to overcome the exceedingly low values encountered in some soils. Figure 2 shows that, whereas HCl-$H_2SO_4$ - extractable phosphorus is comparable to aluminum phosphate-P in a Congaree l.s., it is much lower than aluminum phosphate-P in a Davidson c. In addition, a more serious drawback is that there is essentially no difference between the HCl-$H_2SO_4$ - extractable phosphorus where the lowest yield of oats was obtained and the level where the highest yield of oats was obtained in Davidson c.l.

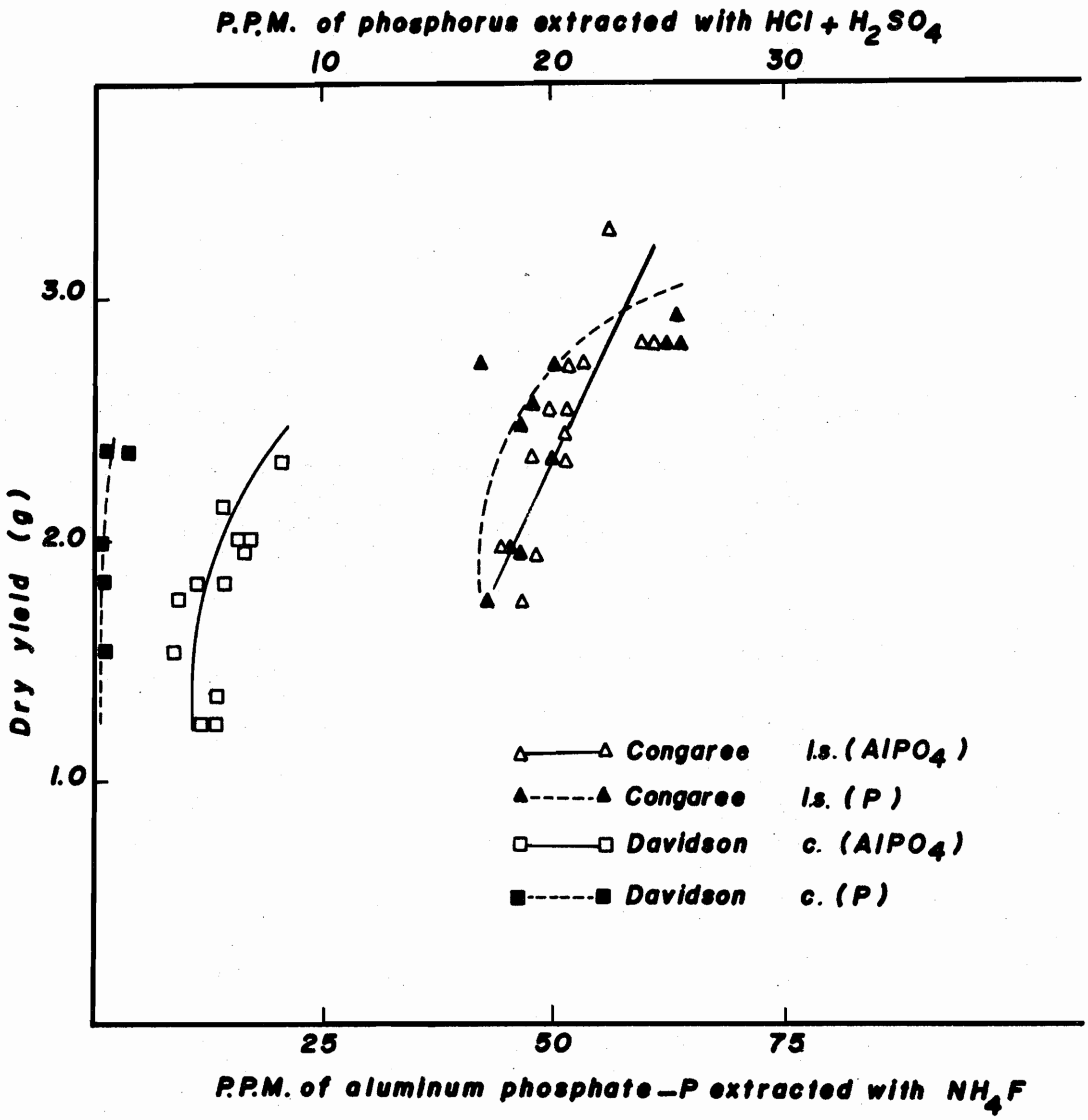
An investigation into the reason for this insensitivity of extractable phosphorus in Davidson c.l. showed that most of the added acid was exhausted by contact with the heavy soil. A similar result was obtained by Pratt et al. (1964) in heavy California soils. By increasing the amount of acid used with the soil, this insensitivity can be overcome to a degree. Figure 3 shows the relationship between the normality of the acid (after it was shaked with Davidson c.l. previously fertilized at 6.0 and 12.0 ppm of phosphorus for a 10-year period) and the amount of HCl-$H_2SO_4$ - extractable phosphorus. It is apparent that only when rather high normality was reached, did the soils show the effect of past fertilization. In contrast, corn grown in these soils showed the effect quite markedly (Table 4).

It would appear that one way of overcoming the poor sensitivity of the present test is to increase the strength of acid used or the ratio of acid to soil. Another possibility is to use a test based on

Figure 2.- Yield of oats grown on two soils as related to:

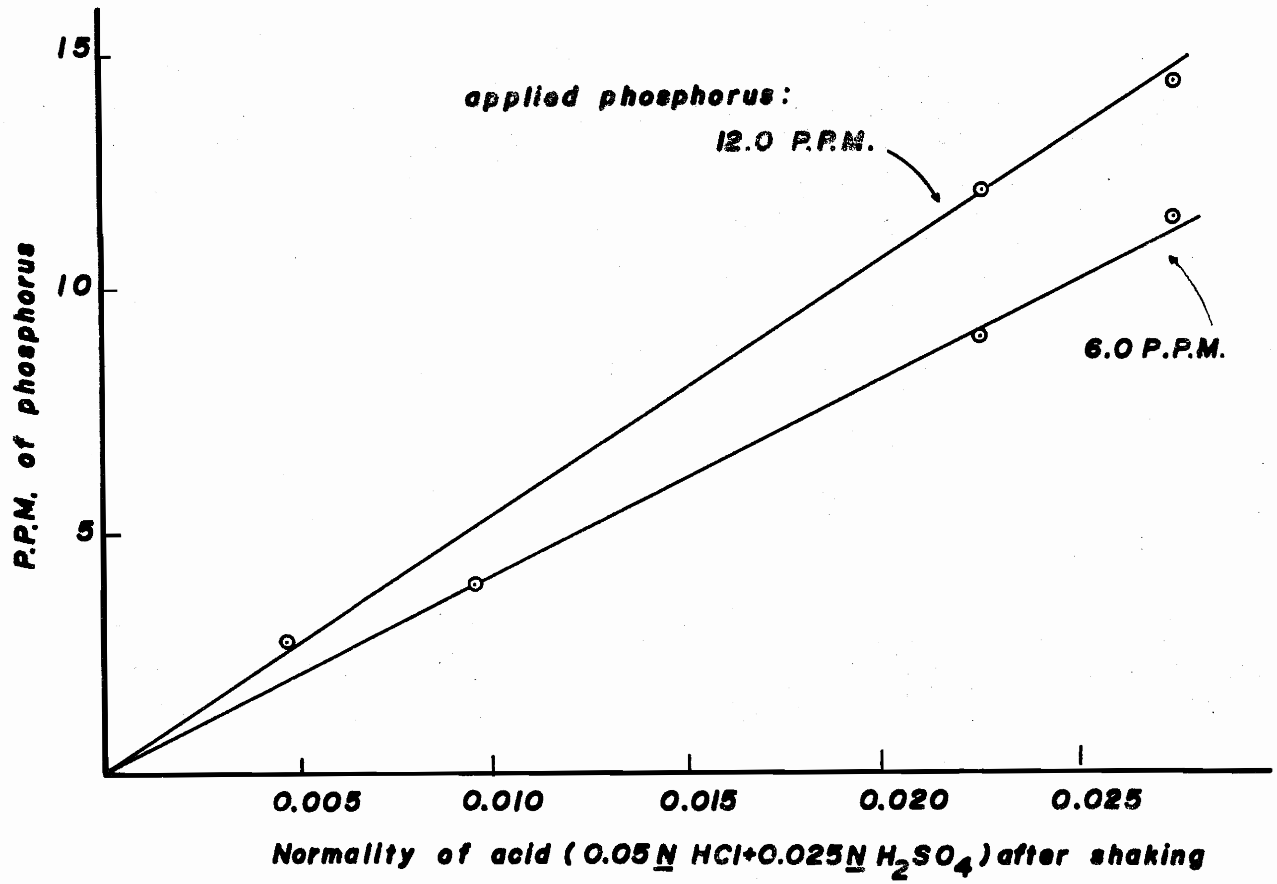
(a) Aluminum phosphate-P extracted with $NH_4F$.

(b) Soil phosphorus extracted with 0.05 N HCl + 0.025 N $H_2SO_4$.



P.P.M. of phosphorus extracted with HCl + $H_2SO_4$
10
20
30
3.0
2.0
1.0
Dry yield (g)
25
50
75
P.P.M. of aluminum phosphate—P extracted with $NH_4F$
Congaree l.s. ($AlPO_4$)
Congaree l.s. (P)
Davidson c. ($AlPO_4$)
Davidson c. (P)

Figure 3.- Effect of normality of acid (0.05 N HCl + 0.025 N $H_2SO_4$, after shaking) on the amount of phosphorus extracted from a Davidson c.l.


applied phosphorus:
12.0 P.P.M.
6.0 P.P.M.
P.P.M. of phosphorus
15
10
5
0.005
0.010
0.015
0.020
0.025
Normality of acid ( 0.05 N HCl+0.025 N $H_2SO_4$ ) after shaking

the $NH_4F$ extraction of aluminum phosphate-P. In an effort to compare the usefulness of these two methods, curvilinear regression between yield and aluminum phosphate and between yield and $HCl-H_2SO_4$ - extractable phosphorus was run at the V.P.I. Computing Center. Analyses were run on each individual experiment, and then, by adjusting to percentage of maximum yield all experiments, crops and soils were combined.

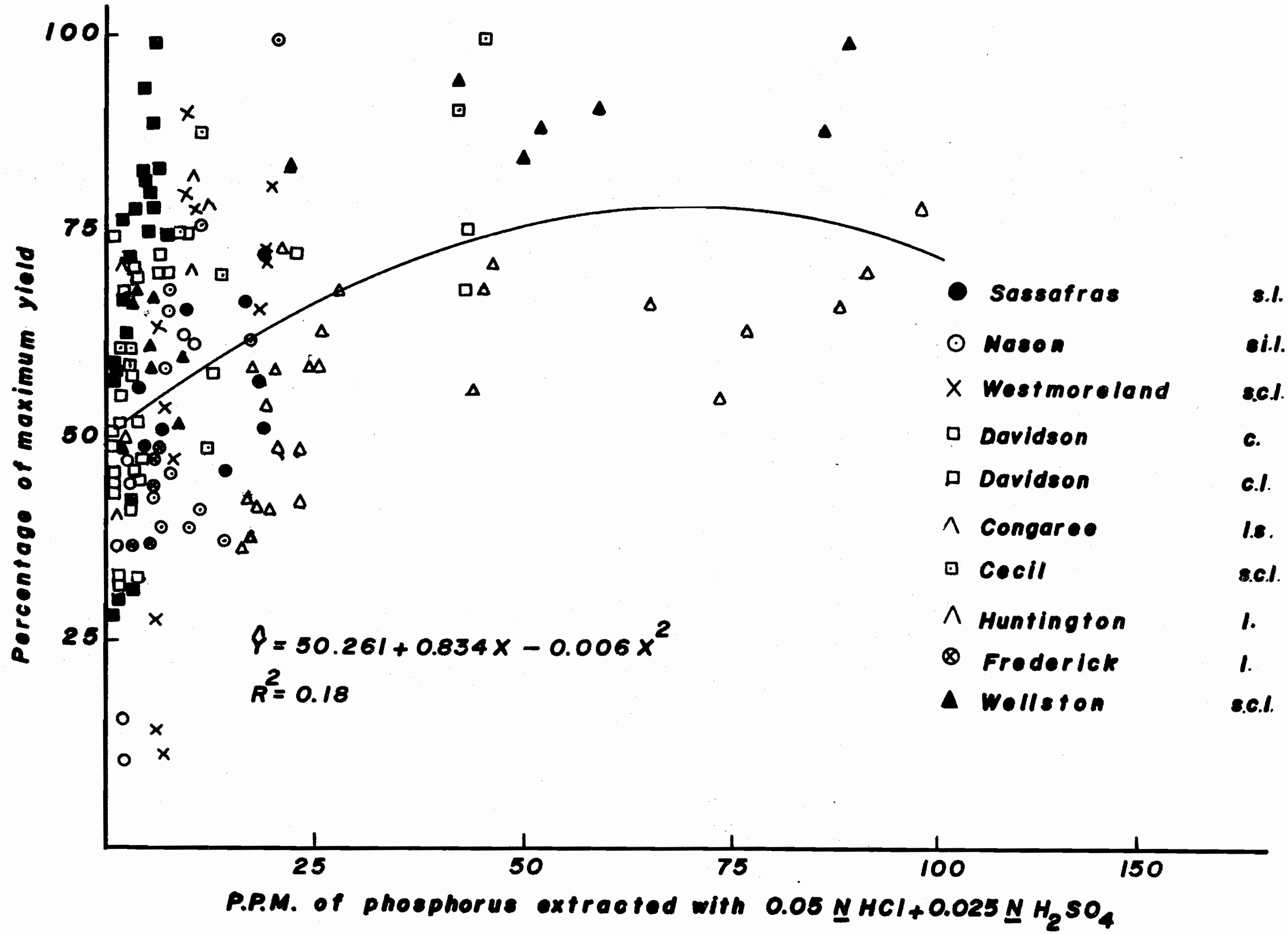
$R^2$ values for both methods are given in Table 9. Except in the case of the Ladino clover experiment, where difficulties in determining phosphorus precisely were encountered, the $NH_4F$-extractable phosphorus always was correlated somewhat better with yield than was the $HCl-H_2SO_4$ soil test. The combined analysis gave fairly low $R^2$ for both methods, but this would be expected since the experiments were conducted under widely varying conditions.

Figure 4 shows the regression for the combined analysis for $HCl-H_2SO_4$ - extractable phosphorus. It is apparent that the points are bunched up at the low side of available phosphorus, but the scatter is not very great. Figure 5 shows the regression of yield on aluminum phosphate-P. In this case the distribution of points horizontally is better, but the scatter is worse. Neither of the methods adequately explains yield of crops when combined over all experiments. Nor does $NH_4F$ - extractable phosphorus entirely overcome the main objection to the $HCl-H_2SO_4$ method, i.e., the heavy soils have low values compared to light-textured soils. This stands out very clearly in Figure 4 and 5, where Davidson c., Huntington l., Wellston s.c.l. and Cecil s.c.l. have rather low values of phosphorus even with very good yields.

Table 9.- $R^2$ for curvilinear regressions between percentage of maximum yields and two extractants of phosphorus.

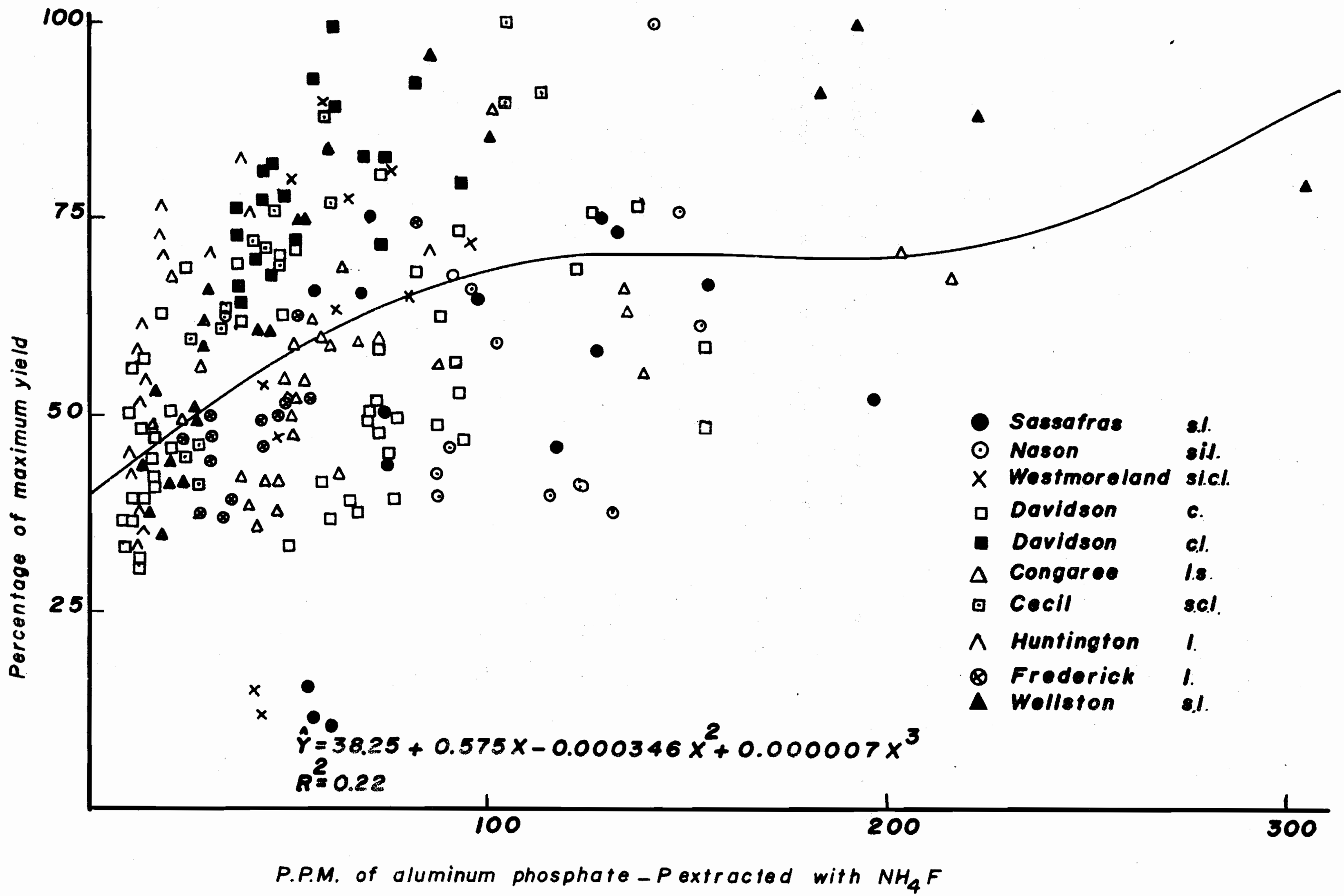
| Crop | Soils | $R^2$ for $HCl-H_2SO_4$ P vs. Yield | $R^2$ for $NH_4F$-P vs. Yield |
|---|---|---|---|
| Ladino clover | Sassafras s.l. | 0.35 | 0.18 |
| | Davidson c. | | |
| | Westmoreland s.c.l. | | |
| | Mason si.l. | | |
| Corn | Davidson c.l. | 0.35 | 0.40 |
| Oats | Congaree l.s. | 0.43 | 0.47 |
| | Davidson c. | | |
| | Wellston s.c.l. | | |
| | Cecil s.c.l. | | |
| | Huntington l. | | |
| | Frederick l. | | |
| Snap beans | Congaree l.s. | 0.39 | 0.44 |
| | Davidson c. | | |
| | Wellston s.c.l. | | |
| All Crops | All Soils | 0.18 | 0.22 |

Figure 4.- Percentage of maximum yield of Ladino clover, corn, oats, and snap beans, as related to soil phosphorus extracted with 0.05 N HCl + 0.025 N $H_2SO_4$.



Percentage of maximum yield
100
75
50
25
25
50
75
100
150
P.P.M. of phosphorus extracted with 0.05 N HCl + 0.025 N H2SO4
Ŷ = 50.261 + 0.834X − 0.006X²
R² = 0.18
Sassafras s.l.
Nason si.l.
Westmoreland s.c.l.
Davidson c.
Davidson c.l.
Congaree l.s.
Cecil s.c.l.
Huntington l.
Frederick l.
Wellston s.c.l.

Figure 5.- Percentage of maximum yield of Ladino clover, corn, oats, and snap beans, as related to aluminum phosphate-P extracted with 0.5 N $NH_4F$.



100
75
50
25
Percentage of maximum yield
100
200
300
P.P.M. of aluminum phosphate – P extracted with $NH_4F$
Sassafras s.l.
Nason sil.
Westmoreland si.c.l.
Davidson c.
Davidson cl.
Congaree l.s.
Cecil s.cl.
Huntington l.
Frederick l.
Wellston s.l.
$\hat{Y} = 38.25 + 0.575X - 0.000346X^2 + 0.000007X^3$
$R^2 = 0.22$

Because of this relationship, it was assumed that some adjustment for soil texture should be made. Regression of yield on the product of aluminum phosphate-P and the square root of the clay content gave an $R^2$ of 0.29, which showed improvement, but not nearly enough to be worth the trouble. Because of the lack of fit encountered, further experiments were undertaken.

Rate of Phosphorus Renewal

A column experiment was undertaken with the soils which were used in the growth chamber experiment with snap beans. Glass columns containing 100 g. of samples of Davidson c., Wellson s.c.l. and Congaree l.s., which had not been fertilized with phosphorus and similar samples which had received 320 ppm of phosphorus were leached continuously with dilute $CaCl_2$. Phosphorus was determined on each 50 ml. of solution which came from the soils. Results are plotted in Figure 6 for the unfertilized soils and in Figure 7 for the fertilized soils. The concentration of phosphorus removed from unfertilized Davidson c., and Wellston s.c.l. was about 0.03 ppm and remained constant throughout the experiment. Congaree l.s. delivered much more phosphorus in the first aliquot, but phosphorus rapidly dropped to a value somewhat less than twice as high as that from the other two soils. Effluent from fertilized soils showed a tendency to start rather high in phosphorus and to decrease with increasing leaching. In all cases, phosphorus remained higher than in the unfertilized soils, but not markedly so in the case of Davidson c. or Wellston s.c.l.

Figure 6.- Phosphorus removed from three unfertilized soils by successive 50 ml. extractions with 0.02 $\underline{N}$ $CaCl_2$.

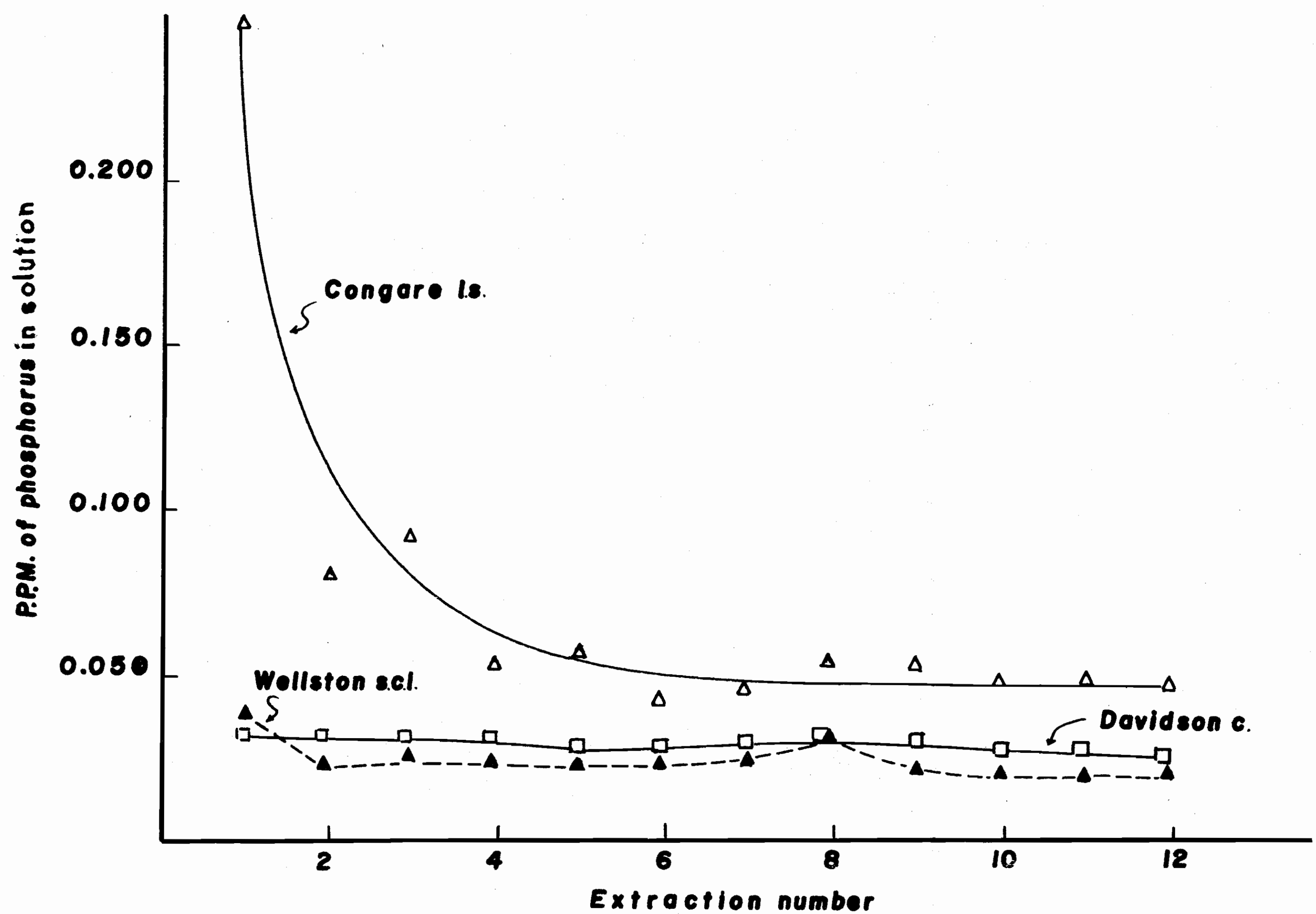
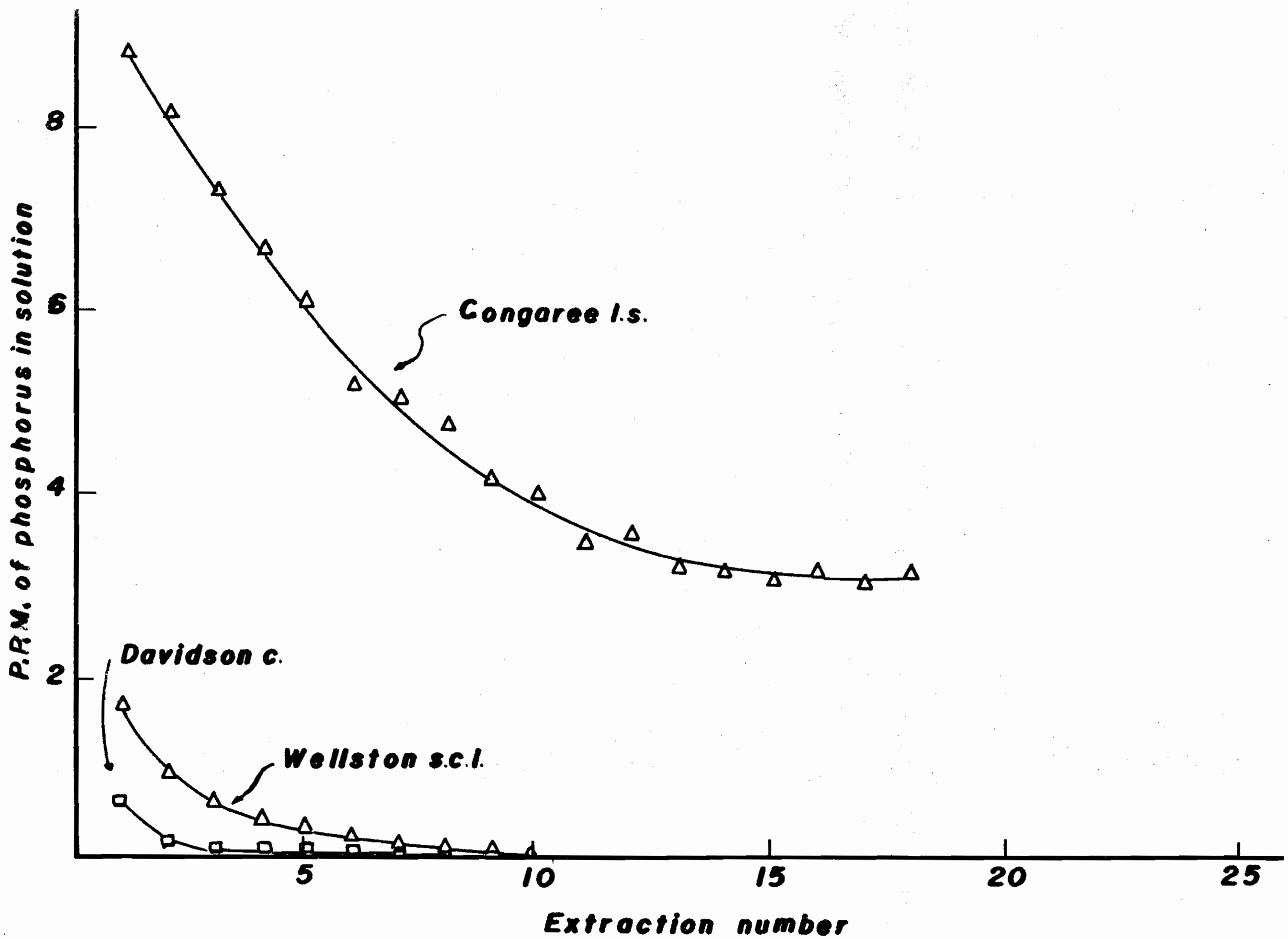

P.P.M. of phosphorus in solution
0.200
0.150
0.100
0.050
Congaree l.s.
Wellston s.c.l.
Davidson c.
2
4
6
8
10
12
Extraction number

Figure 7.- Phosphorus removed from three soils fertilized with 320 ppm of phosphorus, by successive 50 ml. extractions with 0.02 N $CaCl_2$.


Congaree l.s.
Davidson c.
Wellston s.c.l.
P.P.M. of phosphorus in solution
8
6
4
2
5
10
15
20
25
Extraction number

Effluent from Congaree l.s. remained at about 3 ppm even after 850 ml of $CaCl_2$ had passed through, suggesting that some dicalcium phosphate or other soluble material remained in the soil.

As in the unfertilized soils, the amount of phosphorus from all fertilized soils tended to become almost constant after a few washings. Fast leaching compared with slow leaching on Congaree l.s. showed no difference in concentration, and it must be concluded that, under the conditions of these experiments, the renewal rate of phosphorus in solution was infinitely fast. It should be remembered that saturated flow was employed in this work whereas renewal of phosphorus in field soils must take place under relatively dry conditions.

Application of Olsen's Theory

A recent paper by Olsen and Watanabe (1963) indicated that the two foregoing observations, (1) the effect of texture on efficiency of phosphorus fertilizer and (2) the marked difference of phosphorus in solution associated with soils could be applied to the prediction of uptake of phosphorus by plants. Accordingly, determination of a number of parameters in the snap bean experiment was undertaken. The measurements necessary were:

(1) Phosphorus in solution for each fertilizer treatment and each soil.

(2) Aluminum phosphate for each treatment. (It should be noted that Olsen and Watanabe used $P^{32}$ exchangeable phosphorus, but his is closely related to aluminum phosphate-P.)

(3) Phosphorus uptake curves of snap beans vs. phosphorus in solution for each soil.

(4) Mechanical analyses of each soil to determine clay content so that a diffusion coefficient could be taken from Olsen's graph of clay percentage vs. "$D_p$" (Figure 9).

In the work of Olsen, an intensity factor, a capacity factor and a rate of renewal are considered, and a relative uptake of phosphorus is computed. This then is compared with the actual relative uptake of phosphorus.

The intensity factor is considered to be the amount of phosphorus in solution at a given time. The capacity factor is the slope of a plot of phosphorus in solution vs. aluminum phosphate and the rate of renewal is taken as the diffusion coefficient of phosphorus. These values for the three soils are shown in Appendix Tables 13 through 15 and in Figures 8 and 9. The practical effect of increasing clay, as we have seen, is to decrease the intensity factor, but to increase the capacity factor and rate of renewal. The actual uptake of phosphorus is shown in Figure 10. Relative uptake at 0.10 and 0.15 ppm phosphorus in solution was calculated and compared with the uptake predicted by $\sqrt{bD_p}$. These values are shown in Table 10. The $\chi^2$ test indicated that at the 1% level of the probability, the difference between the actual and the calculated relative uptake of phosphorus by snap beans is not significant. Therefore, the expression $\sqrt{bD_p}$ may be utilized to predict the phosphorus requirements to provide adequate nutrition of plants.

Figure 8.- Linear regression coefficient between aluminum phosphate-P and phosphorus in solution in three soils.

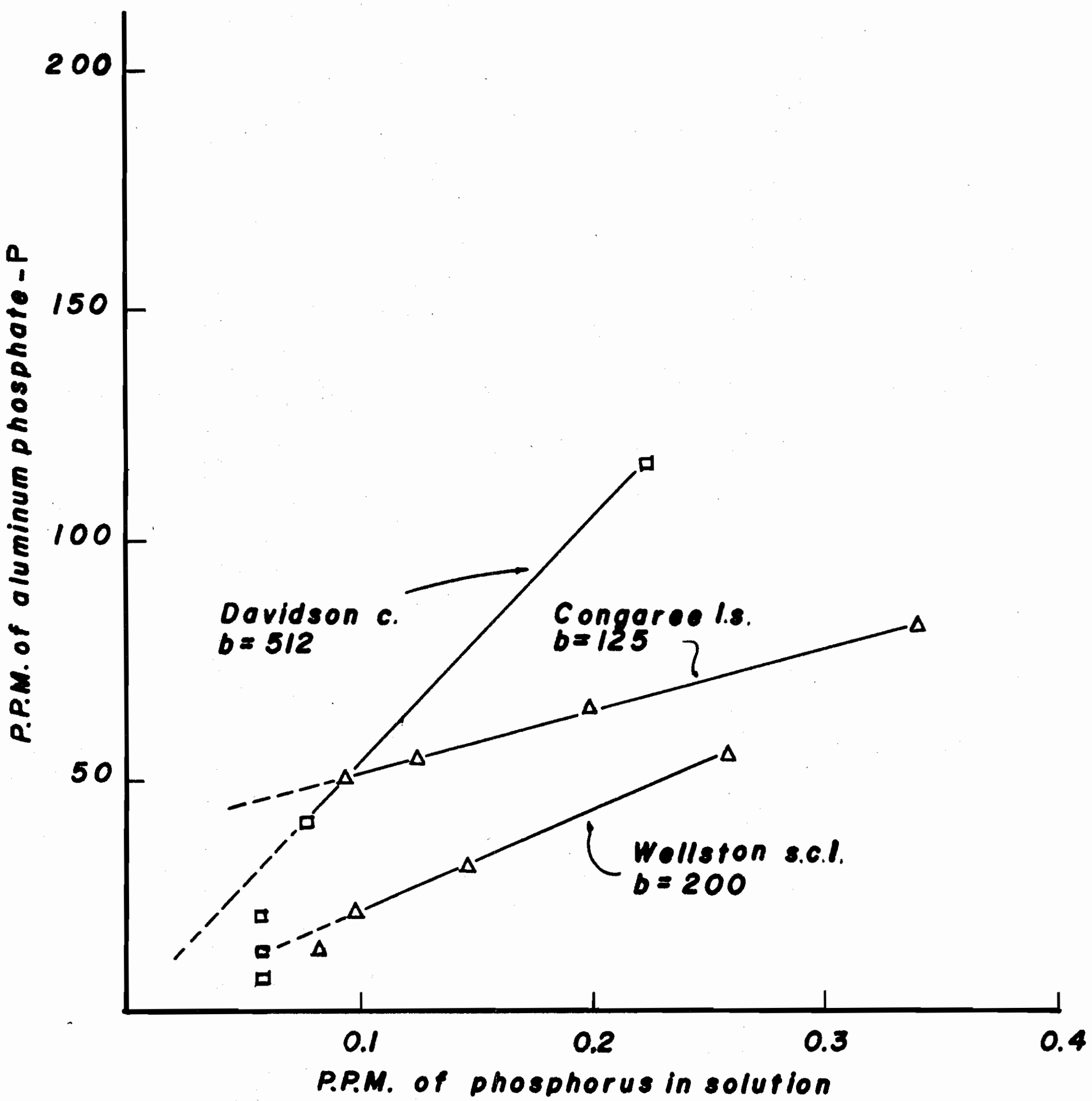
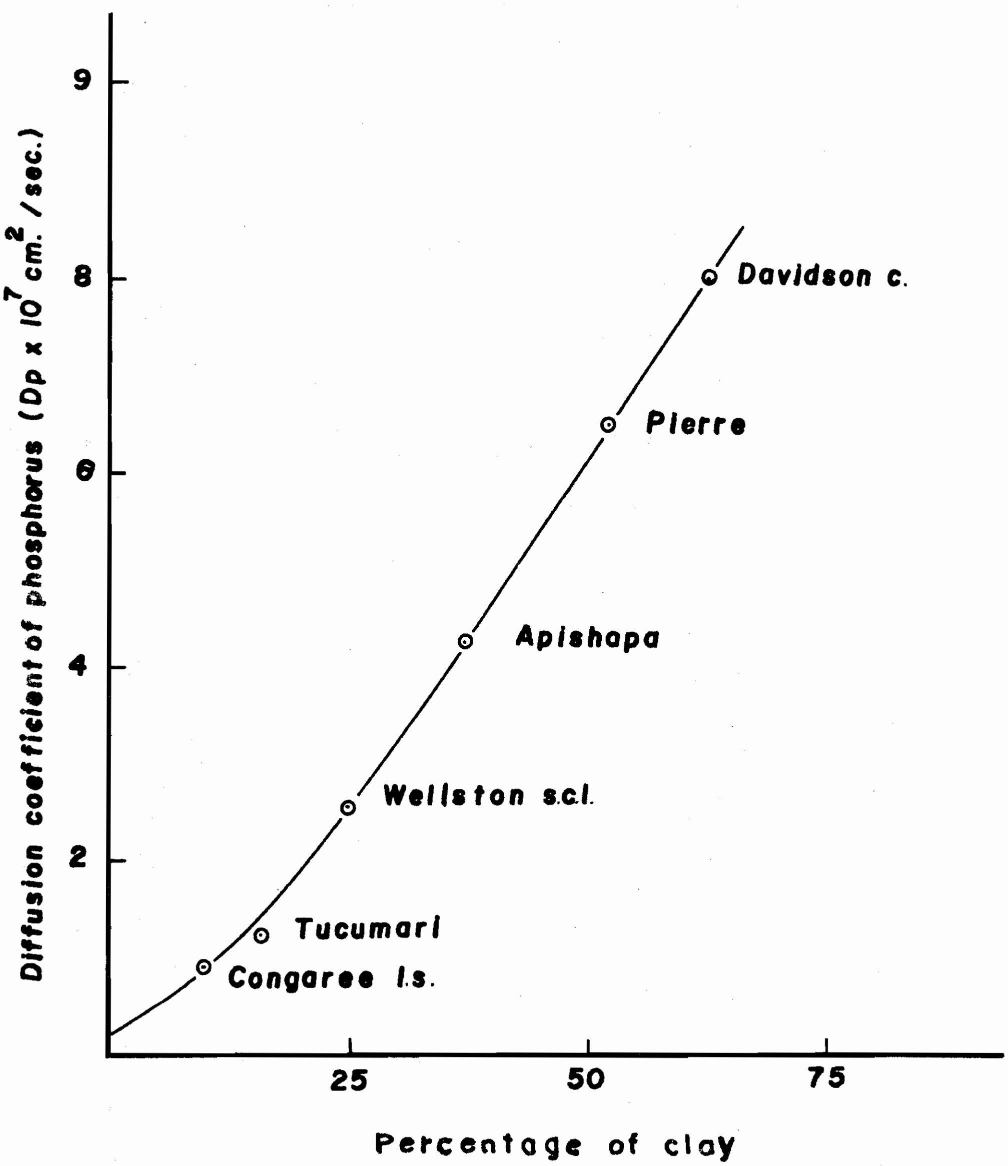

200
150
100
50
0.1
0.2
0.3
0.4
P.P.M. of aluminum phosphate - P
P.P.M. of phosphorus in solution
Davidson c.
b= 512
Congaree l.s.
b= 125
Wellston s.c.l.
b= 200

Figure 9.- Diffusion coefficient of phosphorus of various soils, as related to percentage of clay.



Diffusion coefficient of phosphorus (Dp x 10^7 cm.^2 /sec.)
9
8
6
4
2
Davidson c.
Pierre
Apishapa
Wellston s.c.l.
Tucumari
Congaree l.s.
25
50
75
Percentage of clay

Figure 10.- Uptake of phosphorus by snap beans from three soils as related to the phosphorus in solution.

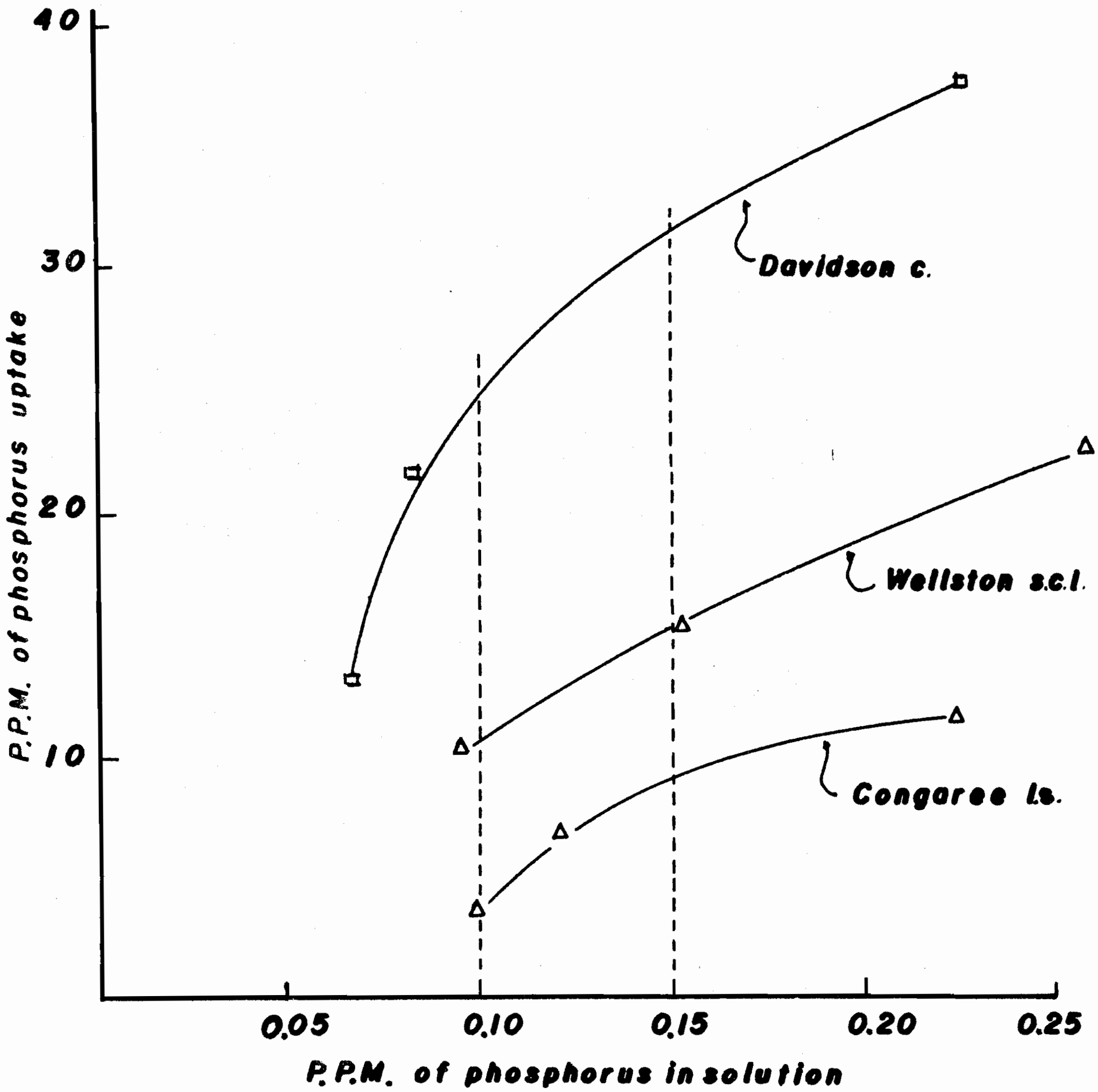

40
30
20
10
P.P.M. of phosphorus uptake
Davidson c.
Wellston s.c.l.
Congaree l.s.
0.05
0.10
0.15
0.20
0.25
P.P.M. of phosphorus in solution

Table 10.- Actual and calculated relative rates of uptake of phosphorus by snap beans.

| Soil | % clay | P concentration | Relative uptake rate | |
|---|---|---|---|---|
| | | | Actual | Calculated |
| | | ppm | | |
| Davidson c. | 63.5 | 0.10 | 1 | 1 |
| | | 0.15 | 1 | 1 |
| Wellston s.c.l. | 22.5 | 0.10 | 0.45 | 0.32 |
| | | 0.15 | 0.51 | 0.32 |
| Congaree l.s. | 10.0 | 0.10 | 0.18 | 0.17 |
| | | 0.15 | 0.29 | 0.17 |

The actual and the calculated relative uptake of phosphorus by snap beans grown in Davidson c., Wellston s.c.l. and Congaree l.s., indicate that there is a strong tendency for uptake of phosphorus to increase as the percentage of clay increases for a given amount of phosphorus in solution. It should be clearly understood however, that there is a good deal more difficulty in achieving a certain level of phosphorus in solution with heavier soils. For example, in the present experiment, to obtain 0.15 ppm of phosphorus in solution would require about 25 ppm of phosphorus in Congaree l.s., 40 ppm in Wellston s.c.l. and 230 ppm in Davidson c.

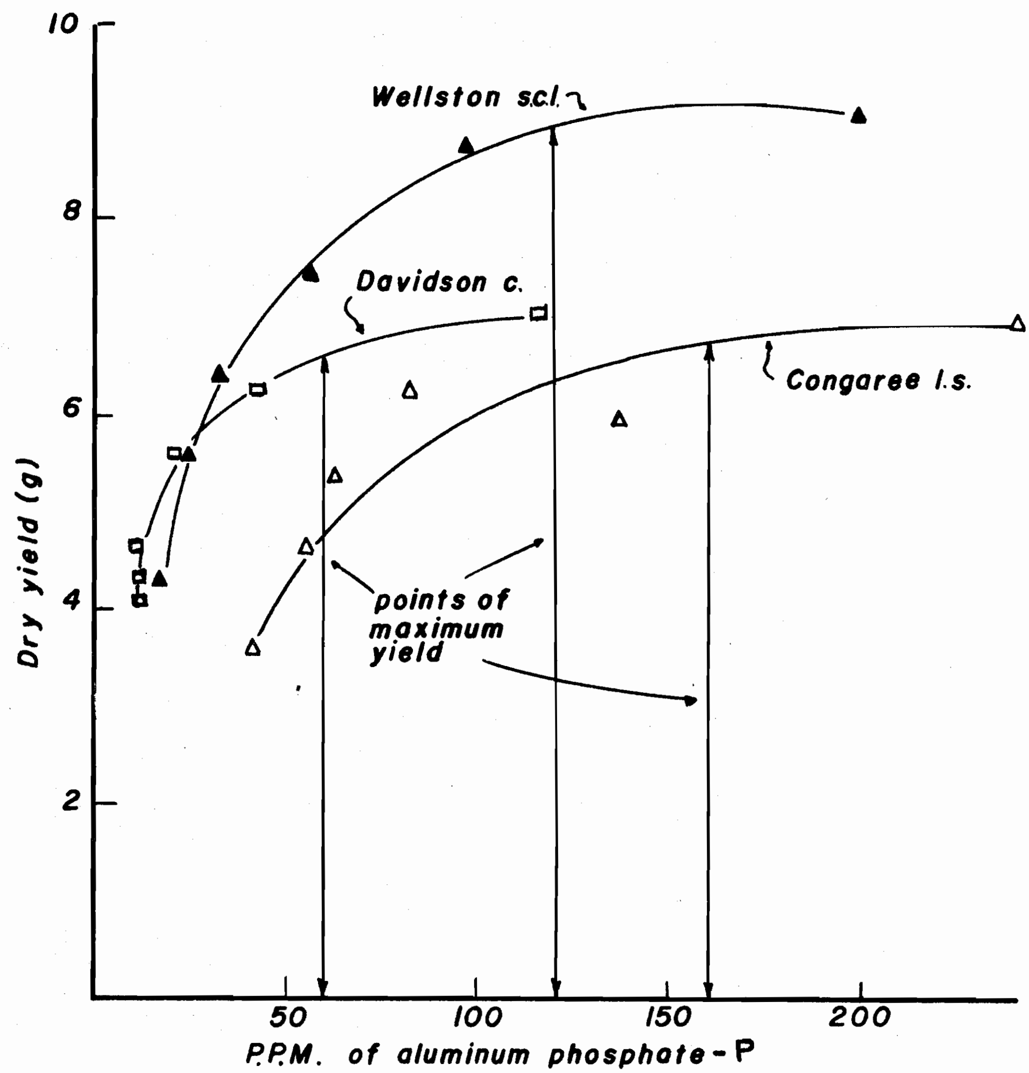
The results of this experiment, which agree with Olsen's suppositions, do not necessarily prove the hypothesis upon which Olsen's work is based. It does show two basic things, however. First, the concentration of phosphorus needed in solution for proper plant nutrition is much lower in heavy-textured soils than in sandy soils. Olsen ascribes this to the shorter effective length for phosphorus and to the fact that there is more water in clays even when they are dry. This later fact must be very important, since the present author has found that the rate of renewal is infinitely fast in saturated systems. The second fact is that to achieve adequate phosphorus nutrition of plants, it is necessary to fertilize soils high in clay heavier than sandy soils. This may sound contradictory, but it is not. Past research has shown very clearly that heavy soils need higher phosphorus fertilization than do lighter soils. What it has not shown clearly is that the level of available phosphorus does not need to be as high in heavy soils as in light soils. This is the practical importance of Olsen's work.

Empirical Approach to Soil Phosphorus Fertilization.

An approach which shows the same sort of experiments as Olsen's but which is entirely empirical, was employed to determine the relative needs of Davidson c., Wellston s.c.l. and Congaree l.s. for phosphorus fertilization. This is not unlike typical soil test calibration, but in addition employs a measure of "efficiency" of phosphorus fertilization so that not only optimum levels of phosphorus may be ascertained, but also optimum rates of phosphorus fertilization. Figure 11, shows the response curves for snap beans grown on these three soils vs. aluminum phosphate-P for Davidson c., Wellston s.c.l. and Congaree l.s., respectively. Figure 12 is a plot of phosphorus added vs aluminum phosphate-P. Arrows drawn from the above aluminum phosphate-P values to the abscissa show that Congaree l.s. needs 180 ppm of phosphorus to reach 160 ppm of aluminum phosphate-P, Wellston s.c.l. requires 200 ppm of phosphorus, and Davidson c. requires 210 ppm of phosphorus. These results agree qualitatively with those obtained using the ideas of Olsen and Watanabe (1963).

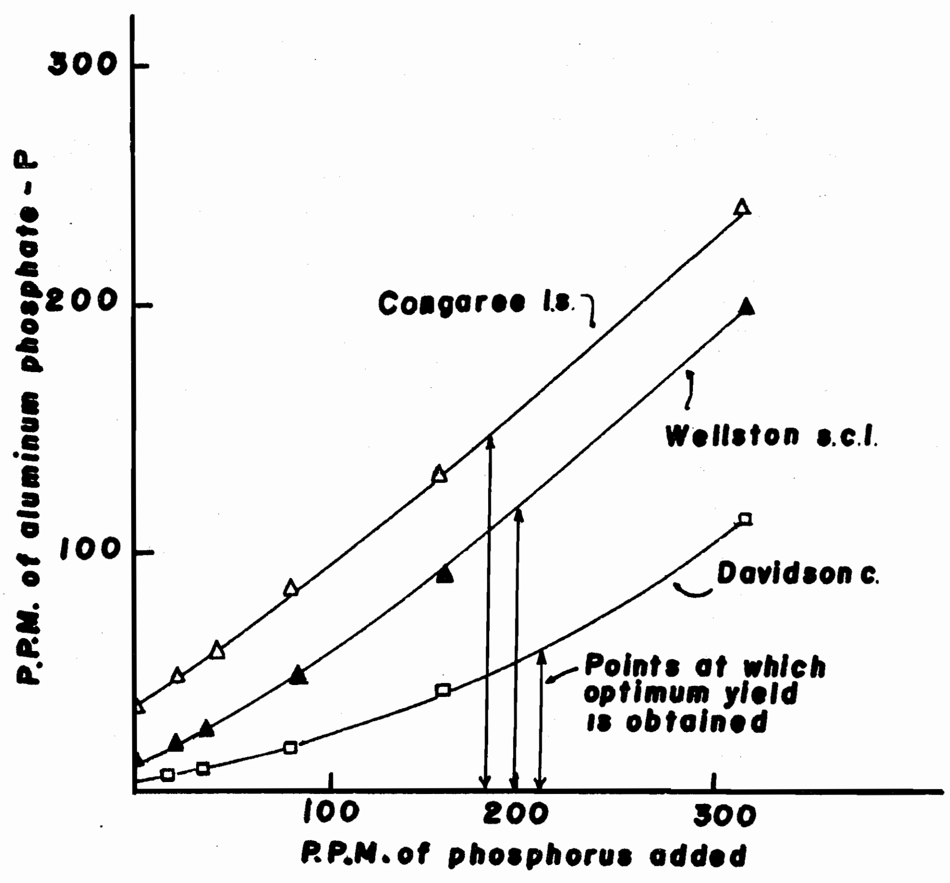
It seems apparent that response curves obtained in the greenhouse cannot be transferred entirely without change to the field. Principles can, however, and the general idea enunciated here should hold. Field experiments to obtain response curves and an additional plot of phosphorus added vs. some measure of available phosphorus should give an

Figure 11.- Yield of snap beans as related to the content of aluminum phosphate-P of three soils.



10
8
6
4
2
Dry yield (g)
Wellston s.c.l.
Davidson c.
Congaree l.s.
points of maximum yield
50
100
150
200
P.P.M. of aluminum phosphate - P

Figure 12.- Effect of phosphorus additions on the content of aluminum phosphate-P of three soils planted to corn.



300
200
100
P.P.M. of aluminum phosphate - P
Congaree l.s.
Wellston s.c.l.
Davidson c.
Points at which
optimum yield
is obtained
100
200
300
P.P.M. of phosphorus added

exceedingly precise estimate of the amount of phosphorus fertilization required for various soils. After a number of soils have been checked in a given area, interpolation, based on soil texture and other considerations probably will be sufficient for predictive measures.

It should be noted from Figure 12 and the Appendix tables that the effect of phosphate fertilization on the yield of plants, is lower with low rates than it is with high rates of phosphorus. In practical terms this means that banding, row applications, topdressing or any other means of concentrating fertilizer phosphorus is likely to give superior results. The fact that, after phosphorus is built up in soils, banding does not appreciably improve phosphorus response is simply a reflection of the increased efficiency of phosphorus fertilization after an initial lag is overcome.

## VI. SUMMARY AND CONCLUSIONS

An attempt was made to improve the present soil test for available plant phosphorus employed by the Virginia Extension Service. For this purpose, the procedure of soil phosphorus fractionation proposed by Chang and Jackson (1957) was utilized. The study also involved soil and plant-growth experiments, chemical extractions of available phosphorus, and the analyses of relationships between some soil properties and the yield of plants grown in these soils. The results of this study suggested the following conclusions concerning the availability of phosphorus to plants:

(1) The texture of soils has a marked influence on the amount of available phosphorus determined by $HCl$-$H_2SO_4$ and by $NH_4F$.

(2) In a Congaree l.s. the amount of available plant phosphorus extracted with $HCl$-$H_2SO_4$ was comparable to the amount of available phosphorus extracted with $NH_4F$.

(3) In a Davidson c.l. the amount of available plant phosphorus extracted with $HCl$-$H_2SO_4$ was much lower than the amount of available plant phosphorus extracted with $NH_4F$. This insensitivity of the $HCl$-$H_2SO_4$ solution in Davidson c.l. was attributed to the fact that when $HCl$-$H_2SO_4$ was added to Davidson c.l., most of the acid was exhausted by the heavy soil.

(4) In order to improve the sensitivity of the present soil phosphorus test, the strength of the $HCl-H_2SO_4$ used, or the ratio $HCl-H_2SO_4$ to soil should be increased. Another possibility is to use a test based on $NH_4F$ extraction of phosphorus from aluminum phosphate.

(5) For a given amount of phosphorus in the soil solution, the uptake of phosphorus by snap beans increased as the clay percentage of soils increased. However, to accomplish the same level of phosphorus in solution, soils high in clay percentage appeared to require higher amounts of phosphorus additions than light-textured soils. Therefore, it is suggested that, in order to achieve adequate phosphorus nutrition of plants, soils high in clay content should be fertilized heavier than light-textured soils.

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# VIII. VITA

The author was born in Mexico D. F., Mexico; on April 4, 1929. In 1953 he was awarded the degree of B.S. at the National School of Agriculture at Chapingo, Mexico. In 1958 he obtained the degree of M.A. at the North Carolina State College; Raleigh, North Carolina, U.S.A. The author was married to Celia Arteaga of Hidalgo, Mexico on July 2, 1960. In the fall of 1960, he undertook special courses of Plant Physiology at the Institute of Botany, Sao Paulo, Brazil. In 1961-1962, he participated in the programs of teaching and research of Plant Physiology of the National School of Agriculture at Chapingo, Mexico. In the fall of 1962, the O.E.A. awarded him a scholarship to attend a program of work leading to the Ph.D. in Agronomy at V. P. I. U. S. A.

On March 26, 1964, his advisory committee recommended him as a candidate for the Ph.D. On June 2, 1964, he accepted a teaching position at the National School of Agriculture, at Chapingo, Mexico.

# IX. APPENDIX

Table I.- Yield and uptake of phosphorus by three cuttings of Ladino clover as related to some soil phosphorus fractionation of a Sassafras s.l.

| P Added | Yield | P Uptake | $AlPO_4$ | $FePO_4$ | $Ca_3(PO_4)_2$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ---ppm-P--- | | | |
| 0 | 1.25 | 3.20 | 58.0 | 45.5 | 12.5 | 1.75 |
| | 1.74 | 3.15 | 55.5 | 45.5 | 7.5 | 1.75 |
| | 1.19 | 2.78 | 59.0 | 40.0 | 10.5 | 1.75 |
| Avg. | 1.39 | 3.04 | 57.5 | 43.7 | 10.2 | 1.75 |
| 25 | 5.76 | 14.33 | 75.0 | 61.1 | 13.8 | 5.46 |
| | 6.57 | 14.60 | 66.0 | 55.0 | 10.5 | 3.27 |
| | 7.93 | 18.72 | 66.0 | 56.3 | 15.0 | 4.15 |
| Avg. | 6.75 | 15.88 | 69.0 | 57.5 | 13.1 | 4.29 |
| 50 | 5.29 | 14.30 | 118.5 | 70.2 | 16.0 | 14.63 |
| | 7.58 | 19.40 | 97.5 | 66.3 | 12.5 | 8.95 |
| | 6.63 | 18.64 | 127.5 | 67.6 | 14.5 | 16.59 |
| Avg. | 6.50 | 17.45 | 114.5 | 68.0 | 14.3 | 13.72 |
| 100 | 7.72 | 28.05 | 155.5 | 80.9 | 11.3 | 16.57 |
| | 8.46 | 27.25 | 133.0 | 78.6 | 12.5 | 18.56 |
| | 5.99 | 20.86 | 197.5 | 95.7 | 10.5 | 17.88 |
| Avg. | 7.39 | 25.39 | 162.0 | 85.1 | 11.4 | 17.67 |

Table 2.- Yield and uptake of phosphorus by three cuttings of Ladino clover as related to some soil phosphorus fractions of a Davidson c.

| P Added | Yield | P Uptake | $AlPO_4$ | $FePO_4$ | $Ca_3(PO_4)_2$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ppm P | | | |
| 0 | 4.72 | 8.52 | 59.0 | 123.5 | 12.5 | 2.84 |
| | 3.78 | 6.17 | 50.0 | 149.5 | 15.0 | 1.96 |
| | 4.23 | 7.16 | 60.7 | 130.0 | 14.8 | 1.96 |
| Avg. | 4.24 | 7.28 | 56.6 | 134.3 | 14.1 | 2.25 |
| 25 | 6.76 | 16.22 | 73.2 | 124.8 | 12.5 | 2.40 |
| | 7.83 | 20.41 | 83.1 | 150.8 | 10.0 | 2.40 |
| | 5.87 | 12.58 | 73.2 | 163.8 | 10.0 | 2.84 |
| Avg. | 6.82 | 16.40 | 76.5 | 146.5 | 10.8 | 2.55 |
| 50 | 5.54 | 12.05 | 88.4 | 158.6 | 18.8 | 4.15 |
| | 5.28 | 11.92 | 94.6 | 195.0 | 7.5 | 4.15 |
| | 8.67 | 22.14 | 128.6 | 117.0 | 17.5 | 7.64 |
| Avg. | 6.50 | 15.37 | 103.9 | 156.9 | 14.6 | 5.31 |
| 100 | 6.14 | 16.03 | 93.8 | 149.5 | 17.5 | 4.15 |
| | 6.74 | 20.56 | 155.4 | 188.5 | 7.5 | 12.00 |
| | 5.60 | 18.04 | 153.6 | 182.0 | 12.5 | 12.66 |
| Avg. | 6.16 | 18.21 | 134.3 | 173.3 | 12.5 | 9.60 |

Table 3.- Yield and uptake of phosphorus by three cuttings of Ladino clover as related to some soil phosphorus fractions of a Westmoreland s.c.l.

| P Added | Yield | P Uptake | $AlPO_4$ | $FePO_4$ | $Ca_3(PO_4)_2$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ----------------- | ----------------- | ppm P | ----------------- |
| 0 | 1.38 | 3.11 | 42.5 | 20.8 | 32.5 | 7.20 |
| | 1.66 | 2.98 | 41.3 | 15.6 | 37.5 | 6.33 |
| | 3.22 | 5.21 | 37.5 | 44.2 | 40.0 | 5.89 |
| Avg. | 2.09 | 3.77 | 40.4 | 26.9 | 36.7 | 6.47 |
| 25 | 7.38 | 16.22 | 61.3 | 28.6 | 47.5 | 6.33 |
| | 5.39 | 14.37 | 47.5 | 31.2 | 52.5 | 7.64 |
| | 6.24 | 17.19 | 42.5 | 20.8 | 40.0 | 7.20 |
| Avg. | 6.34 | 15.93 | 50.4 | 26.9 | 46.7 | 7.06 |
| 50 | 8.43 | 24.85 | 50.0 | 28.6 | 42.5 | 8.51 |
| | 8.98 | 22.44 | 65.0 | 28.6 | 30.0 | 10.26 |
| | 10.44 | 24.57 | 58.8 | 65.0 | 45.0 | 9.39 |
| Avg. | 9.28 | 23.95 | 57.9 | 40.7 | 39.2 | 9.39 |
| 100 | 8.34 | 22.93 | 96.3 | 46.8 | 62.5 | 18.56 |
| | 7.64 | 26.33 | 80.0 | 49.4 | 37.5 | 17.90 |
| | 9.35 | 28.43 | 76.3 | 44.2 | 45.0 | 19.21 |
| Avg. | 8.44 | 25.90 | 84.2 | 46.8 | 48.3 | 18.56 |

Table 4.- Yield and uptake of phosphorus by three cuttings of Ladino clover as related to some soil phosphorus fractions of a Mason sl. l.

| P Added | Yield | P Uptake | $AlPO_4$ | $FePO_4$ | $Ca_3(PO_4)_2$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ---------------- | ---------------- | ppm P | ---------------- |
| 0 | 5.34 | 10.74 | 91.1 | 78.0 | 22.5 | 6.77 |
| | 4.31 | 8.21 | 88.4 | 65.0 | 25.7 | 6.33 |
| | 4.90 | 8.24 | 89.3 | 84.5 | 19.4 | 5.02 |
| Avg. | 4.85 | 9.06 | 89.6 | 75.8 | 22.5 | 6.04 |
| 25 | 7.64 | 19.25 | 95.6 | 78.0 | 15.6 | 7.20 |
| | 7.90 | 19.43 | 91.1 | 84.5 | 25.0 | 7.20 |
| | 6.83 | 18.30 | 103.6 | 97.5 | 22.5 | 7.20 |
| Avg. | 7.46 | 18.99 | 96.8 | 86.7 | 21.0 | 7.20 |
| 50 | 4.28 | 13.18 | 132.2 | 83.2 | 16.9 | 14.63 |
| | 4.55 | 14.89 | 116.1 | 78.0 | 18.8 | 9.82 |
| | 4.75 | 11.74 | 123.2 | 91.0 | 24.4 | 11.13 |
| Avg. | 4.53 | 13.27 | 123.8 | 84.1 | 20.0 | 11.86 |
| 100 | 8.85 | 28.59 | 149.1 | 143.0 | 10.0 | 11.13 |
| | 7.11 | 24.50 | 154.8 | 110.5 | 16.9 | 16.59 |
| | 11.56 | 39.16 | 142.9 | 117.0 | 21.9 | 19.87 |
| Avg. | 9.17 | 30.75 | 148.9 | 123.5 | 16.3 | 15.86 |

Table 5.- Yield and uptake of phosphorus by two crops of corn as related to some soil phosphorus fractions of a Davidson c.l. previously fertilized with 6.0 ppm of phosphorus.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | ----------ppm P------- | |
| 0 | 3.40 | 1.86 | 36.6 | 4.15 |
| | 3.50 | 1.76 | 39.9 | 3.27 |
| | 3.44 | 2.06 | 48.9 | 3.27 |
| | 3.30 | 1.65 | 37.0 | 2.40 |
| Avg. | 3.41 | 1.83 | 40.6 | 3.27 |
| 10 | 3.61 | 1.79 | 36.6 | 3.27 |
| | 3.76 | 2.09 | 43.6 | 4.15 |
| | 3.78 | 2.07 | 39.1 | 1.96 |
| | 3.14 | 1.77 | 38.6 | 2.40 |
| Avg. | 3.57 | 1.93 | 39.5 | 2.95 |
| 40 | 4.60 | 2.59 | 56.3 | 4.15 |
| | 3.81 | 2.56 | 49.3 | 3.27 |
| | 3.52 | 1.92 | 51.0 | 3.27 |
| | 4.40 | 2.83 | 62.3 | 5.02 |
| Avg. | 4.08 | 2.48 | 54.7 | 3.93 |

Table 6.- Yield and uptake of phosphorus by two crops of corn as related to some soil phosphorus fractions of a Davidson c.l. previously fertilized with 12.0 ppm of phosphorus.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | ----------ppm P----- | |
| 0 | 3.43 | 1.82 | 41.0 | 4.15 |
| | 3.98 | 2.30 | 45.5 | 4.15 |
| | 3.52 | 2.20 | 73.5 | 6.33 |
| | 3.94 | 2.11 | 75.3 | 4.58 |
| Avg. | 3.72 | 2.11 | 58.8 | 4.80 |
| 10 | 3.72 | 2.39 | 69.5 | 5.46 |
| | 4.09 | 2.80 | 86.0 | 6.77 |
| | 3.34 | 1.95 | 44.5 | 3.27 |
| | 3.75 | 2.48 | 43.5 | 4.15 |
| Avg. | 3.73 | 2.41 | 60.9 | 4.91 |
| 40 | 4.94 | 2.95 | 60.6 | 5.02 |
| | 4.12 | 2.41 | 69.0 | 4.15 |
| | 4.56 | 2.73 | 81.0 | 4.15 |
| | 3.90 | 2.58 | 93.8 | 5.46 |
| Avg. | 4.38 | 2.67 | 76.1 | 4.70 |

Table 7.- Yield and uptake of phosphorus by two crops of oats as related to some soil phosphorus fractions of a Congaree l.s.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | --------ppm P-------- | |
| 0 | 2.01 | 3.05 | 46.49 | 17.90 |
| | 2.02 | 2.58 | 43.81 | 18.56 |
| | 1.80 | 2.69 | 46.76 | 17.25 |
| Avg. | 1.94 | 2.77 | 45.69 | 17.90 |
| 10 | 2.41 | 3.84 | 47.30 | 19.87 |
| | 2.64 | 4.33 | 49.45 | 19.21 |
| | 2.82 | 4.33 | 52.14 | 17.25 |
| Avg. | 2.62 | 4.17 | 49.63 | 18.78 |
| 20 | 2.52 | 4.52 | 51.06 | 18.56 |
| | 2.41 | 3.90 | 50.79 | 19.87 |
| | 2.83 | 5.15 | 51.60 | 20.52 |
| Avg. | 2.59 | 4.52 | 51.15 | 19.65 |
| 40 | 3.04 | 7.51 | 56.71 | 25.11 |
| | 2.89 | 7.40 | 58.86 | 25.11 |
| | 2.85 | 5.86 | 59.66 | 23.80 |
| Avg. | 2.93 | 6.92 | 58.41 | 24.67 |

Table 8.- Yield and uptake of phosphorus by two crops of oats as related to some soil phosphorus fractions of a Davidson c.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | --------ppm-------- | |
| 0 | 1.61 | 1.46 | 8.87 | 0.65 |
| | 1.51 | 1.58 | 12.36 | 0.65 |
| | 1.53 | 1.52 | 12.09 | 0.65 |
| Avg. | 1.55 | 1.52 | 11.11 | 0.65 |
| 10 | 1.74 | 2.09 | 11.02 | 0.65 |
| | 1.38 | 1.30 | 13.17 | 0.65 |
| | 1.78 | 1.98 | 9.14 | 0.65 |
| Avg. | 1.63 | 1.79 | 11.11 | 0.65 |
| 20 | 2.02 | 2.98 | 15.32 | 0.65 |
| | 2.10 | 2.43 | 14.78 | 0.65 |
| | 1.92 | 2.50 | 13.98 | 0.65 |
| Avg. | 2.01 | 2.64 | 14.69 | 0.65 |
| 40 | 2.14 | 3.29 | 15.86 | 0.65 |
| | 2.27 | 3.27 | 14.24 | 0.65 |
| | 2.45 | 3.61 | 20.16 | 1.31 |
| Avg. | 2.29 | 3.39 | 16.75 | 0.87 |

Table 9.- Yield and uptake of phosphorus by two crops of oats as related to some soil phosphorus fractions of a Wellston s.c.l.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl$-$H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | ---------ppm | ----------- |
| 0 | 1.82 | 1.95 | 15.05 | 0.65 |
| | 1.81 | 1.98 | 13.98 | 0.65 |
| | 1.67 | 1.80 | 19.35 | 0.65 |
| Avg. | 1.77 | 1.91 | 16.13 | 0.65 |
| 10 | 2.09 | 2.87 | 14.24 | 0.87 |
| | 2.13 | 2.86 | 19.62 | 0.65 |
| | 1.97 | 2.43 | 19.89 | 0.65 |
| Avg. | 2.06 | 2.72 | 17.92 | 0.72 |
| 20 | 2.37 | 3.35 | 24.99 | 1.75 |
| | 2.42 | 3.60 | 24.73 | 1.09 |
| | 1.95 | 2.92 | 22.04 | 1.75 |
| Avg. | 2.25 | 3.29 | 23.92 | 1.53 |
| 40 | 2.75 | 5.00 | 27.95 | 3.71 |
| | 3.01 | 4.91 | 27.68 | 4.58 |
| | 2.83 | 4.46 | 27.95 | 4.58 |
| Avg. | 2.86 | 4.79 | 27.86 | 4.29 |
| 80 | 2.92 | 5.43 | 43.27 | 9.39 |
| | 2.91 | 6.68 | 45.42 | 7.64 |
| | 2.54 | 5.14 | 42.73 | 9.39 |
| Avg. | 2.79 | 5.75 | 43.81 | 8.81 |

Table 10.- Yield and uptake of phosphorus by two crops of oats as related to some soil phosphorus fractions of a Cecil s.c.l.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | ---------ppm--------- | |
| 0 | 2.34 | 3.41 | 26.61 | 0.65 |
| | 2.15 | 2.77 | 27.84 | 0.87 |
| ___ | 1.95 | 2.26 | 22.58 | 0.87 |
| Avg. | 2.15 | 2.81 | 25.68 | 0.80 |
| 10 | 2.86 | 4.52 | 24.99 | 1.31 |
| | 2.34 | 3.34 | 27.41 | 1.75 |
| ___ | 1.97 | 2.54 | 27.95 | 1.75 |
| Avg. | 2.39 | 3.47 | 26.78 | 1.60 |
| 20 | 3.00 | 5.17 | 32.25 | 3.27 |
| | 3.04 | 5.29 | 32.79 | 3.71 |
| ___ | 3.04 | 5.29 | 34.40 | 2.40 |
| Avg. | 3.03 | 5.25 | 33.15 | 3.13 |

"continued'

Table 10 (continued). — Yield and uptake of phorphorus by two crops of oats as related to some soil phosphorus fractions of a Cecil s.c.l.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | ----------ppm---------- | |
| 40 | 3.67 | 7.73 | 45.96 | 7.20 |
| | 3.48 | 6.76 | 43.27 | 7.20 |
| | 3.38 | 5.19 | 46.76 | 6.77 |
| Avg. | 3.51 | 6.56 | 45.33 | 7.06 |
| 80 | 3.48 | 9.60 | 50.79 | 13.97 |
| | 3.73 | 8.13 | 60.47 | 11.57 |
| | 4.30 | 9.46 | 60.20 | 11.13 |
| Avg. | 3.84 | 9.06 | 57.15 | 12.22 |
| 160 | 4.88 | 15.51 | 107.50 | 39.90 |
| | 4.41 | 13.08 | 113.14 | 33.18 |
| | 4.37 | 12.86 | 104.28 | 27.29 |
| Avg. | 4.55 | 13.82 | 108.31 | 33.46 |

Table 11.- Yield and phosphorus uptake by two crops of oats as related to some soil phosphorus fractions of a Huntington l.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | ---------ppm P-------- | |
| 0 | 1.70 | 1.53 | 13.17 | 0.65 |
| | 1.84 | 1.83 | 10.75 | 0.65 |
| | 1.61 | 1.43 | 12.09 | 0.65 |
| Avg. | 1.72 | 1.60 | 12.00 | 0.65 |
| 10 | 1.83 | 1.92 | 13.17 | 0.65 |
| | 1.83 | 1.96 | 12.63 | 0.65 |
| | 2.13 | 2.41 | 10.75 | 0.65 |
| Avg. | 1.93 | 2.10 | 12.18 | 0.65 |
| 20 | 2.28 | 2.70 | 12.90 | 0.65 |
| | 2.48 | 3.75 | 12.36 | 0.65 |
| | 2.08 | 2.89 | 11.29 | 0.65 |
| Avg. | 2.28 | 3.11 | 12.18 | 0.65 |

"continued"

Table 11 (continued).- Yield and phosphorus uptake of two crops of oats as related to some soil phosphorus fractions of a Huntington l.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | --------ppm P-------- | |
| 40 | 2.98 | 5.70 | 13.17 | 0.65 |
| | 2.86 | 5.23 | 11.83 | 0.65 |
| | 2.63 | 4.91 | 13.98 | 0.65 |
| Avg. | 2.82 | 5.28 | 12.99 | 0.65 |
| 80 | 3.55 | 7.01 | 16.93 | 3.27 |
| | 3.51 | 6.90 | 18.01 | 1.96 |
| | 3.70 | 8.62 | 18.54 | 2.40 |
| Avg. | 3.59 | 7.51 | 17.83 | 2.54 |
| 160 | 4.00 | 9.92 | 38.43 | 10.70 |
| | 3.50 | 8.60 | 30.64 | 10.26 |
| | 3.71 | 9.54 | 40.85 | 12.01 |
| Avg. | 3.74 | 9.35 | 36.64 | 10.99 |

Table 12.- Yield and phosphorus uptake by two crops of oats as related to some soil phosphorus fractions of a Frederick I.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | ---------ppm P-------- | |
| 0 | 2.13 | 1.64 | 30.91 | 5.46 |
| | 2.22 | 2.16 | 23.38 | 2.84 |
| | 1.82 | 1.81 | 28.49 | 2.84 |
| Avg. | 2.06 | 1.87 | 27.59 | 3.71 |
| 10 | 2.20 | 2.80 | 27.95 | 2.84 |
| | 2.30 | 2.78 | 29.56 | 3.27 |
| | 2.39 | 2.69 | 30.10 | 5.45 |
| Avg. | 2.30 | 2.76 | 29.20 | 3.85 |
| 20 | 2.41 | 2.49 | 31.98 | 5.02 |
| | 1.80 | 1.62 | 32.79 | 5.89 |
| | 1.88 | 1.90 | 35.74 | 5.02 |
| Avg. | 2.03 | 2.00 | 33.50 | 5.31 |

"continued"

Table 12 (continued).- Yield and phosphorus uptake by two crops of oats as related to some soil phosphorus fractions of a Frederick l.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) |
|---|---|---|---|---|
| ppm | g/pot | mg/pot | -----------ppm P------ | |
| 40 | 2.21 | 2.22 | 41.93 | 6.77 |
| | 2.40 | 3.15 | 43.27 | 6.33 |
| | 2.51 | 3.67 | 47.84 | 6.33 |
| Avg. | 2.37 | 3.01 | 44.35 | 6.48 |
| 80 | 3.06 | 4.63 | 52.68 | 8.51 |
| | 3.06 | 4.86 | 54.02 | 10.26 |
| | 2.54 | 3.44 | 56.44 | 10.26 |
| Avg. | 2.89 | 4.31 | 54.38 | 9.68 |
| 160 | 3.60 | 6.66 | 81.70 | 18.56 |
| | 2.80 | 5.64 | 89.49 | 17.90 |
| Avg. | 3.20 | 6.15 | 85.60 | 18.23 |

Table 13.- Yield and uptake of phosphorus by snap beans as related to some soil phosphorus fractions and phosphorus in solution of a Congaree l.s.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) | P in solution |
|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ppm | | |
| 0 | 3.77 | 3.67 | 40.58 | 18.56 | 0.096 |
| | 4.11 | 4.46 | 37.89 | 16.59 | -- |
| | 3.50 | 3.07 | 40.58 | 16.59 | -- |
| Avg. | 3.79 | 3.73 | 39.68 | 17.25 | |
| 20 | 4.75 | 6.68 | 50.53 | 23.80 | -- |
| | 5.30 | 7.16 | 55.63 | 19.21 | 0.121 |
| | 4.00 | 7.17 | 59.39 | 19.87 | -- |
| Avg. | 4.68 | 7.00 | 55.18 | 20.96 | |
| 40 | 5.84 | 12.38 | 67.99 | 25.11 | 0.203 |
| | 6.68 | 12.09 | 61.81 | 28.82 | -- |
| | 4.14 | 9.27 | 61.54 | 23.14 | -- |
| Avg. | 5.55 | 11.25 | 63.78 | 25.69 | |

"continued"

Table 13 (continued).- Yield and uptake of phosphorus by snap beans as related to some soil phosphorus fractions and phosphorus in solution of a Congaree l.s.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract | P in solution |
|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ---------------ppm--------------- | | |
| 80 | 6.79 | 19.20 | 73.37 | 45.41 | 0.344 |
| | 5.50 | 14.15 | 89.23 | 43.88 | -- |
| | 7.01 | 18.03 | 85.73 | 40.82 | -- |
| Avg. | 6.43 | 17.13 | 82.77 | 43.37 | |
| 160 | 6.22 | 27.65 | 135.18 | 76.85 | -- |
| | 6.55 | 27.38 | 134.38 | 59.82 | 1.76 |
| | 5.40 | 23.25 | 139.75 | 74.01 | -- |
| Avg. | 6.06 | 26.09 | 136.44 | 70.23 | |
| 320 | 6.59 | 43.74 | 216.08 | 89.07 | -- |
| | 6.91 | 33.06 | 204.25 | 92.13 | -- |
| | 7.78 | 59.27 | 307.73 | 98.24 | 4.60 |
| Avg. | 7.09 | 45.36 | 242.69 | 93.15 | |

Table 14.- Yield and phosphorus uptake by snap beans as related to some soil phosphorus fractions and phosphorus in solution of a Davidson c.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) | P in solution |
|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ------------ppm P | ------------ | ------------ |
| 0 | 5.45 | 7.25 | 9.94 | 3.27 | 0.058 |
| | 4.05 | 4.28 | 10.21 | 0.65 | -- |
| | 4.82 | 6.46 | 10.48 | 0.65 | -- |
| Avg. | 4.77 | 6.00 | 10.21 | 1.52 | |
| 20 | 4.50 | 6.47 | 11.56 | 1.09 | -- |
| | 3.80 | 5.14 | 11.02 | 0.87 | 0.086 |
| | 3.70 | 5.29 | 12.63 | 0.65 | -- |
| Avg. | 4.00 | 5.63 | 11.74 | 0.87 | |
| 40 | 3.95 | 7.71 | 14.51 | 1.75 | 0.061 |
| | 5.65 | 9.98 | 12.63 | 1.09 | -- |
| | 3.95 | 7.88 | 13.98 | 1.31 | -- |
| Avg. | 4.52 | 8.52 | 13.71 | 1.38 | |

"continued"

Table 14 (continued).- Yield and phosphorus uptake by snap beans as related to some soil phosphorus fractions and phosphorus in solution of a Davidson c.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) | P in solution |
|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ---------------------ppm P------------- | | |
| 80 | 4.42 | 6.43 | 19.62 | 2.40 | 0.058 |
| | 6.80 | 16.60 | 23.11 | 3.25 | -- |
| ___ | 6.09 | 15.47 | 18.28 | 2.84 | -- |
| Avg. | 5.77 | 12.83 | 20.34 | 2.83 | |
| 160 | 6.00 | 18.24 | 38.16 | 10.70 | -- |
| | 7.15 | 21.12 | 40.04 | 7.20 | 0.080 |
| ___ | 6.12 | 26.01 | 49.18 | 8.95 | -- |
| Avg. | 6.42 | 21.79 | 42.46 | 8.95 | |
| 320 | 6.78 | 32.15 | 121.21 | 37.77 | -- |
| | 7.15 | 40.29 | 94.33 | 23.14 | -- |
| ___ | 7.49 | 41.22 | 138.14 | 43.88 | 0.220 |
| Avg. | 7.14 | 37.89 | 117.89 | 34.93 | |

Table 15.- Yield and uptake of phosphorus by snap beans as related to some soil phosphorus fractions and phosphorus in solution of a Wellston s.c.l.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) | P in solution |
|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ---------------------------ppm--------------------------- | | |
| 0 | 4.61 | 5.83 | 15.59 | 0.65 | 0.080 |
| | 5.07 | 6.19 | 17.20 | 0.65 | - |
| | 3.70 | 5.53 | 13.44 | 0.65 | - |
| Avg. | 4.46 | 5.85 | 15.41 | 0.65 | |
| 20 | 4.70 | 8.86 | 22.04 | 3.71 | - |
| | 5.84 | 9.93 | 24.99 | 2.40 | 0.096 |
| | 6.63 | 11.92 | 20.43 | 2.84 | - |
| Avg. | 5.72 | 10.24 | 22.49 | 2.98 | |
| 40 | 6.48 | 14.33 | 28.49 | 6.33 | 0.152 |
| | 6.94 | 14.71 | 29.56 | 5.89 | - |
| | 6.10 | 18.15 | 35.48 | 9.39 | - |
| Avg. | 6.51 | 15.73 | 31.18 | 7.20 | |

"continued"

Table 15 (continued). - Yield and uptake of phosphorus by snap beans as related to some soil phosphorus fractions and phosphorus in solution of a Wellston s.c.l.

| P Added | Yield | P Uptake | $AlPO_4$ | P ($HCl-H_2SO_4$ extract) | P in solution |
|---|---|---|---|---|---|
| ppm | g/pot | mg/pot | ppm | | |
| 80 | 7.29 | 21.70 | 54.29 | 21.83 | 0.259 |
| | 7.30 | 23.71 | 53.75 | 17.90 | - |
| | 8.30 | 23.42 | 59.66 | 22.49 | - |
| Avg. | 7.63 | 22.94 | 55.90 | 20.74 | |
| 160 | 8.39 | 34.35 | 101.05 | 49.99 | - |
| | 8.75 | 37.38 | 102.93 | 51.52 | 0.532 |
| | 9.32 | 41.96 | 86.27 | 42.35 | - |
| Avg. | 8.82 | 37.90 | 96.75 | 47.95 | |
| 320 | 8.69 | 57.42 | 223.33 | 86.01 | |
| | 9.83 | 55.28 | 193.77 | 89.07 | |
| | 8.91 | 57.79 | 181.88 | 68.33 | 0.117 |
| Avg. | 9.14 | 56.83 | 199.66 | 81.14 | |

## ABSTRACT

An attempt was made to improve the present soil test for available plant phosphorus employed by the Virginia Extension Service. For this purpose, the procedure of soil phosphorus fractionation proposed by Chang and Jackson (1957) was utilized. The study involved soil and plant-growth experiments, chemical extractions of available phosphorus and the analysis of relationships between some soil properties and the yield of plants grown in these soils. The results of this study were as follows:

The regressions of the yields of Ladino clover and the soil phosphorus extracted with $NH_4F$, NaOH and $H_2SO_4$ gave correlation coefficients of 0.43, 0.38 and 0.29 respectively.

Aluminum phosphate-P appeared to be better related to the amounts of added phosphorus to the soils sampled than iron phosphate-P and/or calcium phosphate-P.

In a Congaree l.s., the amount of available plant phosphorus extracted with $HCl$-$H_2SO_4$ was comparable to the amount of available plant phosphorus extracted with $NH_4F$.

In a Davidson c.l., the amount of available plant phosphorus extracted with $HCl$-$H_2SO_4$ was much lower than the amount of available plant phosphorus extracted with $NH_4F$. Most of the $HCl$-$H_2SO_4$ added to Davidson c.l., was exhausted by contact with the heavy soil.

The $R^2$ values of the regression between: (a) Percentage of maximum yield of Ladino clover, corn, oats and snap beans vs. available plant phosphorus extracted with $NH_4F$, and (b) Percentage of maximum yield of Ladino clover, corn, oats and snap beans vs. available plant phosphorus extracted with $HCl$-$H_2SO_4$ were 0.22 and 0.18 respectively.

The actual and the calculated relative rates of uptake of phosphorus by snap beans grown in Davidson c., Wellston s.c.l. and Congaree l.s. were statistically similar. For a given amount of phosphorus in the soil solution, Davidson c. appeared to require larger amounts of added phosphorus than Wellston s.c.l. and Congaree l.s. The uptake of phosphorus by snap beans grown in Davidson c. was higher than the uptake of snap beans grown in Wellston s.c.l. and/or Congaree l.s.

From the results of this investigation, it is concluded that, in order to insure proper phosphorus nutrition of plants, heavy-textured soils should receive more phosphate fertilizer than light-textured soils.