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I am submitting herewith a thesis written by Charles K. Mulbah entitled "Comparison of the Availability of Applied and Residual Phosphorus as Measured by Plant Uptake and Chemical Analysis." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant and Soil Science.

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COMPARISON OF THE AVAILABILITY OF APPLIED AND RESIDUAL PHOSPHORUS AS MEASURED BY PLANT UPTAKE AND CHEMICAL ANALYSIS

A Thesis

Presented for the

Master of Science

Degree

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ABSTRACT

The purpose of this investigation was to evaluate several techniques for measuring phosphorus (P) availability. The data obtained were used to compare the relative availability of applied and residual P.

Plant P uptake and soil extraction methods were used in estimating the availability of applied and residual P. Five Tennessee soils and three extractant solutions used in three Southern states were utilized. The plants were started in nutrient solutions and then transferred to the soil. The plants grew in the soils for 20 days. Plant yields, ^{32}P, total P and P uptake determinations were made.

The extractable P data for the original soils showed similarities between some soils and differences between others. The Minvale high P soil was shown to have the highest extractable P. The 1 percent ammonium sulfate in 0.05 N Sulfuric Acid (Solution I) and the 0.03N Ammonia fluoride in 0.1N hydrochloric acid (Solution III) were very similar in their extracting abilities for the original soils. Solution III extracted more P than did Solutions I and II (0.7N NH_4OAc in 0.54N HOAc adjusted to pH 4.8). The extractable P data of the cropped soils showed that Solution III again extracted more P than did either of the other two solutions. All the solutions were different from each other in their extracting abilities. Some cropped soils had similar extractable P values. There were, however, significant differences between the extractable soil P values of other soils. Significant

correlations were obtained between plant uptake and extractable P using Solutions I and II.

Both plant yield and extractable soil P after cropping were increased when P was added to the low P soils prior to growing the plants. No significant correlation was obtained between the available P ("A" value) and plant uptake. The "A" values did show the same trends as the extraction solutions.

The major portion of the P in the plant came from residual sources. Phorphorus uptake from applied P ranged up to 42 percent of the total P in the plants.

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CHAPTER I

INTRODUCTION

For several years, soil scientists have sought ways to evaluate available soil nutrient levels. Soil-fertilizer-plant relationships and their interdependence have been studied. These studies have involved application rates, times of application, kinds of fertilizers, and methods of application. Phosphate availability studies have involved the usage of phrases such as native and residual phosphates and phosphate fixation. For the purpose of this study, native phosphate is that derived from soil parent materials and residual phosphate is the remanent of applied phosphate after harvesting crops will be called "residual phosphates." Where distinction is required, clarification shall be made. Phosphate fixation involves processes where available phosphate is converted into unavailable forms. Fixation processes are found to be influenced by soil clay content, the amounts and activities of iron, aluminum, calcium, magnesium, soil pH, and the oxidation-reduction status of the soil.

Phosphate availability determinations certainly necessitate the studies of phosphate reactions. Phosphate fixation and transformation processes must first be understood before further knowledge of phosphate availability can be obtained. The knowledge of phosphate chemistry leads investigators to study more about phosphate availability through field and greenhouse experiments. Long-term phosphorus applications

lead to residual phosphate buildup. Unlike early experiments which relied on crop yield response to applied phosphates, present studies also utilize extraction methods for soil availability studies.

Because soil phosphate is known to exist in low concentrations, due to its presence in slightly soluble compounds, available phosphate studies have involved indirect measuring techniques. The extraction solutions cannot effectively remove phosphates that are sometimes available to plants because plants selectively absorb nutrients. It is also true that some soils have high fixing power so easily soluble phosphate added becomes partly unavailable to plants. It is also realized that salts, toxic substances and differing soil conditions at planting, harvesting and sampling of plants have profound affects on experimental results as measured by plant uptake and laboratory tests.

In this experiment, plants were grown in nutrient solution and soil in a manner similar to the Standford and DeMent (46) procedure. Five Tennessee soils were extracted with three extractant solutions; 1 percent $(NH_4)_2SO_4$ in $0.05NH_2SO_4$, $0.7NNH_4OAc$ in 0.54N HOAc and 0.03N NH_4F in 0.1N HCl. The quantity of P extracted was compared with plant uptake of P. The primary purpose of this study was to compare the availability of applied and residual P in different soils as measured by plant uptake and chemical analysis.

CHAPTER II

SELECTED LITERATURE REVIEW

Nearly all soil phosphorus exists as orthophosphates. Soil phosphates are derivatives of phosphoric acid. The amounts of inorganic phosphates are very small, generally 0.01 to 0.30 percent. Organic phosphates vary directly with the organic matter content of the soil and are generally most abundant in the surface layer of the soil (2, 54).

A. FORMS OF PHOSPHORUS IN SOILS

Among the major organic phosphorus forms are nucleic acids, phospholipids and inositol phosphorus. Nucleic acids account for nearly 2 percent of the total organic phosphorus. Phospholipids make up 1 percent of soil organic phosphorus, while inositol phosphorus accounts for 35 percent. The nature of the remaining compounds is unknown. Organic phosphorus mineralization increases with temperature up to 30°C. In temperate regions, mineralized organic phosphorus is very small. However, in tropical soils, the mineralization of organic phosphorus plays a major role in plant-phosphorus availability (2, 54).

Rankama and Sahama (40) found that apatite is a primary source of inorganic phosphates. The main form is fluoroapatite. Some other forms of phosphate are vivianite, waveite, varicite, and strengite (54, 55).

Calcium phosphates exist mainly in less weathered soils and are more soluble in dilute hydrochloric acid. They are primary sources of

phosphate ions in soil systems and exist mostly above pH 7 (2, 5). Aluminum and iron phosphates are present mainly in more highly weathered soils at pH values below 5, and are soluble in sodium hydroxide (2, 38). The "occluded" form of phosphate identified by Chang and Jackson (6) was found to remain in constant quantity as pH increased. The "occluded" phosphate was found in highly weathered soils (2). Patrick and Mikkelsen (38) isolated the "reductant soluble form." They stressed that this form was very insoluble but became soluble in lowland rice soils.

The inorganic phosphate derivatives of phosphoric acid are formed by successive removals of hydrogens forming the following ions: $H_2PO_4^-$, $HPO_4^=$, $PO_4^{\equiv}$. The quantities of each form is pH dependent. The $H_2PO_4^-$ exists at low pH values, while the $PO_4^{\equiv}$ exists at high pH values. These forms of phosphoric acid undergo reactions that play major roles in the availability of phosphorus to plants. These phosphorus forms may become fixed onto mineral surfaces and thus become unavailable. The interactions and relationships of the phosphate forms described above to soils and other nutrients influence phosphate availability to plants at a given pH value (2).

Bray (3) divided soil phosphorus into (1) difficulty soluble phosphorus, (2) easily soluble phosphorus, and (3) highly soluble phosphorus. In a field study on a low phosphorus soil with corn as the indicator crop, Bray found that the difficulty soluble phosphorus existed in large quantities and sometimes became available. He stressed that the acid soluble fraction was used the most and was subject to fluctuations. Its uptake was found to be species dependent.

The highly soluble fraction was very small and was constantly being changed into unavailable forms despite the equilibrium status of all forms. However, he found that each soil has a fixing capacity and once that was exceeded the highly soluble form became available and could be extracted by chemical methods or plants.

Burd (5) emphasized that calcium, aluminum and iron phosphates are the compounds of interest in soil phosphate behavior investigations. He particularly linked phosphate fixation to calcium concentration in solutions.

B. PHOSPHATE FIXATION

Phosphate fixation or retention by soil involves adsorption, chemical precipitation and fixation by soil organic matter. The removal of phosphate from solution by soils and the conversion of soluble phosphate to a less soluble form are all involved. The soil-solution is the site of many chemical reactions. Since the cations and anions are dissolved in water, cations may remove anions such as phosphates from solution. The presence of ammonium ions increases the adsorption of phosphate ions. Chemical precipitation depends on the acidity and alkalinity of the soils (24, 32).

Kurtz (24) and Williams (55) both associated phosphate fixation with soil acidity and iron and aluminum concentrations. In his studies of some prairie soils, Metzer (31) concluded that phosphate fixation under acid field conditions was due to precipitation of phosphate from solution by several cations through not necessarily aluminum and iron. However, in a later study (31) he also found that the removal of iron

and aluminum from a soil solution greatly decreased fixation between pH 5 and 6. Heck (16) found that fixation did not necessarily depend on the amount of iron and aluminum in soil solution, but upon the state of hydration of their oxides.

MacIntire et al. (26) did some work at the Tennessee Experiment Station on the affect of fluorine on phosphate availability. This work revealed that fluoroapatite may be produced in nonacid-forming fertilizer and cause a decrease in phosphate availability. Unlike Burd (5), MacIntire et al. (31) and Perkins and King (39), who stressed precipitation affects of aluminum, iron and calcium ions, Taylor (48) attributed the decrease in nutrient availability to plants to the micro-organism content of the soil. He found that the higher the microbe content, the greater the fixation of soil phosphates.

The earlier theories on the retention of phosphate ions by soils were centered around chemical precipitation. It was believed that in acid soils iron and aluminum phosphates were the precipitates while in neutral and alkaline soils calcium and other divalent ions were the precipitating agents (32). However, relatively recent solubility and plant growth studies failed to validate the precipitation theory in acid soils. These researchers were able to give some validity to the calcium effects in calcaceous soils.

In a relatively recent extensive phosphate fixation study, Patrick and Mikkelsen (38) showed that in acid soils phosphate was "precipitated as aluminum phosphate or adsorbed on clay surfaces" and later "converted to the more insoluble ferric phosphate."

C. ROOT PHOSPHATE ABSORPTION

Root absorption processes greatly affect the chemistry of soil phosphates. The dissolution of more phosphate into solution depends on the relative rate of phosphate uptake by roots. As phosphate is taken up, more phosphate comes into solution (8). Until lately, there was no generally accepted explanation of absorption processes. Overstreet and Dean (37) discussed reasons for the exchange between phosphate ions and root surfaces, and between phosphate ions and soil solution. They also reported that organic matter and liming increased phosphate availability. Investigations by Overstreet and Dean (37), McAuliffe et al. (29) helped explain the mechanism of ion absorption by roots.

Research by McAuliffe et al. (29) indicated that some of the phosphate ions adsorbed onto the soil surfaces were exchangeable with phosphate ions in solution. The first of the two reactions mentioned was the rapid exchange between phosphate ions in solution and those on the soil surfaces. Then there was the exchange between the solution and the root surfaces.

Phosphate absorption processes are more difficult to understand in the study of submerged soils. Rice yield response to phosphate is less pronounced under waterlogged conditions. On the other hand, upland rice yield response to fertilizer application has been found to be higher than in submerged soils (38).

Patrick and Mikkelsen (38) and Mandal and Das (27) found that native phosphate became more available under submerged conditions. These workers stressed that the increase was due to the reduction of ferric

phosphate to the more soluble ferrous phosphate under anaerobic conditions caused by submergence. The increase in pH caused by waterlogging was also cited as a reason in phosphate availability.

D. AVAILABILITY OF RESIDUAL SOIL PHOSPHATE

Agricultural chemists have always been confronted with the task of estimating the specific nutrient requirements of a given soil for adequate plant growth. Many of them approached their task by measuring the amount of phosphate in the ash of a given plant in comparison with the amount of available phosphate in the soil in terms of crop yield response to added phosphates. However, most of the earlier methods were found to be misleading and unreliable (19).

Of the many methods proposed, only those that relate to available phosphorus will be considered here. Acids, bases, neutral salts, and water have been used to extract phosphate from soils. Bray and Kurtz (4) proposed several methods for extracting total available P and adsorbed P forms from soils. Each form of soil P has a specific extractant solution. Hibbard (19) showed that the amount of phosphate dissolved from a soil by an acid increases as the volume of solvent is increased, up to a limit. He also found that the volume relationship depends on the particular soil being extracted and its pH level.

Seatz (44) did an extensive study of 32 kaolinitic soils, using a number of extracting solutions, and found that neutral 0.1N ammonium fluoride alone dissolved the least amount of extractable P while 0.03N ammonium fluoride in 0.1N sulfuric acid released the most extractable phosphate. The Bray strong acid extracting solution released less

phosphorus than the 0.1N sulfuric acid but more than the 0.1N hydrochloric acid. In a comparative study of iron and aluminum phosphates prepared in the laboratory, he found that similar concentrations of hydrochloric and sulfuric acids showed little differences in their extracting capacities of aluminum phosphate. Sulfuric acid was more effective in extracting phosphate from iron phosphate.

At the same concentration and soil-to-solution ratio, Seatz (44) found that sulfuric acid extracted more phosphorus than did hydrochloric acid from all phosphorus forms. A 0.1N solution of ammonium fluoride and hydrochloric acid removed more phosphorus than any single acid. The ammonium fluoride alone did not extract nearly as much phosphate as the difference between the phosphate extracted by a dilute acid alone and a dilute solution of acid and ammonium fluoride. He stated that the acid prevented the replaced phoshpate from reprecipitating as an insoluble calcium phosphate.

Phosphorus extraction from soils has been investigated by Bray (3), Kurtz (24), Dickman and DeTurk (10), Chang and Jackson (6). Most of their relatively recent works were done using acids or acids buffered to definite pH values to extract the easily acid-soluble forms. The acid solutions were unable to extract the adsorbed phosphate forms, except in cases where large quantities were in the soil. Bray and Kurtz (4) found that acid reagents only removed adsorbed P forms when a large amount of the reagent was used. They also found that the adsorbed form was extracted by ammonium fluoride. Adsorbed phosphates were found to be more abundant in untreated soils below pH 6 than at higher pH values. Their studies revealed that added soluble phosphates were

rapidly changed into adsorbed forms below pH 6. Added acid-soluble phosphates were found to gradually dissolve and eventally changed into adsorbed P forms below pH 6. Above pH 6, soluble and adsorbed P forms were changed into acid-soluble P forms. However, the acid-soluble P, like rock phosphate, did not change. The critical pH value for the Corn Belt was found to be pH 6. In fact these two researchers found that the relative availability of different phosphate forms depended on the nature of the soil colloids.

Midgley (32) reported that several researchers had realized earlier that all the added phosphate was not extractable with either plants or solution. Dean and Fried (8) reported that the residual fraction accounted for 40 percent of the total phosphorus and that this fraction was found to remain unchanged over a fifty-year cropping period at the Rothamstead and Woburn study plots. Dickman and DeTurk (10), in a similar study, accounted for most of the phosphorus in terms of inorganic or organic fractions. Their study of previously cropped soils showed that all the phosphorus fractions could not be recovered.

Independent studies by Dean and Fried (8), and Perkins and King (39), failed to account for the other phosphate compounds in terms of titanium phosphate. Murphy (33) and Williams (55) showed that residual phosphate availability was greatest in neutral soils, less in alkaline calcaceous soils and least in sesquioxides and kaolinitic soils. Olsen (36) found that precipitated phosphate was fixed in the crystal lattice of calcaceous soils.

Rich and co-workers (41) found that five years after applying superphosphate each year for eight years there was no real decline in

yield. In this experiment, superphosphate had a greater residual affect in terms of soluble phosphate than any other phosphate fertilizer. A residual study by Weeks and Miller (53) at the Kentucky Experiment Station revealed that soil phosphate level declined with time. A study of residual phosphate level after a soil had received superphosphate for sixteen years followed by a period of sixteen years of no phosphate application showed that the available phosphate level had declined greatly. The yield decreased to a point about halfway between that of plots receiving phosphate continuously and those that received no inorganic phosphate over the entire period.

A field residual study using oats indicated that phosphorus was still available to plants eight years after application (7). McAuliffe et al. (30) found that the availability of phosphorus depended on the calcium content of the soil. They obtained very good correlations for both the Peach and English, and the Bray extraction methods. These researchers also found that annual phosphorus application was more beneficial in increasing crop yield despite the favorable residual effect.

A field study by Neller and Lundry (34) on a low available phosphate Marlboro soil several years after an application of 116 pounds of P_2O_5 per acre revealed that the phosphate levels increased in plants where a high level of residual phosphate existed. Jones (23) conducted an elaborate residual phosphorus study in which he found that only 10 to 15 percent of the added phosphate fertilizer was recovered by the crops after five years. More phosphate was recovered from water-soluble sources than from insoluble sources such as rock phosphate and tricalcium phosphate. Jones' study further revealed that long contacts of cotton

plant roots with soil increased the availability of insoluble phosphate. He added that annual phosphate application was essential for economical crop production despite increased availability of residual phosphate. Yield response measured by Volk (51) five years after application of varying rates of phosphate to a Hartsells fine loam showed a decline. He found a definite response to accumulated phosphate.

Thomas (49) studied the availability of residual phosphate over a period of five years. He found significant increases in extractable and total P which indicated that residual P was still available after five years of cropping. The average increase in P concentration of alfalfa per 100 pounds of P originally applied were 0.036, 0.020, 0.025, and 0.026 percent for each year. The application rates used in this study were 26.2, 54.4, 104.8, and 209.6 pounds P per acre.

E. RADIOACTIVE PHOSPHORUS

Radioactivity can be measured at extremely low concentrations. Quantitative determinations that can be made by measuring change in specific activity has made ^{32}P very useful in plant and soil research. Specific activity is the amount of radioactive element per unit weight of element present. The change in specific activity is the basis of most fertilizer experiments using ^{32}P (8, 15).

Larsen (25), Dean and Fried (8), hypothesized that quantitative evaluations of soil phosphorus levels using ^{32}P could be made. They assumed that plants absorbed phosphorus from the soil and applied fertilizer sources in proportion to their relative availability. Their assumption included the nondiscriminatory uptake of applied phosphorus

from two different sources. Dean and Fried's hypothesis was stated as:

$$A = \frac{B(1-Y)}{Y}$$

Where A is the amount of available phosphorus in the soil, B is the amount of phosphorus applied in the fertilizer and Y is the proportion of phosphorus in the plant derived from the fertilizer. They further stressed that the available phosphorus calculated is a measure of the quantity of phosphorus in the soil which is equal in availability to that in the fertilizer. Webb and Pesek (52) explained available phosphorus value determination as adding a known quantity of labeled fertilizer to a soil and growing crops, determining the proportion of absorbed phosphorus derived from the fertilizer and using the above equation to calculate the available phosphorus.

Henderson and Jones (17) used ^{32}P to demonstrate the low mobility of phosphorus in some soils. McAuliffe and co-workers (29) also used ^{32}P to measure phosphate uptake by clay minerals and hydrous oxides. Spinks and Barber (45) stated that ^{32}P is independent of any reaction or exchange which phosphorus may subsequently undergo once added to the soil. They emphasized that plants make no distinction between radioactive and nonradioactive phosphorus, as long as the two have similar combination states and are mixed proportionately. They also found that a limitation of labeled phosphorus is that it must be applied uniformly to ensure random distribution. It was found that it must have characteristics similar to known chemical compounds.

Translocation studies paved the way for accurate field and greenhouse studies. Dean et al. (9) studied the residual affects of

phosphorus on rye using labeled phosphorus. The work revealed that (1) an inverse relationship existed between phosphorus fertility status of a soil and phosphorus derived from fertilizer applied at planting time; (2) the type of fertilizer, the rate of application and the placement affected the relative amounts of native and added fertilizer phosphorus absorbed by plants; and (3) growth-influencing factors did not have similar affects on the percentage of phosphorus in the crop derived from applied phosphorus.

Nelson et al. (35) found that the percentage of fertilizer absorbed by potatoes, corn and cotton decreased as the amount of phosphorus in the soil increased. This study also showed that crop yield depended on fertilizer phosphorus. The results of this experiment further revealed that potatoes, corn, cotton, and tobacco differed significantly in fertilizer phosphorus absorption on soils of comparable residual phosphorus contents. Phosphorus absorption by potatoes was found to increase throughout the growing season. Corn, on the other hand, had an initial high absorption rate and declined to slow rates at the end of the growing season. It was revealed that the uptake rates for potatoes and cotton differed greatly in those soils with high native phosphorus contents. The potatoes absorbed the largest amount of radioactive phosphorus.

A residual field study after sixteen years of phosphorus application of various forms, and four years of no application was conducted by Ensminger and Pearson (13). Radioactive phosphorus was applied to the soils to study the residual effects. The results showed that phosphorus was absorbed from residual sources in proportion to their rates of

application. Dean and Fried (8) showed that application of fertilizer phosphorus to soils low in native and residual phosphorus increased both plant growth and total phosphorus absorption. They also found that young plants took most of their phosphorus from the fertilizer phosphorus while older plants acquired most of their phosphorus from native and residual sources.

CHAPTER III

EXPERIMENTAL MATERIALS, METHODS AND PROCEDURES

A. DESCRIPTION OF SOILS

The residual affect of P was studied on soil series from West, Middle and East Tennessee. Except for the Minvale soil series, all the soils were sampled in pairs in terms of high and low extractable P. The basis of high and low P soils was soil test results obtained from The University of Tennessee Soil Testing Laboratory in Nashville. These values were also checked to ascertain the P status of the material collected.

The Memphis silt loam, terrace phase sample came from the West Tennessee Experiment Station. This soil series is a deep, well drained, strongly acidic, silty soil formed on uplands from loess. The soil is brown to reddish-brown on the surface (43). The soil used had received superphosphate over a number of years. The soil test results indicated a pH of 6.4, 65 lbs. of P and 230 lbs. of K per acre for the high P sample. The soil test results for the low P Memphis are pH 6.3, 30 lbs. of P and 190 lbs. of K per acre.

The Hartsells silt loam which had received enough superphosphate to give it a residual buildup was sampled. Also sampled was Hartsells low P which had received little or no P. This series consists of well-drained, loamy soils on gently rolling uplands of the Cumberland

Plateau. The parent materials are acid sandstones. The soil is very acidic and responds well to fertilization (21).

The Hermitage silt loam soil samples were obtained on the Tennessee Tobacco Experiment Station near Greeneville in Greene County. The soil sample was taken from a tobacco field on the Hermitage undulating phase. The soil sample is a well-drained brown soil with alluvial or colluvial parent materials derived from limestone. It is medium to strongly acid and has a high level of plant nutrients. The soil test results for the high P Hermitage soil were pH 6.5, 40 lbs. of P, and 550 lbs. of K per acre. Prior to sampling, this soil had received 1800 lbs. of nitrogen-phosphorus-potassium (NPK) fertilizer containing 80 lbs. of P. The low P Hermitage soil was obtained from a pasture on the Hermitage silt loam eroded rolling phase. The surface of the low P soil is dark brown or reddish-brown silty clay loam. It contains moderate organic matter and is fertile (11). The soil test results for the low P Hermitage were pH 5.8, 30 lbs. of P, and 120 lbs. of K per acre. This soil also received 75 lbs. of P from monocalcium phosphate and received two tons of lime per acre prior to sampling.

The Waynesboro silt loam soil samples were obtained on the same farm as the Hermitage. The Waynesboro undulating phase, from which the soil sample was obtained, is a well-drained soil that developed from old alluvium derived from sandy and shaly rocks and limestones. This phase is medium to strongly acid. The surface of this soil contains some organic matter and is moderately high in plant nutrients (11). The soil test results for the high P sample were pH 7.1, 40 lbs. of P, and 300 lbs. of K per acre. Prior to sampling this soil received 75 lbs.

of P from superphosphate. The soil was under corn production at the time of sampling.

The low P soil sample was taken from the Waynesboro eroded phase in pasture. Its surface layer is light reddish-brown loam or clay loam. It contains a low amount of organic matter and has a moderate level of fertility (11).

The Minvale silt loam, gently sloping phase soil sample was obtained from a tobacco field in Louden County, Tennessee. This phase is slightly eroded and developed from colluvium or local alluvium parent material underlain by limestone. This soil has a brown surface layer and is strongly acidic. It has a moderate to moderately low fertility level (12). The soil test results showed that this soil had high extractable P. This soil had for many years received chicken manure as a major source of fertilizer. Prior to sampling it had received 150 lbs. N, 60 lbs. of P, and 120 lbs. of K per acre.

B. CONTAINERS AND SAND PREPARATIONS

Preliminary preparations consisted of removing the bottoms of sixty-three round plastic containers of 16 oz. capacity and replacing them with cheesecloth. These containers were then set in sixty-three identical ones with their bottoms still intact and 500 grams of sand placed in each container. About thirty Sudangrass seeds were sowed at approximately one inch depths in the sand.

Eighty milliliters of a normal strength P-deficient Hoagland solution (20) and 70 milliliters of distilled water were added to the bottom container after the one containing the sand and seed had been

gently removed and set aside. The iron in the Hoagland solution was prepared by the Steiner and Van Winden recipe for ferric salts of elhylenediaminetetraacetic acid (47). The containers with the seeds were then gently set in the nutrient solution. For the next eight days, the sand received enough distilled water to maintain a high moisture level.

C. SOIL PREPARATION AND TREATMENT ADDITIONS

A large quantity of each soil sample was finely sieved and 400 grams of each weighed and placed in each of sixty-three containers; twelve for each of the low P soils, and three for each high P soil. Other nutrient additions were also made. The Waynesboro low P and the Minvale soil received 0.600 grams of $CaCO_3$ and 0.168 grams of $MgCO_3$ to raise their pH values. The Hartsells low P soil received 0.037 grams of KCl. All additions were thoroughly mixed.

The low P soils were prepared as follows: addition of 25 mg of potassium dihydrogen phosphate ($KH_2PO_4^-$) per gram of soil to each of four containers, addition of 50 mg of KH_2PO_4 per gram of soil to another four containers of each soil. The high P soils received no P additions. Those soils that received P were thoroughly mixed.

Fifty-three microcuries of radioactive P (^{32}P) was added to each of the soil samples as label. All additions were again properly mixed to ensure uniformity.

Forty milliliters of a 20 ppm NH_4NO_3 solution was added to each soil sample to supply adequate nitrogen. The soil samples were randomly set in the greenhouse. The plants which had grown in nutrient solution for a week were thinned to twenty plants per pot and the pots removed

from the solutions and carefully set on each soil sample. Great care was taken to ensure that all roots were in contact with the soil surface. Distilled water was then added to moisten the sand.

During the next twenty days, the plants received enough distilled water to keep the soil and sand moistened. An additional 25 milliliters of NH_4NO_3 solution was added to the soil because some plants started to show N deficiency symptoms.

D. EXTRACTION METHODS, PHOSPHORUS AND pH DETERMINATIONS

Extractable P methods used in three Southern states were employed in this study. They were the Tennessee, Florida and Louisiana Methods. Total plant P and extractable P from the soils were determined by the stannous chloride-molybdenum blue method outlined by Jackson (22), using the Beckman Model "B" spectrophotometer. Soil pH values were determined by using a one-to-one soil-to-water ratio. In this study, 5 grams of soil was saturated with 5 milliliters of water and the pH electrode inserted into the soil and the reading taken.

1. Method I

The Tennessee method uses a 1 percent solution of $(NH_4)_2SO_4$ in 0.05N H_2SO_4. This method extracts 5 grams of finely sieved soil sample with 20 milliliters of extraction solution. The soil and solution are shaken for three minutes and then filtered with a Buchner funnel, and the filtrate saved for analysis.

2. Method II

The Florida procedure involves the extraction of 5 grams of sieved soil sample with 50 milliliters of a 0.7N NH_4OAc (ammonium acetate) in 0.54N HOAc (acetic acid) adjusted to pH 4.8. The soil and extracted solution are shaken for thirty minutes and filtered with a Buchner funnel, and the filtrate saved for analysis.

3. Method III

In the Louisiana method, 2.5 grams of sieved soil sample is extracted with 50 milliliters of a 0.03N NH_4F solution in 0.10N HCl solution. The soil and extraction solution are shaken for fifteen minutes and then filtered, and the filtrate saved for analysis.

The summaries of the soil acidity, extraction methods, and treatment levels are given in Tables I, II and III.

E. HARVEST AND RADIOACTIVE PHOSPHORUS DETERMINATIONS

The plants were harvested by removing the top portions, placing them in labeled paper bags and drying them at 70°C. The plants were weighed, milled and stored in plastic containers. A 0.5 gram portion of each sample was dry ashed according to the method outlined by Jackson (22). Three replications consisting of 1 milliliter of each solution were placed in planchets and evaporated to dryness. The samples were counted with a Geiger tube along with the Nuclear-Chicago Sample Changer and Scaler; Models C110B, C111B and Series 8703. The original radioactive sample was diluted to appropriate dilution and counted along with each set of fifty samples.

TABLE I

SOIL pH VALUES

Soils	pH
Memphis High P	6.6
Memphis Low P	6.5
Hartsells High P	6.0
Hartsells Low P	5.7
Hermitage High P	6.3
Hermitage Low P	6.5
Waynesboro High P	6.9
Waynesboro Low P	5.9
Minvale High P	4.9

TABLE II

EXTRACTION METHODS

Solutions	Soil-to-Solution Ratio
I. 1% $(NH_4)_2SO_4$ in 0.05N H_2SO_4	1:4 w/v
II. 0.7N NH_4OAc in 0.54N HOAc adjusted to pH 4.8	1:10 w/v
III. 0.03N NH_4F in 0.1N HCl	1:20 w/v

TABLE III

TREATMENT LEVELS

Soils	Treatments	Replications
	(µgP/g Soil)	
High P Soils	0	3
Low P Soils	0	4
	25	4
	50	4

All samples also received 53 µC of ^{32}P as label.

F. STATISTICAL ANALYSES

The extractable P levels of the soils were analyzed using the analysis of variance and the Duncan's Multiple Range Test. Correlation coefficients were determined for plant uptake and extractable soil P and for available P ("A" value) and plant uptake. A probability level of 0.05 was chosen for tests of significance unless otherwise stated.

CHAPTER IV

RESULTS AND DISCUSSION

The results of the chemical analyses of both phosphate treated and nonphosphate treated soils, the yield, P uptake and the relationships of radioactive to total and extractable P, "A" values and the percent P from the fertilizer are presented in the various tables included in this chapter. The elaborate root proliferation of the Sudangrass made the phosphate uptake measurement possible. It is hoped that these results will provide certain useful information about the availability of P in certain soils and the ability of a soil test to correctly measure the availability of P as compared to plant yield response to phosphate fertilizer applications.

A. ORIGINAL SOILS EXTRACTED WITH THREE SOLUTIONS

The data in Table IV show that solutions I and III extracted significantly more P from the soils than did solution II. Solution III extracted more P from seven of the nine soils than did solution I, but the average amount extracted was not significantly greater.

Each of the solutions extracted more P from the Minvale high P than any other soil and the Duncan's Multiple Range Test indicates that this soil was significantly different from all other soils. The next highest quantity of P was extracted from the Hermitage high P soil, which was also significantly different from the other soils. The order of the

TABLE IV

EXTRACTABLE PHOSPHORUS OF ORIGINAL SOILS
IN µg/g OF SOIL

Soil	Solution I	Solution II	Solution III	Average
Memphis High P	52.5	14.8	55.8	41[c]
Memphis Low P	22.5	3.4	18.9	15[d]
Hartsells High P	48.6	5.3	57.6	37[c]
Hartsells Low P	4.7	1.4	4.8	4[e]
Hermitage High P	63.5	10.5	66.6	47[b]
Hermitage Low P	2.8	3.4	12.9	6[e]
Waynesboro High P	52.6	11.1	47.3	37[c]
Waynesboro Low P	8.2	3.6	10.9	8[e]
Minvale High P	122.0	33.6	138.0	98[a]
Average	42[a]	10[b]	46[a]	

Numbers followed by the same letter in the same row or column are not significantly different from each other at the 0.05 probability level.

high P soils in terms of quantity of P extracted is: Minvale, Memphis, Hartsells, and Waynesboro. However, significant differences were not found among the Memphis, Hartsells and Waynesboro soils, as indicated by the letters following their average values.

Solutions I and II extracted nearly equal quantities of P from the Memphis low P soil. A low quantity of P was extracted by Solution II from the low P soils. Both solutions I and III again removed nearly equal quantities of P from the Hartsells and Waynesboro soils. The observed decreasing trend in the low P soil data is Memphis, Waynesboro, Hermitage, and Hartsells soils. The P extracted from the Memphis low P soil was significantly greater than that of all other low P soils which were similar to each other.

The relative affectiveness of the three extracting solutions depend on the form of P each solution is capable of removing. Bray and Kurtz (4) observed that fluoride and acid mixtures extract both acid-soluble and adsorbed phosphates. Seatz (44) also showed that a combination of hydrochloric acid and ammonium fluoride extracted more P than any acid or fluoride alone. The stronger extracting abilities of solutions I and III over solution II depend on the fact that both sulfuric and hydrochloric acids are stronger acids than acetic acid. The presence of greater concentration of hydrogen ions in the stronger acids prevented the desorbed and dissolved phosphate from reprecipitating as an insoluble phosphate (44). The larger amount of P removed by solution III could be linked to the fact that this solution extracted

not only the acid-soluble form but also adsorbed P. The relative amounts of both forms of P could also have had a bearing on the amounts removed from each of the soils. If this was the case, it is safe to assume that among the high P soils, the Minvale had the highest quantities of both types. Significant differences noted among soils is not only dependent on the solution but on kinds and amounts of P fractions present and fixation levels of each soil. In cases where similarities were cited, it is possible that these soils had approximate equal quantities of both P forms. In those soils where solution II, a weaker acid solution, extracted as much P as did solution I, the acid-soluble P levels in these soils may be nearly equal.

There is no definite relationship between pH and total extractable P. However, Hibbard (19) found that "dissolvable phosphate increases as pH decreases." Soil acidity, therefore, affects the availability of soil P. The relationship between pH and extractable P are sometimes influenced by soil type, kinds of clay minerals and organic matter.

B. SOIL PHOSPHORUS, PHOSPHORUS UPTAKE AND PLANT YIELD

The data in Table V show the Sudangrass yield, P uptake and the level of extractable P in the high P soils using solution I. The results show a general increase in yield with increasing levels of soil P. There seem to be some exceptions, but for all practical purposes the Memphis and Waynesboro soils agree with the observations since no significant yield differences are seen.

TABLE V

PLANT YIELD, PHOSPHORUS UPTAKE AND PHOSPHORUS EXTRACTED BY SOLUTION I FROM HIGH PHOSPHORUS SOILS

Soil	Soil P	Sudangrass Yield	P Uptake
	µg/g of Soil	g/pot	mg P/pot
Memphis High P	52.3	2.8	6.3
Hartsells High P	48.6	2.4	2.4
Hermitage High P	63.5	3.3	4.3
Waynesboro High P	52.6	2.6	3.4
Minvale High P	122.0	3.9	6.4

Table VI lists plant yield, P uptake and the sum of added and extractable P of the low P soils as extracted by solution I before cropping. There was a yield response to P application since increases are seen with added P levels. The Sudangrass yield increase from P application to the Memphis low P soil was not as great as in the other soils. The plants grown on the Hermitage soil receiving P fertilization showed a two-fold yield increase over the zero application. Applications of P to the low P Hartsells caused better than 100 percent yield increase. The percent yield increases due to P application to the Waynesboro soil was less than 25 and 50 percent for the 25 and 50 µg/g treatments respectively. The total P uptake showed a general increase with the sum of extractable and added P except for plants grown in the Memphis soil.

The results of plant P uptake from both high and low P soils clearly indicate that P uptake is related to the extractable P and soluble P contents of the soil. Those soils with higher initial P contents have higher yields and P uptake than those soils with lower initial P contents.

The plant yield on the Hartsells high P soil is the lowest among the high P soils, but it is equal to the yield on the zero treatment level of the Memphis low P soil and the 50 µg/g P treatment level of the Hartsells low P. This yield is higher than the zero and 25 µg/g P treatment levels of the Hartsells low P and the zero treatment level of the Hermitage low P. A 50 µg/g soil addition to the Hartsells low P,

TABLE VI

PLANT YIELD, PHOSPHORUS UPTAKE AND SUM OF ADDED AND EXTRACTED PHOSPHORUS FROM LOW PHOSPHORUS SOILS BY SOLUTION I

Soil and Treatment		Add P Plus Extracted P	Yield	P Uptake	% Yield Over Zero
		µg/g Soil	g/pot	mg/pot	
Memphis Low P	0	22.5	2.4	3.4	
	25	47.5	2.6	4.9	8
	50	72.5	2.7	4.2	13
Hartsells Low P	0	4.7	1.0	0.9	
	25	29.7	2.1	2.2	110
	50	54.7	2.4	2.4	140
Hermitage Low P	0	2.8	1.9	1.8	
	25	29.8	2.8	2.9	47
	50	52.6	3.8	3.3	100
Waynesboro Low P	0	8.3	2.9	2.5	
	25	33.2	3.6	3.2	24
	50	58.2	4.1	4.1	41

which had the second lowest soil test value, helped give a yield as high as the Hermitage high P, which also had the lowest soil test value among the high P soils. The Hermitage low P required a 50 µg/g P treatment to give a yield as high as the Minvale which had the highest soil test value. A 50 µg/g P addition to the Waynesboro, which had a much smaller soil test value, resulted in a yield slightly higher than the Minvale with the highest soil test value. The differences probably depend on the specific properties of the soil concerned.

C. PLANT PHOSPHORUS-32, TOTAL PHOSPHORUS, THEIR RATIOS AND PERCENTAGE PHOSPHORUS DERIVED FROM FERTILIZER

The results of the radioactive and total P concentration per gram of plant material and percent P from the fertilizer are given in Table VII. Numerous researchers have shown that plant P concentration depends on crops, soil type and experimental conditions. The data show that the ^{32}P and total P concentrations were greater in plant growth on the Memphis high and fertilized low P soils than any other soil. The plant ^{32}P concentration decreased in the plants from the high P soils in the following order: Memphis, Hermitage, Hartsells, Waynesboro, and Minvale. The total P concentration in the plants however has a different decreasing trend that is Memphis, Minvale, Hermitage, Waynesboro, and Hartsells. The ^{32}P to total P ratios follow the same trend as the ^{32}P uptake by the plants. The high concentration of ^{32}P in the plants grown in the Memphis soil indicates that this soil did not fix or retain as much ^{32}P as did the other soils. The average ^{32}P concentration in the plants from the low P soils decreased in the following order: Memphis,

TABLE VII

PLANT PHOSPHORUS-32, TOTAL PHOSPHORUS, THEIR RATIOS AND PERCENT PHOSPHORUS DERIVED FROM FERTILIZER

Soil and Treatment		^{32}P µg/g Plant	mg/g Plant	$\frac{^{32}P}{\text{Total P}}$	% P From Fertilizer
Memphis High P		0.252×10^{-3}	2.26	0.11×10^{-3}	
Memphis Low P	0	0.164×10^{-3}	1.41	0.12×10^{-3}	
	25	0.284	1.88	0.15	15
	50	0.656	1.56	0.42	42
Hartsells High P		0.093×10^{-3}	0.99	0.09×10^{-3}	
Hartsells Low P	0	0.046×10^{-3}	0.89	0.05×10^{-3}	
	25	0.892	1.05	0.08	8
	50	0.135	0.99	0.14	14
Hermitage High P		0.107×10^{-3}	1.31	0.08×10^{-3}	
Hermitage Low P	0	0.107×10^{-3}	0.94	0.01×10^{-3}	
	25	0.108	1.05	0.10	10
	50	0.163	0.88	0.19	19
Waynesboro High P		0.074×10^{-3}	1.31	0.06×10^{-3}	
Waynesboro Low P	0	0.072×10^{-3}	0.85	0.08×10^{-3}	
	25	0.111	8.88	0.13	13
	50	0.199	0.99	0.20	20
Minvale High P		0.042	1.65	0.03×10^{-3}	

Waynesboro, Hermitage, and Hartsells. The ^{32}P to total P concentration ratios in the plants follow the same trend as the ^{32}P uptake.

The plant P concentration is higher for the 25 µg/g treatment than for the zero and 50 µg/g treatments in all the low P soils except the Waynesboro. There is an increase of ^{32}P concentration and ^{32}P to total P ratios with increasing treatment levels. The increasing ratios could be best seen by observing that the percent P from the fertilizer increased with treatment level. The greatest amount of ^{32}P labeled fertilizer present, the more it is expected to be taken up. However, the greater uptake of P from the 25 µg/g treatments tends to indicate that P was added in such quantities that it could be effectively absorbed with less fixation by the soil. On the other hand, it seems as though the higher treatment level had more P than could be actively taken up by the plants. It is well known that added P must compete with residual P for root uptake. Since the plants cannot differentiate between the source of P, it takes up that form which can easily enter the soil solution. This could have been the case in this study.

The fact that P uptake is dependent on the kind of soil is seen here with each treatment level. The descending order of the soils in terms of the percent P uptake from the fertilizer from both 25 and 50 µg/g treatments is Memphis, Waynesboro, Hermitage, and Hartsells. The low P uptake could have been caused by the adsorption of most of the added P. The low percentages of P uptake from most of the soils could have been caused by the fact that the residual P was being actually absorbed by the plants thus preventing absorption of the added P. Besides those already mentioned, the low P uptake from the fertilizer may have

been influenced by the moisture level in the soils as Standford and DeMent (46) found this to be one of the limiting factors of plant P uptake. These two investigators also found that applied P uptake increased with time. Since this experiment was a short-term investigation, any moisture stress that may have occurred could have limited P uptake by the plants.

One reason for the greater than 10 percent uptake of P from the fertilizer by the plants from most of the soils could be, as Dean and Fried (8) reported, that young plants take up P most readily from applied sources until elaborate root proliferation occurs. In comparison to the amounts applied these recovery values are fairly large. The fairly good plant uptake from the zero treatments is likely due to the residual affects of the superphosphate, which was the source of P added to many of these soils. Superphosphate is known to have a high residual affect (Rich et al., 41). From these observations it can be seen that there was indeed considerable P uptake from both sources.

D. PHOSPHORUS EXTRACTED BY SOLUTION I FROM CROPPED SOILS

The quantities and the ratios of radioactive and total extractable P removed by solution I after cropping and harvesting are given in Table VIII. Among the high P soils, the Hartsells had the highest amount of ^{32}P extracted followed by the Hermitage, Memphis, Minvale, and Waynesboro soils. There is no general relationship between extractable P and the quantity of ^{32}P removed from these soils by solution I. More total P was extracted by solution I from the Hermitage high P than any

TABLE VIII

RADIOACTIVE PHOSPHORUS, TOTAL PHOSPHORUS AND THEIR RATIOS AS EXTRACTED BY SOLUTION I

Soil and Treatment		$\frac{\mu g\ ^{32}P}{g\ Soil}$	Extractable P $\mu g/g$ Soil	$\frac{^{32}P}{Extracted\ P}$
Memphis High P		2.540×10^{-3}	62.3	0.04×10^{-3}
Memphis Low P	0	0.828×10^{-3}	15.6	0.05×10^{-3}
	25	1.770	20.3	0.09
	50	3.380	29.4	0.13
Hartsells High P		4.270×10^{-3}	51.5	0.08×10^{-3}
Hartsells Low P	0	1.130×10^{-3}	8.9	0.13×10^{-3}
	25	2.320	8.7	0.27
	50	5.200	14.3	0.36
Hermitage High P		2.700×10^{-3}	87.6	0.03×10^{-3}
Hermitage Low P	0	0.529×10^{-3}	7.3	0.07×10^{-3}
	25	1.490	10.9	0.14
	50	3.100	16.0	0.19
Waynesboro High P		0.897×10^{-3}	43.2	0.02×10^{-3}
Waynesboro Low P	0	0.977×10^{-3}	8.75	0.11×10^{-3}
	25	2.140	14.7	0.15
	50	4.520	21.7	0.21
Minvale High P		1.470×10^{-3}	84.0	0.02×10^{-3}

other soil. The other high P soils in decreasing order are Minvale, Hartsells and Waynesboro. This order is different from that observed for the ^{32}P. The different trends tend to indicate that most of the added ^{32}P was adsorbed onto the soil surfaces and was thus not extracted by this solution. The order of the high P soils ^{32}P to P ratios decreass as follows: Hartsells, Memphis, Hermitage, Waynesboro, Minvale. The relationship shown by the soils in holding both radioactive and extractable P clearly indicates the existence of conditions in these soils that modified P availability. As shown by the values of ^{32}P, less radioactive P was extracted from the Waynesboro soil than any other high P soil. This fact is probably due to the adsorptive ability of this soil. This soil may have had a high fixation ability as found by Bray (3) and Thomas (49) for other soils.

As expected, there is a definite relationship between treatment level and the quantities of ^{32}P and total extractable P. The only exception is seen in the extractable P values for the Hartsells low P soil. The ratio of ^{32}P to total extractable P increases with increasing values of extractable P because this ratio is in fact a measure of the specific activity. The larger the amount of labeled P added, the greater the amount of radioactive P per unit weight of extractable P becomes. These observations are in fact similar to the relationships Henderson and Jones (17) and Hendericks and Dean (18) found when they did P extractability studies using radioactive P.

The soil test values after cropping were higher for all the low P soils than were for the original soils but were lower than those of most of the original high P soil test values. The uptake of fairly large

quantities of P by the plants and the fixation of some of the added P by the soils may have been responsible. Possible explanations for limited extraction could also be the form of soil P present. If most of the P was changed into nonacid-soluble forms, solution I could not have extracted them.

E. PHOSPHORUS EXTRACTED BY SOLUTION II FROM CROPPED SOILS

The data presented in Table IX represent the radioactive P, extractable P and their ratios as extracted by solution II after the plants had been harvested. The quantity of ^{32}P removed by this solution is higher for the Waynesboro high P soil than any other high P soil. The order of the other high P soils in decreasing amounts of ^{32}P is Hermitage, Memphis, Hartsells, and Minvale soils. There is not a direct relationship between the quantities of ^{32}P and P extracted by solution II from all the high P soils. The differences in soil properties among the soils may be responsible for the differences in trends observed for the high P soils. This also indicates that those soils from which more P was extracted could have had high levels of acid-soluble P since solution II is known to extract mainly this form as Bray (3) found. He noticed that dilute acetic acid removed easily acid-soluble P forms.

The quantity of ^{32}P extracted is found to increase with treatment levels. There is also a general increase in extractable P with increasing P additions in all but the Memphis low P soil. As expected, the ^{32}P to extractable P ratio does increase with treatment rates. The magnitudes of the ^{32}P extracted from the zero rate of the low and high P soils are the same though the high P soil values are higher. The observation is

TABLE IX

RADIOACTIVE PHOSPHORUS, TOTAL PHOSPHORUS AND THEIR RATIOS AS EXTRACTED BY SOLUTION II

Soil and Treatment		$\frac{\mu g\ ^{32}P}{g\ Soil}$	Extractable P µg/g Soil	$\frac{^{32}P}{Extracted\ P}$
Memphis High P		0.470×10^{-3}	101.0	0.01×10^{-3}
Memphis Low P	0	0.146×10^{-3}	5.9	0.03×10^{-3}
	25	0.330	9.0	0.04
	50	0.660	8.9	0.07
Hartsells High P		0.376×10^{-3}	16.6	0.02×10^{-3}
Hartsells Low P	0	0.255×10^{-3}	1.6	0.16×10^{-3}
	25	0.478	3.6	0.13
	50	0.956	4.8	0.20
Hermitage High P		0.694×10^{-3}	16.2	0.04×10^{-3}
Hermitage Low P	0	0.249×10^{-3}	2.9	0.09×10^{-3}
	25	0.466	5.1	0.09
	50	0.210	8.7	0.14
Waynesboro High P		0.892×10^{-3}	34.8	0.03×10^{-3}
Waynesboro Low P	0	0.347×10^{-3}	6.5	0.11 ×
	25	0.695	6.5	0.11
	50	3.340	9.9	0.34
Minvale High P		0.347×10^{-3}	19.9	$0.02 \quad 10^{-3}$

not unique since they received identical rates of labeled P. However, this finding tends to indicate that there were not major differences in the soil factors that influenced the extractability of applied ^{32}P. The fairly high values for ^{32}P extracted from the high P soils could depend on the fact that more of the added P was retained rather than fixed and was therefore extracted by the dilute acid solution. Another explanation could be that the low P soils may have had high fixing powers. Because the high P soils had more adsorbed P their abilities to adsorb added P were reduced and less of the added labeled P was adsorbed than in the case of the low P soils.

F. PHOSPHORUS EXTRACTED BY SOLUTION III FROM CROPPED SOILS

The results for the ^{32}P and P extracted by solution III are given in Table X. Also presented are the ratios of ^{32}P to total extractable P. The data show that the order of the high P soils in decreasing amounts of ^{32}P extracted is Memphis, Hartsells, Hermitage, Waynesboro, and Minvale. The decreasing order of the total extractable P is Minvale, Hermitage, Hartsells, Memphis, and Waynesboro. The fact that the order of extractable P is not the same as that for ^{32}P indicates that several soil factors influenced the extraction process. As Chang and Jackson (6) found, this solution is capable of removing acid-soluble and adsorbed P forms, especially iron and aluminum phosphates. The fact that there was limited release of both residual and labeled P suggests that these soils did indeed have high retention powers. The decreasing order of the high P soils in terms of their ^{32}P to total extractable P ratios is Memphis, Hartsells, Waynesboro, Hermitage, and Minvale.

TABLE X

RADIOACTIVE PHOSPHORUS, TOTAL PHOSPHORUS AND THEIR RATIOS AS EXTRACTED BY SOLUTION III

Soil and Treatment		$\frac{\mu g\ ^{32}P}{g\ Soil}$	Extractable P µg/g Soil	$\frac{^{32}P}{Extracted\ P}$
Memphis High P		5.070×10^{-3}	129.0	0.04×10^{-3}
Memphis Low P	0	1.710×10^{-3}	49.8	0.03×10^{-3}
	25	3.620	68.3	0.05
	50	7.640	78.9	0.09
Hartsells High P		4.540×10^{-3}	135.0	0.03×10^{-3}
Hartsells Low P	0	1.680×10^{-3}	19.6	0.09×10^{-3}
	25	3.320	35.0	0.09
	50	7.520	46.6	0.16
Hermitage High P		3.790×10^{-3}	218.0	0.02×10^{-3}
Hermitage Low P	0	1.400×10^{-3}	42.6	0.03×10^{-3}
	25	2.740	54.6	0.05
	50	5.800	60.8	0.10
Waynesboro High P		3.180×10^{-3}	96.0	0.03×10^{-3}
Waynesboro Low P	0	1.360×10^{-3}	32.6	0.04×10^{-3}
	25	3.040	46.9	0.06
	50	6.080	59.1	0.10
Minvale High P		2.240×10^{-3}	282.0	0.01

Among the low P soils, there is an increase in both ^{32}P and extractable P with added P treatments. The ^{32}P extractable P ratios increase with increase in treatment levels as anticipated. As expected and observed for the first two solutions, there is an increase in both P concentrations with treatment rates in all soils. The fairly large extractable P values can be attributed to the ability of solution III to extract both acid-soluble and adsorbed P. The magnitudes of the ^{32}P and ^{32}P to P ratios are the same for the zero treatment levels of the low P and high P soils. The fact that the actual value for the high P is more than three times larger tends to indicate the same causes cited in the discussion under solution II. The main factors that influence P recovery according to Thomas (49) are the soil's capacity to adsorb and the initial level of P adsorbed. He found that the more sites already occupied, the less the adsorption of added P fertilizer.

Table XI gives the ratios of ^{32}P to total P as extracted by each of the solutions. The general trend seen here is that the ratio for a high P soil is lower than the ratio for the zero treatment of its corresponding low P soil. These tendencies clearly show that more P was removed from the high P soils than the corresponding low P soils. As indicated by Tables V and VI (pp. 29, 31), the P uptake data clearly support this observation. For the Memphis and Hartsells high P soils, solution I has the higher ratios followed by solution III. For the Hermitage, Waynesboro and Minvale high P soils, the ratios for solution I are either less than or equal to that of solution II. These findings show that solution I extracts as much applied P as solution II depending on the type of soil. The table also shows that for those soils receiving

TABLE XI

RATIOS OF RADIOACTIVE PHOSPHORUS TO TOTAL PHOSPHORUS EXTRACTED BY THREE SOLUTIONS

Soil and Treatment		Solutions I	Solutions II	Solutions III
Memphis High P		0.04×10^{-3}	0.01×10^{-3}	0.04×10^{-3}
Memphis Low P	0	0.05×10^{-3}	0.03×10^{-3}	0.03×10^{-3}
	25	0.09	0.04	0.05
	50	0.13	0.07	0.09
Hartsells High P		0.08×10^{-3}	0.02×10^{-3}	0.03×10^{-3}
Hartsells Low P	0	0.13×10^{-3}	0.16×10^{-3}	0.09×10^{-3}
	25	0.27	0.13	0.09
	50	0.36	0.20	0.16
Hermitage High P		0.03×10^{-3}	0.04×10^{-3}	0.02×10^{-3}
Hermitage Low P	0	0.07×10^{-3}	0.09×10^{-3}	0.03×10^{-3}
	25	0.14	0.09	0.05
	50	0.19	0.14	0.10
Waynesboro High P		0.02×10^{-3}	0.03×10^{-3}	0.03×10^{-3}
Waynesboro Low P	0	0.11×10^{-3}	0.09×10^{-3}	0.04×10^{-3}
	25	0.15	0.11	0.06
	50	0.21	0.34	0.10
Minvale High P		0.02×10^{-3}	0.02×10^{-3}	0.01×10^{-3}

the two higher rates of P fertilization, solution I extracts more P than either of the other two solutions. This means that solution I reflects recent fertilization application more than does the other two solutions.

It is most likely that the plants did improve the chances of more release of extractable P. As seen in Tables VIII (p. 36), IX (p. 39), and X (p. 41), more P was extracted than before cropping, Table IV, (p. 26). The fairly good recoveries support the findings of Ensminger and Pearson (13) that added P accumulates in the soil and that the quantity extracted or residual affect is proportional to the rate of application. The values of extractable P are not strange as Bray (3) found, P (especially superphosphate) addition increases the highly soluble P fraction directly. The inability to get total recovery is one of the accepted tendencies of all added P since some is adsorbed or fixed by the soils.

G. STATISTICAL ANALYSES AND "A" VALUES

A statistical analysis was performed on the P extracted by all three solutions from the cropped high P soils. The analysis of variance of the average P values in Tables VIII (p. 36), IX (p. 39), and X (p. 41), showed that significant differences existed between the P extracted from the soils and also between the extractant solutions. Solution III had the highest average P value followed by solutions I and II in decreasing order. The results of the analyses are given in Table XII. The Minvale soil had the highest level of extractable P. No significant differences were found between the Memphis and Hermitage or between the Hartsells and Waynesboro soils. The trend observed earlier for the extractable P

TABLE XII

PHOSPHORUS EXTRACTED FROM HIGH PHOSPHORUS SOIL AFTER CROPPING

Soil	Solutions			Average
	I	II	III	
Memphis	62.3	101.0	129.0	95[b]
Hartsells	51.5	16.6	135.0	68[c]
Hermitage	87.6	16.2	218.0	107[b]
Waynesboro	43.2	34.8	96.0	58[c]
Minvale	84.0	19.9	282.0	129[a]
Average	66[b]	36[c]	172[a]	

Numbers followed by the same letter in the same row or same column are not significantly different at the 0.05 probability level.

of uncropped soils is also present here. Solution III extracted more P than either of the other two solutions but all solutions are significantly different in their extracting abilities. There is no need to belabor the idea but the effectiveness of solution III has something to do with the fact that this solution does not only extract the acid-soluble P but it also removes some other adsorbed P forms.

The Duncan's Multiple Range Test was not performed for the P extracted from the low P soils. However, an analysis of variance of the quantity of P extracted by each solution from the cropped soils was performed. Solution III, as expected, extracted the highest amount of P averaged across the soils and was significantly different from the other two solutions which were similar in their extraction capabilities.

A simple correlation coefficient was determined for the data given in Table XIII. Phosphorus uptake by Sudangrass was correlated with P extracted by each of the three solutions from the cropped soils. The results show that the extractable P removed by solution I had a highly significant value of 0.689. The correlation coefficient of P uptake with P extracted by solutions II and III are 0.611 and 0.233, respectively. The correlation for solution II was also highly significant at the 1 percent probability level. The P extracted by solutions I and II correlated fairly well with P uptake by Sudangrass. These two solutions surely measure the available P levels in soils with greater accuracy than solution III. The good correlation could be based on several factors but the ability of dilute acids to dissolve insoluble P forms may be a factor as found by Seatz (44). The lower correlation coefficient obtained for solution III reflect the widespread differences in P

TABLE XIII

PHOSPHORUS UPTAKE BY PLANTS AND "A" VALUES

Soils and Treatment		P Uptake	"A" Value
		mg/pot	mg/Kg soil
Memphis High P		6.3	119
Memphis Low P	0	3.4	115
	25	4.9	141
	50	4.2	69
Hartsells High P		2.4	143
Hartsells Low P	0	0.9	258
	25	2.2	270
	50	2.4	321
Hermitage High P		4.3	164
Hermitage Low P	0	1.8	118
	25	2.9	174
	50	3.3	343
Waynesboro High P		3.4	156
Waynesboro Low P	0	2.5	165
	25	3.2	173
	50	4.1	200
Minvale High P		6.4	524

extracted from each soil by this solution. Thomas (49) found fairly good correlation for this extractant with plant uptake of P. The finding can be supported by the fact that solution III also extracts P forms normally not available to plants in large quantities. The poor correlation seems understandable because available P determined by chemical extractants depend mainly on the solubility of some desorbed soil P while P used by plants can also be controlled by the levels of other soil nutrients. One of the factors that may have caused the poor correlation, according to Seatz (44) and to Webb and Pesek (52), is the fact that all of the added P cannot be fully recovered by plants or extractant solutions. Also inherent in these limiting factors are the restrictions imposed by the physical and chemical properties of the soils. Murphy (33), Metzer (31), Seatz (44), and Salomon and Smith (42) have shown that soil organic matter, Fe, Al and Ca contents greatly influence the availability and extractability of soil P.

Despite the indicated results, all three of these solutions could be used to determine soil P availability with fairly high degree of accuracy because there was indeed correlations obtained with plant P uptake. Just as Nelson et al. (35) found that different plants absorb differing amounts of P, so do different solutions extract different quantities of P. The choice of method should be geared towards the purpose one seeks to accomplish. If an estimate of the availability is desired, any of these methods is satisfactory. However if the desire is to get an estimate of the acid-soluble P forms, both solutions I and II are highly recommended. Solution III could be used if both acid-soluble and adsorbed P of Fe and Al phosphates are desired.

A nonsignificant simple correlation coefficient of 0.013 was obtained from a correlation of plant uptake with "A" values. The "A" values given in Table XIII (p. 47), show that the Minvale soil had the highest available P among all the soils used in this study. The decreasing order of the remaining high P soils in terms of "A" values is Hermitage, Waynesboro, Hartsells, and Memphis. The high "A" value for the Minvale is understandable since it had the highest extractable P values for all the extractant solutions used.

In both the Memphis and the Hermitage low P soils, the "A" values for the zero treatment levels are less than those for the corresponding high P soil. For the Hartsells and Waynesboro low P soils, the "A" values are greater than they are for the high P soils. In the Hartsells, Hermitage and Waynesboro low P soils, there is an increase of "A" values with increasing treatment levels. The average "A" values among the low P soils decrease in the following order: Hartsells, Hermitage, Waynesboro, and Memphis. Webb and Pesek (52) found that low "A" values were associated with high uptake of P from applied fertilizer. Ensminger and Pearson (13) found very good correlations of P uptake with "A" values in most of their studies. They also reported increases in "A" values with increasing levels of prior fertilizer additions. High "A" values are indicative of high levels of available residual P in the soil.

The low correlation coefficient obtained for the "A" values does not mean that "A" value is not useful. It is indeed useful as Ensminger and Pearson (13) and Webb and Pesek (52) all found excellent correlations of "A" values with plant uptake data. They all stressed the usefulness of this value in obtaining valuable information concerning P availability

in soils. The values calculated in this study give fairly good indications of the P status of these soils. Several investigators including the ones cited above (23, 52) and Thomas (49) found that "A" value is influenced by the crops, age of plants at sampling, method of fertilizer placement, and the fixation rates of P in the study soils.

CHAPTER V

SUMMARY AND CONCLUSIONS

This experiment was conducted in an attempt to obtain data that could help in making meaningful comparisons between the availability of applied and residual P as measured by extractable soil P and plant response. One of its purposes was to find ways to quickly evaluate soil P availability using a short-term plant growth study. Five Tennessee soils and three extractant solutions used in the Southern United States were utilized. Radioactive P was used to help in the calculations of available P and the percent P derived from the applied P fertilizer.

Extractable P was determined both before and after cropping. Sudangrass was grown for twenty days and uptake of total and ^{32}P determined.

After studying the data and doing several statistical analyses, the following conclusions are made:

1. Solution III extracted more P than did the other solutions.

2. Solutions I and II are fairly good estimators of available P levels in the soil, as the P extracted by them gave significant correlations with plant uptake of P.

3. The extractability of added P depends on the soil.

4. Among the high P soils, the Minvale and Hermitage soils had significantly greater levels of extractable P than did the other soils and were different from each other.

5. Some low P soils give high yields even at the zero P treatment level.

6. The total P concentrations in the plants were most often higher for the 25 μg/g treatment than the other treatment levels.

7. There were yield responses to residual P.

8. There was an increase in ^{32}P to total extractable P ratio with increasing treatment rates.

9. The order of the ratios of ^{32}P to total extractable P depends on the soil and solution.

10. Solution I reflected recent fertilizer application more than does the other two solutions.

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