

PHOSPHATE REACTIONS AND AVAILABILITY IN
SIX TYPICAL OKLAHOMA SOILS

By

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1961

Submitted to the faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
May, 1969

SEP 29 1969

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Thesis Approved:



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ACKNOWLEDGEMENTS

The author wishes to thank the Agronomy Department for the facilities and assistance provided for this study.

Special thanks are extended to my major advisor, Dr. Lawrence Morrill, for his help during this study. The assistance of Dr. Gene Guinn is also acknowledged and appreciated.

Thanks are extended to Mrs. Clara Yeck for the typing of this thesis.

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CHAPTER I

INTRODUCTION

The factors to be taken into consideration when extracting available phosphorus from soils are complex. Different reagents may extract varying amounts of phosphorus from the same soil, depending on such properties as soil texture, pH, % CaCO_3 , and the type of phosphorus compounds present in the soil. If it is to be known which reagent is best suited for the removal of available phosphorus from a soil or group of soils, correlation studies must be run between the amount of phosphorus extracted by the reagent and the yield of a crop grown on these soils. In this study sugar drip sorghum was grown on six soils fertilized with phosphate fertilizer. Correlations were determined between the yield of sorghum and the amount of phosphorus initially present in the soil as determined by six extraction procedures. The soils used were considered to be representative of the soil types found in Oklahoma. A variety of extracting reagents were selected in the hope of finding a reagent suited for each soil, or one reagent suited for all soils.

Another objective of this study was to study the extent and rate of conversion of fertilizer phosphate into the various phosphate compounds. This was done by fractionating the phosphorus in the fertilized soils into the various phosphate compounds and also by analyzing the fertilized soils for available phosphorus by the six extracting methods.

CHAPTER II

REVIEW OF LITERATURE

Many methods of extracting available phosphorus from soils have been used. Baver and Bruner (1)¹ used 0.314 N HCl for the extraction of phosphorus. Olson (21) used 0.7 N HCl. Sulfuric acid has been used in various concentrations, such as 0.01 N by Kerr and Von Stieglitz (15), and more commonly 0.002 N buffered with $(\text{NH}_4)_2\text{SO}_4$ as developed by Truog (30). Acetic acid has been used by Ghani (13), Cooke (9), and others. Morgan (18) in 1941 developed his universal extracting solution, consisting of acetic acid buffered to pH 4.8 with sodium acetate. Perhaps the most widely used solution for the extraction of available phosphorus is 0.025 N HCl in 0.03 N NH_4F , commonly known as Bray #1, developed by Bray and Kurtz in 1945 (3). Another solution developed by Bray is 0.1 N HCl in 0.03 N NH_4F , commonly known as the Bray #2 reagent. Olsen et al. (19) in 1954 developed a reagent suited for the extraction of phosphorus from both acid and alkaline soils, 0.5 M NaHCO_3 adjusted to pH 8.5 with NaOH. Another solution, developed in North Carolina, is 0.05 N HCl in 0.025 N H_2SO_4 (16). Ammonium acetate mixed with HCl is used in Texas (2). Van Diest (31) has found a water extraction method best suited for the extraction of available phosphorus from New Jersey soils. A technique using radioactive phosphorus has been developed

¹ Numbers in parentheses refer to literature cited.

by Dean (11), and is useful primarily as a research tool. None of the above methods, nor any other method developed, has been found to be suited for the extraction of phosphorus from all soils.

Factors Influencing the Amounts of Phosphorus Extracted From Soils

Capacity Factor and Intensity Factor

Chang and Juo (8) believe that available soil phosphorus determined by a chemical method includes all forms of inorganic phosphates but mainly calcium, iron, and aluminum phosphates (hereafter referred to as Ca-P, Fe-P, and Al-P).² The amount of phosphate dissolved from a particular soil depends not only on the amount of each form present but also on the solubilities of these forms in the extracting reagent. Williams and Knight (34) believe that the amount of available phosphorus depends on a capacity factor and an intensity factor. The capacity factor refers to the amount of available phosphorus in the soil, while the intensity factor reflects the ease, or difficulty of withdrawal. The capacity factor is reflected in the amounts of Al-P, Fe-P, and Ca-P in the soil, while the intensity factor may be reflected in the solubilities of these forms of phosphorus. The phosphorus extracted by a particular reagent should reflect both the capacity and the intensity factors. Susuki, et al. (26) found the phosphate removed by the Bray #1, Truog, and Olsen procedures (hereafter referred to as Bray-P, Truog-P, and Olsen-P) to be related to Al-P. Truog-P was also found to be related to Ca-P. For their soils (Michigan) Susuki states

²Ca-P, Fe-P, and Al-P refer to general, not specific forms of phosphorus.

that a test which would evaluate the more easily soluble portions of the Ca-P and Al-P fractions, such as the Truog test, would give the best measure of immediate availability, while a test which gives a measure of the less soluble portion of the Al-P fraction, such as the Bray test or Olsen test would give a better evaluation of long term availability. Their findings may be interpreted to mean that Truog-P reflects the intensity factor while Bray-P and Olsen-P reflect the capacity factor.

Thomas (29) working with South Dakota soils, found that Olsen-P increased in relation to Bray-P over a four year period. He interpreted this to mean that Olsen-P is more available than Bray-P and hence more readily absorbed by plants. Thus, in this case, Olsen-P reflected the intensity factor.

The accuracy of measurement of the capacity factor depends, to a significant degree, on the soil texture. Thomas (28), believes that for heavy soils a soil test does not truly measure the capacity factor and never measures the rate of renewal in the soil solution. Therefore, soil test extractants tend to underestimate phosphorus availability to plants grown in high clay soils. Thomas also believes that one reason for inaccuracy of measurement of the capacity factor is that the reagent reacts with the clay instead of with phosphates. Pratt and Garber (22) found this to be true when they used the Bray and Olsen reagents. Westin and Buntley (33) also found exhaustion of reagents to occur when extracting phosphates from South Dakota soils.

When considering the capacity and intensity factors in the selection of a reagent, the concentration of the reagent must be considered. Taluburdeen (27) found that at very dilute concentrations of

the extracting agent, only the balance between the intermicellular phosphate and the phosphate in solution is disturbed. With increasing concentration the rapidly and slowly exchanging phosphate is progressively stripped off the soil matrix until only the very slowly exchanging solid phosphate remains.

Relation of Extractable Phosphorus to Forms of Phosphorus in Soils

Although reagents for extracting available phosphorus do not extract all of a specific form of phosphorus and, in fact, extract some of several forms of phosphorus from the soil, there is a relationship between the form of phosphorus extracted by a reagent and the dominant form of phosphorus in the soil.

Breland and Sierra (4), when testing Florida soils, found the Olsen method satisfactory for extracting available phosphorus from acid soils. They found the Olsen method satisfactory, compared to sodium acetate or ammonium acetate, because the bicarbonate ion replaced more phosphorus than did the acetate ion. Olsen-P was found to be correlated with the Al-P and Fe-P fractions, which dominate in acid soils. Phosphorus extracted by sodium acetate and ammonium acetate was found to be correlated with the Ca-P fraction, which is not dominant in acid soils.

Chang (5) tested several procedures on rice soils. He found that either 0.1 N NaOH or 0.5 N NaHCO_3 worked well on all soils he tested. He attributed this to the extraction of Fe-P and Al-P by these two reagents.

Susuki, et al. (26) found Bray-P higher than Truog-P on Michigan soils of pH 5.6 or lower, but lower than Truog-P on soils of pH 6.0 or higher. He, like other workers, found Bray-P, Olsen-P, and Truog-P to

be related to Al-P, and Truog-P to be related also to Ca-P.

Caution must be used with the Truog reagent and other sulfuric acid reagents. While Truog-P is correlated with Ca-P, Chang says it can remove Ca-P not available to the plant. Miller and Axley (17) also found that sulfuric acid, when used on soils treated with rock phosphate, can remove more phosphorus than is available to the plant.

Extraction of Phosphorus by Dilute Acids - Effect of Anions

The solution of Ca-P by dilute acids is straightforward. However, the solution of phosphorus from iron and aluminum phosphates depends on the nature of the anion in the extractant. The fluoride ion was found to be highly effective in dissolving phosphates and is responsible for the effectiveness of the Bray reagents. Bray #1 is recommended for replacing adsorbed phosphate and Bray #2 is recommended for removing combined acid-soluble and sorbed forms of phosphate. In calcareous soils and soils containing rock phosphate the fluoride ion suppresses the solubility of forms of phosphates with low availability to plants. In acid soils the fluoride ion dissolves available phosphate not removed by dilute acid alone.

Miller and Axley (17) used the fluoride ion in conjunction with H_2SO_4 to suppress the extraction of phosphates that were of low availability to plants. They found a solution 0.03 N in NH_4F and 0.03 N in H_2SO_4 to be superior to Bray #1 for the removal of available phosphorus from soils.

Soil:Solution Ratio

The ratio of soil to extractant has an important influence on the amount of phosphorus extracted from soils. This is particularly true

in the case of the Bray reagents. Smith and Cook (24) found a soil:solution ratio of 1:50 effected a more complete removal of the adsorbed phosphorus from Michigan soils than did a ratio of 1:10 when Bray #1 was used. Smith, et. al. (25) found a 1:50 ratio for the Bray #1 extractant necessary for the determination of available phosphorus in calcareous soils and in soils containing rock phosphate. They found no advantage in going to a 1:100 ratio. At soil:solution ratios lower than 1:50 the extractant may be neutralized by the CaCO_3 in the soil. With a 1:50 ratio there are enough hydrogen ions available to react with 6.25% CaCO_3 .

Conversion of Applied Phosphorus

It is believed that fertilizer phosphate added to soils is converted to Al-P and Fe-P in acid soils and to Ca-P in calcareous soils. Chang and Jackson (7) developed a method to fractionate inorganic phosphates into Al-P, Fe-P, Ca-P, and occluded phosphate. An attempt was made to use this procedure to study the conversions of fertilizer phosphorus in soils.

Chang and Chu (6) used the Chang and Jackson fractionation procedure to study the fate of applied phosphorus in Taiwan soils. They found that phosphorus was recovered almost completely as Al-P, Fe-P, and Ca-P, with very little Ca-P being formed even in calcareous soils. With increasing time the amount of Fe-P increased accompanied by a corresponding decrease in the amounts of Al-P and Ca-P.

Chang and Jackson (5) studied the effects of liming on the conversion of applied phosphorus. They found that the application of phosphorus fertilizer increased the amounts of Al-P and Fe-P at all

lime levels, but Ca-P increased only slightly even at the highest lime level. They attributed the lack of increase of Ca-P to both crop removal (since they maintain that Ca-P is more available to plants) and the precipitation of applied phosphorus as less soluble Fe-P and Al-P. Chang and Jackson maintain that immediately after the application of phosphate fertilizer Al-P and Ca-P are more apt to be formed than Fe-P, because of the higher activities of calcium and aluminum in the soil than iron. They also found that Ca-P and Al-P gradually changed into Fe-P.

CHAPTER III

METHODS AND MATERIALS

Six soils were used in this study: Parsons silt loam from the Eastern Oklahoma Pasture Station at Muskogee; Eufaula loamy sand from McAlester; Ulysses silty clay from Goodwell; Canadian sandy loam from Beaver; Norge loam and Kirkland loam from Stillwater.

Each soil was mixed and passed through a one-quarter inch sieve. Twenty-four 3000g portions, on an oven-dry basis, of each soil were weighed and placed into No. 10 food cans lined with polyethylene bags.

Experiment I

Four levels of triple superphosphate were added to each of the six soils and the treatments were replicated three times in this experiment. $\text{Ca}(\text{H}_2\text{PO}_4)_2$ was ground and applied in solid form at rates to give 0, 25, 50, and 100 ppm of added phosphorus. Sufficient $(\text{NH}_4)_2\text{SO}_4$ was applied to give 200 ppm of added nitrogen in all treatments. The fertilizers were thoroughly mixed with each soil and the 72 cans were arranged in a randomized block design in the greenhouse.

Sugar drip sorghum was planted on September 18, 1967. Enough distilled water was added to bring the soil to approximately field capacity, as previously determined by observation. The weight of each can of moist soil was recorded. The plants had all emerged on September 21, 1967 and were thinned to three plants per pot after they had become

established. The pots were watered to weight when necessary, daily after some growth was established. The estimated weight of the plants was added to the weight of water needed to bring the pots to weight.

The plants were harvested on October 24, 1967, approximately five weeks after planting. They were oven dried in a forced air oven and the combined weight of all three plants in each pot was recorded.

An attempt was made to regrow the plants from the stalks remaining in the pots but this failed.

The pots were replanted on November 5, 1967. An additional 100 ppm nitrogen as NH_4NO_3 was applied in solution. After the seedlings had emerged and become established, they were again thinned to three plants per pot. They were harvested on December 16, 1967 and were dried and weighed as before.

Analyses of Soil Samples

The following determinations were made on the six soils used in this study: Available phosphorus was determined by the Bray #1 method (3) consisting of 0.025 N HCl in 0.03 N NH_4F with soil:solution ratios of 1:10, 1:20, and 1:50; 0.5 M NaHCO_3 adjusted to pH 8.5 with NaOH, used in a soil:solution ratio of 1:20 (19); 0.73 N CH_3COONa (NaOAc) in 0.5 N CH_3COOH (HOAc) buffered at pH 4.8 (18) used in a soil:solution ratio of 1:10; and 1.4 N $\text{CH}_3\text{COONH}_4$ (NH_4OAc) in 1 N HCl buffered at pH 4.2 used in a soil:solution ratio of 1:10 (2). Extraction periods were 30 minutes for all except the Bray solutions, where a 5 minute extraction period was used. Color was developed using the ascorbic acid method of Watanabe and Olsen (32) on all extracts except the ammonium acetate-hydrochloric acid extracts, where the method of Dickman and

Bray (12) was used. Cation exchange capacity, % CaCO_3 , particle size distribution, pH, total phosphorus, and the content of $\text{NH}_4\text{Cl-P}$, Al-P , Fe-P , and Ca-P by phosphate fractionation were determined. Cation exchange capacity was determined by the calcium saturation-sodium displacement method described by Jackson (14). The CaCO_3 content was determined as outlined by Richards (23). Particle size distribution was carried out by use of the hydrometer method described by Day (10). Soil pH was determined in a 1:1 soil:water ratio. Total phosphorus was determined by the perchloric digestion method of Olsen and Dean (20), the color being developed by the vanadomolybdophosphoric method described by Jackson (14). The phosphate fractionation procedure used was that of Chang and Jackson (7).

Experiment II

No plants were grown in the remaining 72 cans of soil, but they were used instead for periodic sampling in order to estimate changes in extractability of the soil phosphorus. The soils were fertilized and watered the same as those used for growing sorghum, except that corrections in the amount of water added were made because of the removal of portions of the soil. An attempt was made to keep the soil mass moist at all times. A representative sample of each soil was removed from the pots at two-week intervals from October 2 to December 11, 1967, for a total of six samplings. The weighed samples were air dried, ground, and stored until they could be analyzed for available phosphorus.

The soil samples were analyzed for available phosphorus by the same extraction methods used in Experiment I. The phosphorus in the

soils samples on the first and last sampling dates (at the 50 ppm rate) was fractioned into $\text{NH}_4\text{Cl-P}$, Al-P , Fe-P , and Ca-P by the Chang and Jackson fractionation procedure. Triple superphosphate was also mixed with each of the six soils and the phosphate fractionation procedure immediately initiated.

CHAPTER IV

RESULTS AND DISCUSSION

Experiment I

Extraction of Available Phosphorus From Unfertilized Soils and Its Relation to Phosphorus Fractions

A reagent used for the extraction of available phosphorus does not extract a particular form of phosphorus, but extracts varying combinations of Al-P, Fe-P, Ca-P, and surface adsorbed phosphate (hereafter referred to as $\text{NH}_4\text{Cl-P}$), depending on the type of reagent used and the amount of each form of phosphorus in the soil. This section is concerned with the amounts of available phosphorus extracted with the reagents used in this study and their relationship to the amounts of $\text{NH}_4\text{Cl-P}$, Al-P, Fe-P and Ca-P present in the soil as determined by Chang and Jackson procedure for fractionating soil phosphorus. The amount and type of available phosphorus extracted is also compared to other soil properties, such as pH, percent CaCO_3 , and texture. The various soil properties are shown in Table I.

Phosphorus Extracted by Bray #1

Effect of the Soil:Solution Ratio. Widening the soil:solution ratio had considerable effect on the amount of phosphorus extracted from soils as can be seen in Table II. Widening the soil:solution

TABLE I
THE CHEMICAL AND PHYSICAL PROPERTIES OF SOILS

Soil	% Sand	% Silt	% Clay	CEC meq/100g	pH	% CaCO ₃	Total p-ppm	ppm NH ₄ -P	ppm Al-P	ppm Fe-P	ppm Ca-P
Eufaula	89.59	7.90	2.51	1.78	6.95	0.69	171	1.87	16.23	11.24	60.28
Parsons	22.22	66.39	11.39	8.45	5.50	0.94	202	1.00	6.50	19.49	9.75
Kirkland	41.86	40.32	17.82	13.18	6.40	1.12	273	1.00	21.23	38.47	18.49
Canadian	64.11	25.74	10.15	11.11	7.95	1.50	282	4.00	15.12	5.88	103.68
Ulysses	20.96	41.27	37.77	26.47	8.15	4.81	457	2.56	16.84	2.87	137.89
Norge	44.76	43.79	11.45	12.72	6.15	1.25	331	2.31	10.50	19.25	13.00

TABLE II
THE AMOUNTS OF AVAILABLE PHOSPHORUS EXTRACTED BY
SIX EXTRACTING SOLUTIONS (ppm)

Soil	Reagent					
	Bray 1:10	Bray 1:20	Bray 1:50	NaHCO ₃	NH ₄ OAc - HCl	NaOAc
Eufaula	19.20	20.96	24.00	4.00	4.46	7.55
Parsons	3.92	5.68	7.60	1.70	1.07	0.86
Kirkland	20.60	27.04	35.60	11.10	7.95	7.08
Canadian	12.76	16.16	21.00	4.10	14.80	11.20
Ulysses	8.28	13.20	16.80	2.95	12.65	8.24
Norge	10.08	11.68	12.20	3.80	2.95	4.18

ratio resulted in a considerable increase in the amount of phosphorus extracted from all soils with the exception of Norge where only a slight increase occurred. Table III shows the effect of widening the soil:solution ratio on the percentage increase of phosphorus extracted. The largest percentage increase was obtained from Ulysses, when the soil:solution ratio was widened from 1:10 to 1:50, but a large percentage increase also occurred when the ratio was widened from 1:10 to 1:20. These increases were expected since Ulysses had the highest percentage of CaCO_3 . It is likely that the CaCO_3 in Ulysses tended to neutralize the acid in the Bray reagents at the 1:10 and 1:20 ratios.

The data in Table III also indicate that an increase in the percentage of CaCO_3 present in a soil has a greater effect on the amount of phosphorus extracted than does an increase in pH. Results obtained with Parsons and Canadian soils may be used to illustrate the effect of pH on the amount of phosphorus extracted at the three soil:solution ratios with the Bray reagent. Parsons has a pH of 5.5, Canadian has a pH of 7.95. A higher percentage increase in the amount of phosphorus extracted was obtained by widening the soil:solution ratio for Parsons than for Canadian. This indicates that an increase in the hydroxyl ion concentration may not necessarily cause neutralization of the Bray reagents.

All soils with the exception of Ulysses are low in CaCO_3 . When Ulysses is omitted the data in Table III have no general pattern. Thus it cannot be said which of the five remaining soils, if any, should be extracted with a soil:solution ratio wider than 1:10. Widening the soil:solution ratios on these soils may, in fact, result in the extraction of forms of phosphorus not available to plants.

TABLE III

THE PERCENTAGE INCREASE IN AVAILABLE PHOSPHORUS OBTAINED BY
WIDENING THE SOIL:SOLUTION RATIO OF BRAY #1

Soil	Ratios Compared		
	$\frac{1:20-1:10}{1:10}$ (100)	$\frac{1:50-1:10}{1:10}$ (100)	$\frac{1:50-1:20}{1:20}$ (100)
Eufaula	9.17	25.00	14.50
Parsons	44.90	93.88	33.80
Kirkland	31.26	72.81	31.66
Canadian	26.65	64.58	29.95
Ulysses	59.42	102.90	27.27
Norge	15.87	21.03	4.45

Other factors must be considered when studying the effect of wider ratios on the extraction of phosphorus from soils. For example, as can be seen from Table I, Norge and Kirkland are similar in pH, % CaCO_3 , and in the relative proportion of Al-P, Fe-P, and Ca-P. It might be expected that widening the soil:solution ratio would produce similar increases in the amounts of phosphorus extracted from these soils. However, the increase in phosphorus extracted when using the wider ratios was much greater in the case of Kirkland than Norge. One possible explanation may be found in the clay content. Kirkland has a higher percentage of clay than Norge. It is possible that the Bray reagents in the lower ratios may become exhausted in reacting with surfaces that expose phosphates. Use of the 1:50 ratio for the extraction of phosphorus from Kirkland may alleviate this to some extent.

Relation of Bray #1 to Phosphorus Fractions. As can be seen from Table IV the Bray reagents are well correlated with the Al-P fraction. Thus it can be theorized that Al-P is the form of phosphorus extracted in the largest quantity by the Bray reagents. However, as noted previously, other forms of phosphorus are also extracted. Pratt and Garber (22) found that the Bray reagent removed quantities of phosphorus nearly equal to the sum of the $\text{NH}_4\text{Cl-P}$ and Al-P fractions. This was also found to be true, to a degree, for the soils used in this study. However, for Al-P + $\text{NH}_4\text{Cl-P}$ to be equal to Bray-P in this study particular attention must be given the soil:solution ratio. The relationship of Bray phosphorus to $\text{NH}_4\text{Cl-P}$ + Al-P is given in Table V. The underlined numbers best correspond to the $\text{NH}_4\text{Cl-P}$ + Al-P fractions. None of the Bray values for Ulysses were as high as the $\text{NH}_4\text{Cl-P}$ + Al-P values.

TABLE IV
CORRELATION COEFFICIENTS (r) BETWEEN PHOSPHORUS REMOVED BY
EXTRACTING SOLUTIONS AND PHOSPHORUS FRACTIONS
CONTAINED IN SOILS

Reagent	Fraction		
	Al-P	Fe-P	Ca-P
Bray 1:10	.807	.400	-.063
Bray 1:20	.910	.437	.025
Bray 1:50	.923	.467	.049
NaHCO ₃	.759	.767	-.267
NH ₄ OAc-HCl	.589	-.436	.837
NaOAc	.726	-.391	.741

TABLE V
THE RELATIONSHIP BETWEEN THE AMOUNTS OF PHOSPHORUS EXTRACTED BY
THE BRAY REAGENTS TO THE AMOUNTS OF PHOSPHORUS CONTAINED IN
THE NH₄Cl-P + Al-P FRACTIONS (ppm)

Soil	Reagent			NH ₄ Cl-P + Al-P
	Bray 1:10	Bray 1:20	Bray 1:50	
Eufaula	<u>19.20</u>	20.96	24.00	18.10
Parsons	3.92	5.68	<u>7.60</u>	7.50
Kirkland	<u>20.60</u>	27.04	35.60	22.23
Canadian	12.76	16.16	<u>21.00</u>	19.12
Ulysses	8.28	13.20	16.80	19.40
Norge	10.08	11.68	<u>12.20</u>	12.81

Phosphorus Extracted by NH_4OAc and NaOAc

Sodium acetate-P and NH_4OAc -P are correlated with the Ca-P fraction. These two reagents extracted more phosphorus from the two soils highest in Ca-P, Canadian and Ulysses (see Table I), than from the other soils. Ammonium acetate-P had a higher correlation with Ca-P than did NaOAc-P. Ammonium acetate also extracted more phosphorus from Canadian and Ulysses than did NaOAc (see Table II).

Phosphorus Extracted by NaHCO_3

Phosphorus extracted by NaHCO_3 is correlated equally well with the Al-P and Fe-P fractions. Kirkland is higher in Fe-P of any soil tested and NaHCO_3 removed more phosphorus from Kirkland than it did from any other soil. Kirkland also contains considerable Al-P and part of the phosphorus extracted by NaHCO_3 must have come from the Al-P fraction.

Parsons is proportionally higher in Fe-P than are the other soils, but very little phosphorus was removed from Parsons by NaHCO_3 or any other reagent. Parsons is low in available phosphorus and has a high phosphorus fixing capacity. The phosphorus in Parsons is probably in less soluble forms than it is in the other soils. Thus, NaHCO_3 and the other reagents, extracted little phosphorus from Parsons (see Table II).

Since NaHCO_3 -P is not correlated with Ca-P (Table IV), the values for NaHCO_3 -P consist primarily of Al-P and Fe-P, the amounts removed from a particular soil being proportional to the amounts of Al-P and Fe-P in the soil and the solubilities of these phosphorus forms.

Relationship of Available Phosphorus to Yield

The primary purpose of this study was to determine which reagent(s)

extracted amounts of phosphorus proportional to the amounts of phosphorus taken up by plants from each soil. To accomplish this use was made of the correlation coefficient (r) between available phosphorus and yield. A comparison of the amount of phosphorus extracted from each soil by each of the six reagents and the amount and proportion of $\text{NH}_4\text{Cl-P}$, Al-P , Fe-P , and Ca-P present in each soil was also made.

Yield of Sugar Drip Sorghum

The response of sugar drip sorghum to phosphorus, in terms of dry weight and percentage increase in yield is given in Table VI. Figure 1 is a graphic illustration of the response of sugar drip sorghum to phosphorus. Only five soils are considered. Sorghum on the sixth soil, Eufaula, did not respond to phosphorus fertilization. The cause for this lack of response is unknown. Sorghum on Parsons and Ulysses benefited most from the higher fertilization rates. Growth of sorghum on the other soils began leveling off at 25 ppm of added phosphorus.

Duncan's multiple range test was used to determine if the yield differences between rates on each soil were significant. The results are shown in Table VII. There was no significant difference in yield at the 100 ppm fertilization rates compared to the 50 ppm rates on Canadian, Kirkland, and Norge nor was there a significant difference in yield at the 50 ppm rate compared to the 25 ppm rate on Canadian and Kirkland. There was a significant difference in yield at the 100 ppm rate compared to the 25 ppm rate on Canadian, Kirkland, and Norge.

Correlation of Available Phosphorus With Yield

The correlation between the amount of phosphorus extracted by each

TABLE VI
THE RESPONSE OF SUGAR DRIP SORGHUM TO DIFFERENT
RATES OF PHOSPHATE FERTILIZER

Soil	Rate of Application ppm P	Yield/grams	% Increase in Yield
Parsons	0	1.10	
	25	9.56	869
	50	18.57	1688
	100	27.11	2464
Kirkland	0	12.80	
	25	23.83	186
	50	27.04	211
	100	29.50	230
Canadian	0	9.07	
	25	20.59	227
	50	24.78	262
	100	26.68	294
Ulysses	0	2.50	
	25	4.79	192
	50	9.62	385
	100	14.47	579
Norge	0	11.05	
	25	30.30	274
	50	37.84	342
	100	43.32	392

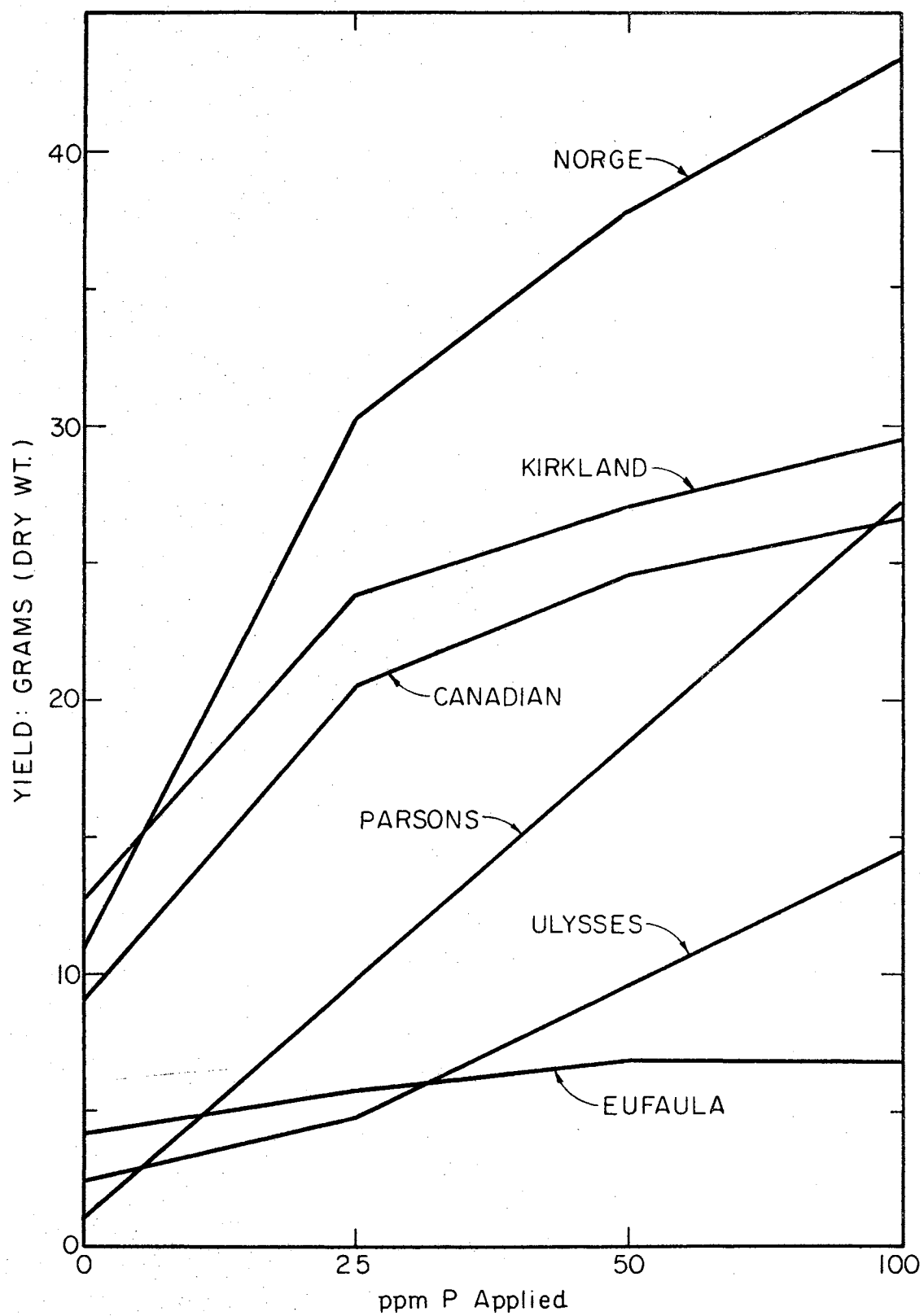


Figure 1. The Effect of Applied Phosphorus on the Yield of Sugar Drip Sorghum.

TABLE VII
AN ANALYSIS OF YIELD DIFFERENCES OF SUGAR DRIP SORGHUM

Soil	Rates Compared	Yield Difference (gms./pot)	Standard Deviation
Parsons	25, 0	8.46**	1.06
	50, 25	9.01**	
	100, 50	8.54**	
	100, 25	17.55**	
Kirkland	25, 0	11.03**	1.10
	50, 25	3.21	
	100, 50	2.46	
	100, 25	5.67**	
Canadian	25, 0	11.52**	1.30
	50, 25	4.19	
	100, 50	1.90	
	100, 25	6.09*	
Ulysses	25, 0	2.29*	0.69
	50, 25	4.83**	
	100, 50	4.85**	
	100, 25	9.68**	
Norge	25, 0	19.25**	1.75
	50, 25	7.54**	
	100, 50	5.48	
	100, 25	13.02**	

*Significant at 5% level.

**Significant at 1% level.

of the reagents with percent relative yield (hereafter referred to simply as yield) is given by the correlation coefficient (r) in Table VIII. For statistical analysis percent relative yield may be defined as:

$$\frac{\text{Yield with no applied P}}{\text{Yield with applied P}} \times 100$$

Bray 1:10-P at the 100 ppm fertilization gave the best correlation with yield. Good correlations were also obtained between the 1:20 and 1:50 soil:solution ratios of Bray #1 and yield, especially at the 50 and 100 ppm rates of added phosphorus. Sodium bicarbonate-P at the 50 and 100 ppm rates gave good, but lower correlations with yield than did Bray-P. Ammonium acetate-P and NaOAc-P gave r values comparable with those of Bray-P at the 25 ppm rate, but the r values at the 50 and 100 ppm rates were lower than those for the other reagents.

Effect of the Phosphate Distribution Pattern. When considering the r values in Table VIII the amounts and types of phosphorus compounds in the soil must be considered. Ammonium acetate-P and NaOAc-P correlate best with the Ca-P fraction (see Table IV). Only two soils high in Ca-P were included in this study, Ulysses and Canadian. If more soils high in Ca-P were included, the correlations of $\text{NH}_4\text{OAc-P}$ and NaOAc-P would be expected to be higher, and conversely, the correlations would be lower if no soils high in Ca-P were included. Accordingly, the correlations of Bray-P with yield would be expected to be higher if more soils high in Al-P were included; $\text{NaHCO}_3\text{-P}$ would be expected to correlate better with yield if more soils high in Al-P and Fe-P were included.

Correlation of Bray-P With Yield. It was stated earlier that it is difficult to determine which soil:solution ratio of the Bray reagent is

TABLE VIII
CORRELATION COEFFICIENTS (r) COMPARING ppm P EXTRACTED
BY VARIOUS EXTRACTANTS WITH RELATIVE YIELD

Method	Rate		
	0/25	0/50	0/100
Bray 1:10	.731	.951	.962
Bray 1:20	.787	.935	.922
Bray 1:50	.757	.896	.885
NaHCO ₃	.604	.831	.844
NH ₄ OAc-HCl	.733	.538	.463
NaOAc	.799	.706	.653

best suited for the extraction of phosphorus from a particular soil when the percentage increase in phosphorus extracted is studied. When correlations with yield are studied and all soils are considered, it appears that both the 1:10 and 1:20 ratios are satisfactory (see Table VIII). However, Bray 1:20 is probably best for soils similar to those in this study, with the exception of Ulysses. The additional volume of acid present when Bray 1:20 is used would be adequate to neutralize the small amounts of CaCO_3 found in many soils. The 1:50 ratio gave good correlations with yield, but the correlations are lower than either the 1:10 or 1:20 ratios at the 50 and 100 ppm rates. The lower r values at these rates can probably be attributed to the extraction of phosphorus not available to plants. The forms of phosphorus and the amount of CaCO_3 in the soil must be considered. Bray 1:50 is probably best suited for the extraction of phosphorus from Ulysses, which is high in Ca-P and contains more CaCO_3 than the other soils. Bray 1:50 would probably give a very good correlation with yield if more soils similar to Ulysses were included in this study.

Correlation of NaHCO_3 -P With Yield. The status of NaHCO_3 in this study is questionable. It is supposed to be satisfactory for the extraction of phosphorus from soils of high or low pH (19). It did give good r values, at the 50 and 100 ppm fertilization rates, but these values were lower than those obtained for the Bray reagents.

Phosphorus extracted by NaHCO_3 is correlated equally with the Al-P and Fe-P fraction (Table IV). Aluminum-P is thought to be more available to plants than Fe-P, and the correlation of NaHCO_3 -P with Al-P was lower than the correlation of Bray-P with Al-P. This reason plus the longer period of time required for the extraction of phosphorus by

NaHCO_3 makes NaHCO_3 less suitable than Bray for the extraction of phosphorus.

Correlation of $\text{NH}_4\text{OAc-P}$ and NaOAc-P With Yield. Phosphorus extracted by NH_4OAc and NaOAc was found to be correlated with the Ca-P fraction. It would thus appear that these two reagents are best suited for the extraction of phosphorus from the two soils highest in Ca-P, Canadian and Ulysses.

Observation of Table II reveals a rather interesting fact. It can be seen that the amounts of phosphorus extracted from Canadian by either acetate reagent differed little from the amount extracted by Bray 1:10. Also, NaOAc extracted about the same amount of phosphorus from Ulysses as did Bray 1:10. The form of phosphorus extracted by Bray 1:10 was primarily Al-P, while the form extracted by NaOAc or NH_4OAc was Ca-P. Either NaOAc-P or Bray 1:10-P should give the same correlation with yield from soils similar to Ulysses. Bray 1:10-P should give about the same correlation with yield as does NaOAc-P or $\text{NH}_4\text{OAc-P}$ when extracting phosphorus from soils similar to Canadian. Thus entirely different reagents can extract similar amounts of phosphorus from certain soils, and the phosphorus extracted by these reagents will correlate similarly with yield, although the forms of phosphorus extracted may be different.

Summary

On the basis of the preceding discussion, the following factors should be considered when selecting an extractant for available phosphorus.

1. The forms of phosphate in the soil.
2. The amount of CaCO_3 in the soil.

3. The soil texture - particular emphasis should be given the clay fraction.

4. The pH of the soil. The pH should not be ignored, but it is extremely difficult to select a reagent on the basis of soil pH alone.

Bray 1:20 appears to be the best extractant for available phosphorus when all soils in this study are considered as a group, with the exception of Ulysses where possible neutralization of the extracting reagent may occur. Bray 1:50 is probably best suited for the extraction of phosphorus from Ulysses because there is enough solution present to prevent neutralization by CaCO_3 . Ammonium acetate and NaOAc are satisfactory for the extraction of phosphorus from Canadian and Ulysses, since they are correlated with the Ca-P fraction. The lower correlations of NaOAc-P and $\text{NH}_4\text{OAc-P}$ with yield are due to there being only two soils dominant in Ca-P in this study. It is suggested that the lower correlations of $\text{NaHCO}_3\text{-P}$ with yield as compared to the correlations of Bray-P with yield were due to Fe-P, which may not be available to plants, being extracted by NaHCO_3 . NaHCO_3 is not as suitable as Bray for soils high in Al-P but it may find use for soils in which the quantity of Fe-P is high, or the Fe-P is soluble enough to be of benefit to plants.

Experiment II

Fixation of $\text{Ca}(\text{H}_2\text{PO}_4)_2$ by the Soil and Release to Extracting Reagents

Some soils fix more phosphorus than others, and more applied phosphorus is available to some extracting reagents than to others. In this section the fixation of applied phosphorus by each soil and the release of applied phosphorus to each extracting reagent will be discussed.

Figures 2 through 19 are plots of phosphorus extracted from each soil at each application rate by each reagent, vs. time. In general there was a pattern of increase in the amount of phosphorus extracted with time. The rate and extent of this increase is dependent upon the application rate, the particular soil in question, and the reagent used for extraction.

The increase in extractable phosphorus is thought to be due to the applied $\text{Ca}(\text{H}_2\text{PO}_4)_2$ being transformed into the four phosphorus fractions, $\text{NH}_4\text{Cl-P}$, Al-P , Fe-P and Ca-P . This increase cannot be explained by the decomposition of organic matter, causing the conversion of organic phosphorus to inorganic phosphorus, since the available phosphorus content of the check pots remained constant throughout the experiment. Different extracting solutions measure varying amounts of these four forms of phosphorus, and the amount of each form changes with time.

Release of Applied Phosphorus to the Bray Reagents. In general, more applied phosphorus was extracted from all soils by the Bray reagents than by any of the other reagents.

When observing the amounts of applied phosphorus extracted from soils (Figures 2 through 7), it is noted that, in general, little difference in the pattern of increase or decrease of phosphorus occurred when the soil:solution ratio was widened. There was an increase in the amount of phosphorus extracted at a given time, but generally this increase was about the same regardless of the time of sampling.

The amounts of applied phosphorus extracted from Norge (Figure 3) initially were about the same as were extracted from Kirkland (Figure 4) at the 25 and 50 ppm fertilization rates. However, the rate of increase of phosphorus extracted with time was greater for Norge than Kirkland.

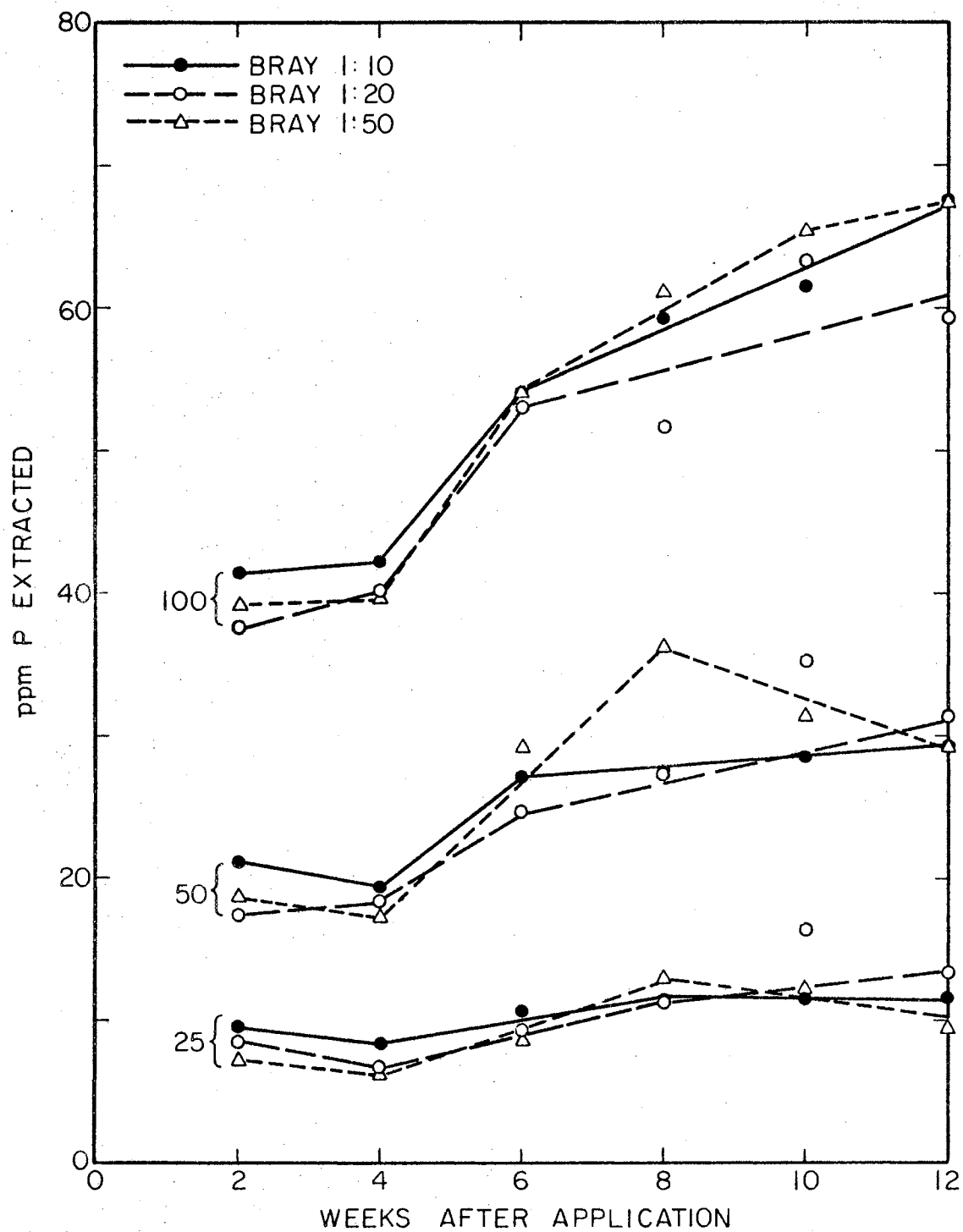


Figure 2. The Amounts of Applied Phosphorus Extracted from Eufaula Loamy Sand by the Bray Reagents.

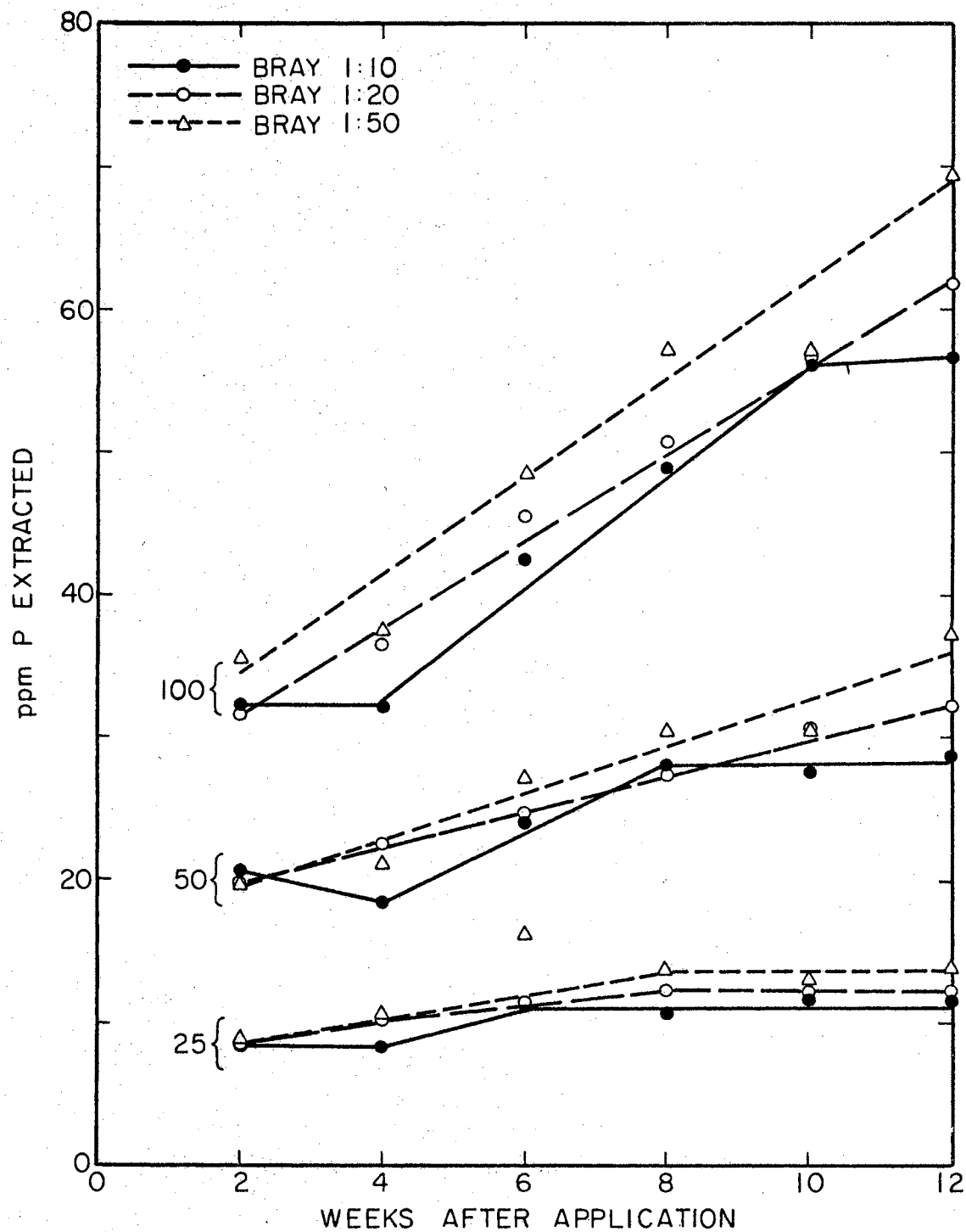


Figure 3. The Amounts of Applied Phosphorus Extracted from Norge Loam by the Bray Reagents.

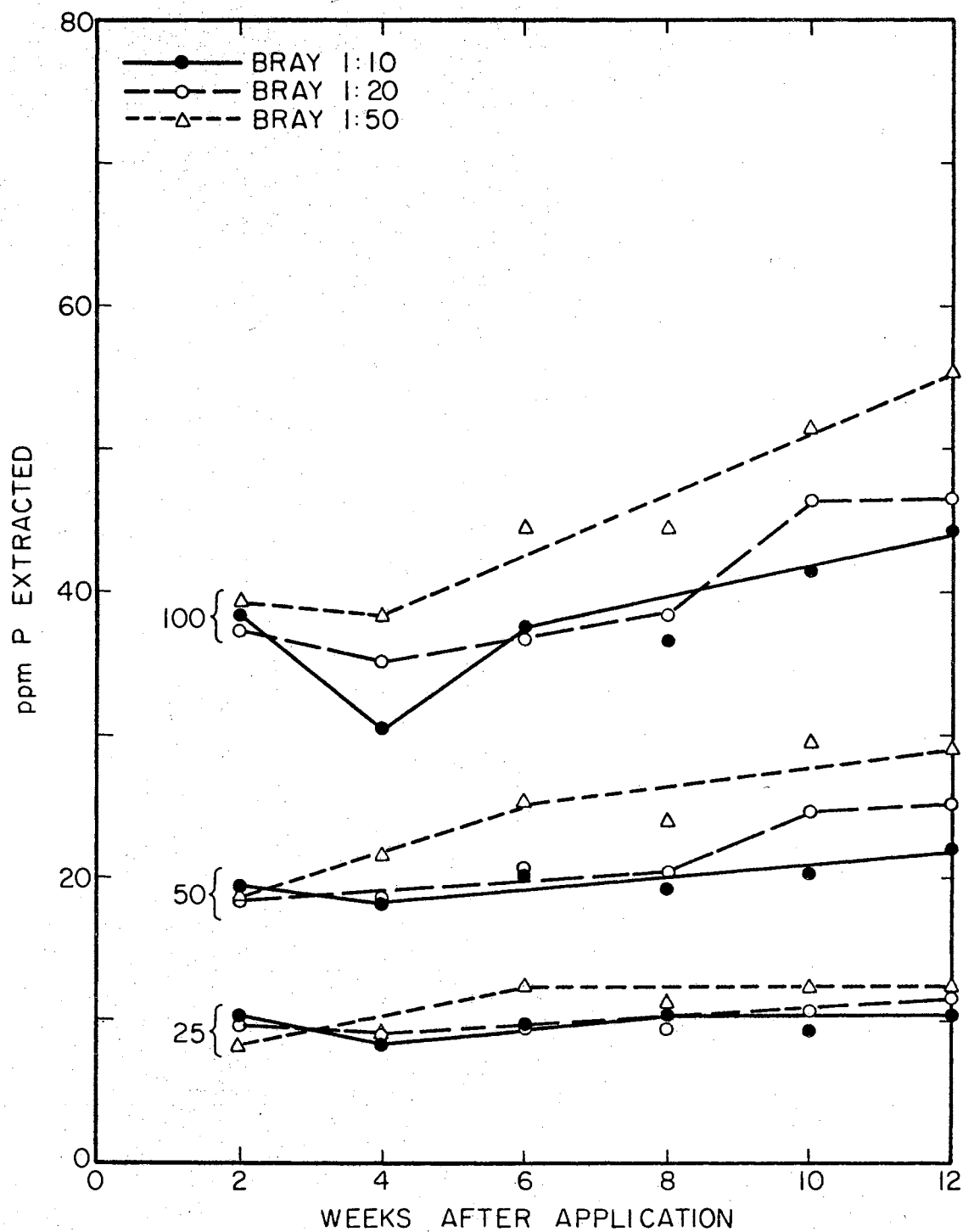


Figure 4. The Amounts of Applied Phosphorus Extracted from Kirkland Loam by the Bray Reagents.

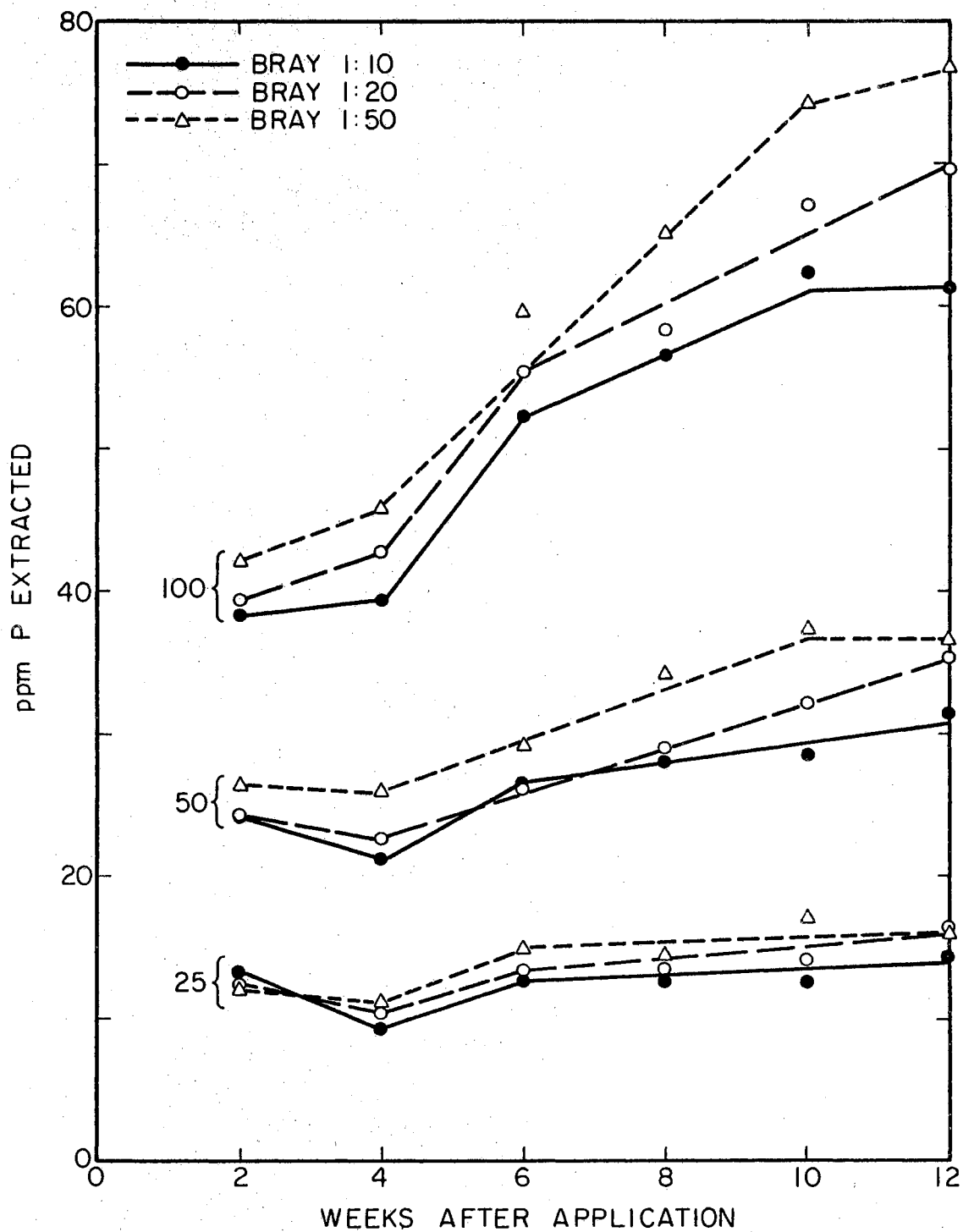


Figure 5. The Amounts of Applied Phosphorus Extracted from Canadian Sandy Loam by the Bray Reagents.

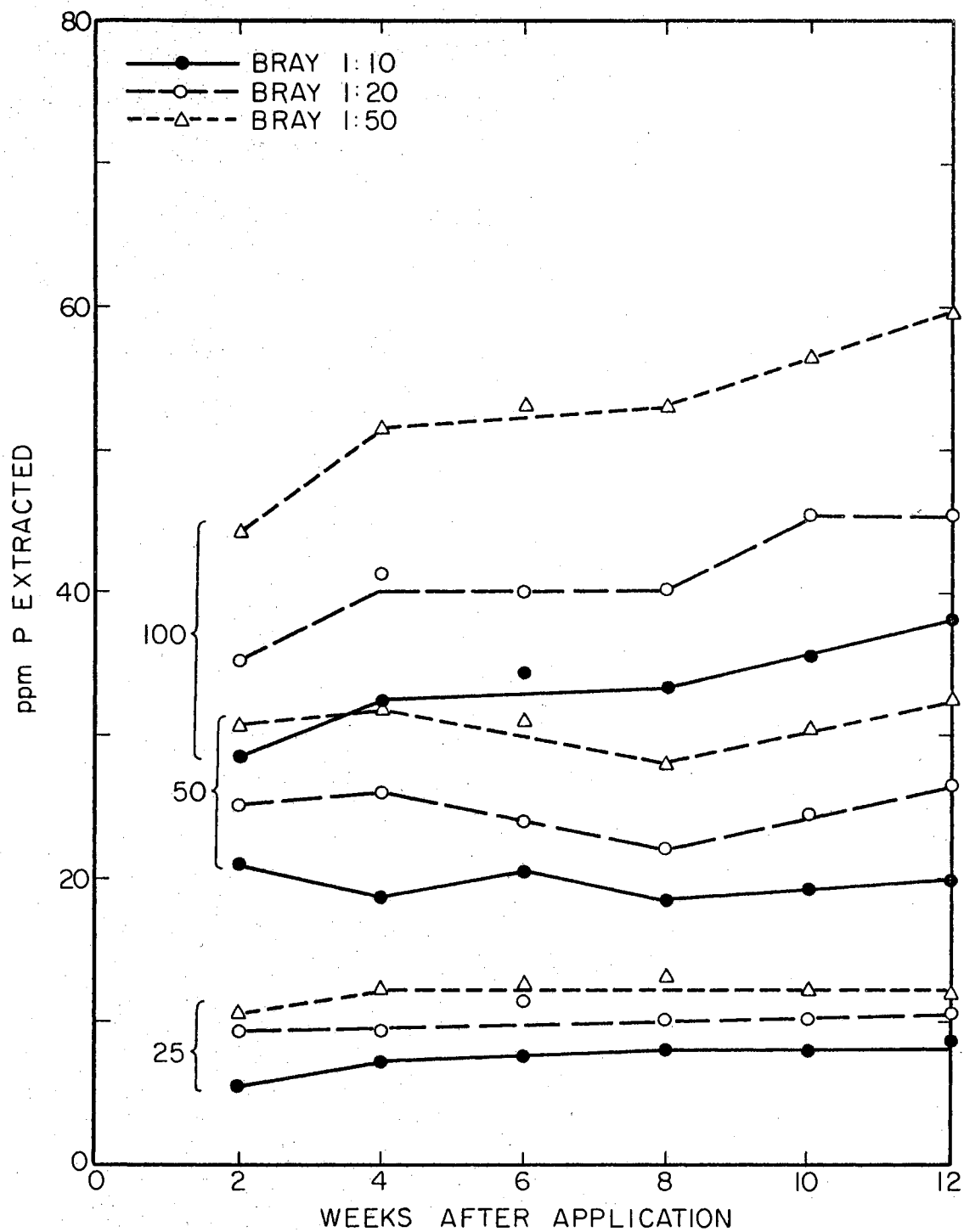


Figure 6. The Amounts of Applied Phosphorus Extracted from Ulysses Silty Clay by the Bray Reagents.

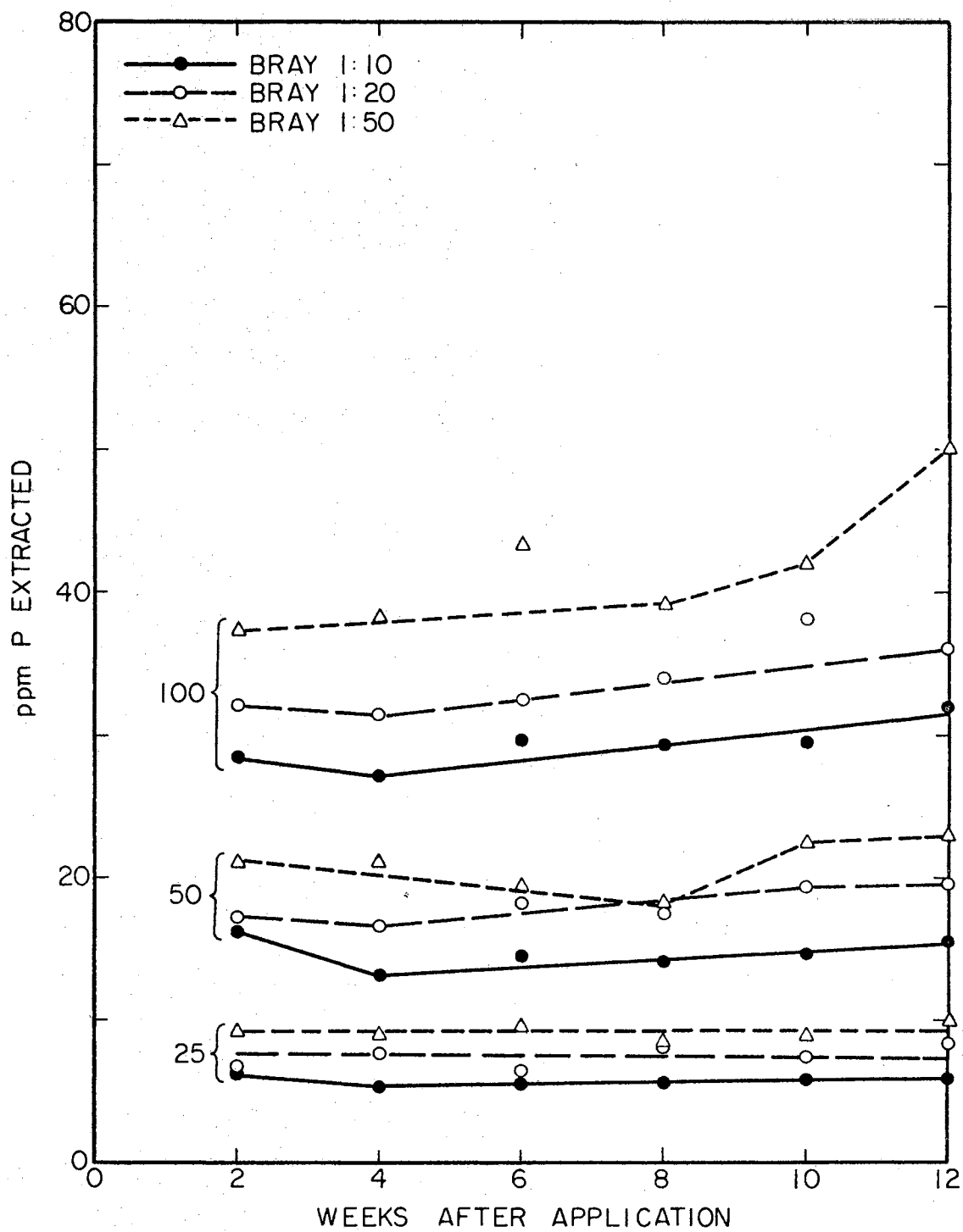


Figure 7. The Amounts of Applied Phosphorus Extracted from Parsons Silt Loam by the Bray Reagents.

This indicates that fertilizer phosphorus applied to Kirkland was fixed in more insoluble forms than phosphorus applied to Norge. Canadian (Figure 5) was similar to Norge in the increase in the amount of phosphorus extracted with time. Ulysses and Parsons (Figures 6 and 7) were similar to Kirkland in that much of the applied phosphorus was converted to forms of phosphorus insoluble in the Bray reagents. The amount of phosphorus extracted from Ulysses showed little overall change at the 25 and 50 ppm rates.

Release of Applied Phosphorus to NH_4OAc and NaOAc . There was little difference in the amount of applied phosphorus extracted by either NH_4OAc or NaOAc from a particular soil (Figures 8 through 13). In general NH_4OAc extracted slightly more phosphorus than NaOAc , however this difference is not significant.

More applied phosphorus was extracted from Canadian and Ulysses by NH_4OAc and NaOAc (Figures 8 and 9) than from the other soils. Canadian and Ulysses are dominant in Ca-P and applied phosphorus was thought to be recovered as Ca-P from these two soils. The increase in applied phosphorus extracted from Canadian with increasing time, was therefore thought to be due to an increase in the Ca-P fraction. The lesser increase in applied phosphorus extracted from Ulysses was probably due to the conversion of phosphorus to a Ca-P form not soluble in these reagents.

The phosphorus recovered by NH_4OAc and NaOAc from Parsons, Kirkland and Norge (Figures 10, 12 and 13) was small because most of the applied phosphorus was converted to forms not soluble in these reagents. Consequently, there was little or no increase in the amount of phosphorus extracted with increasing time. The slight increase in the

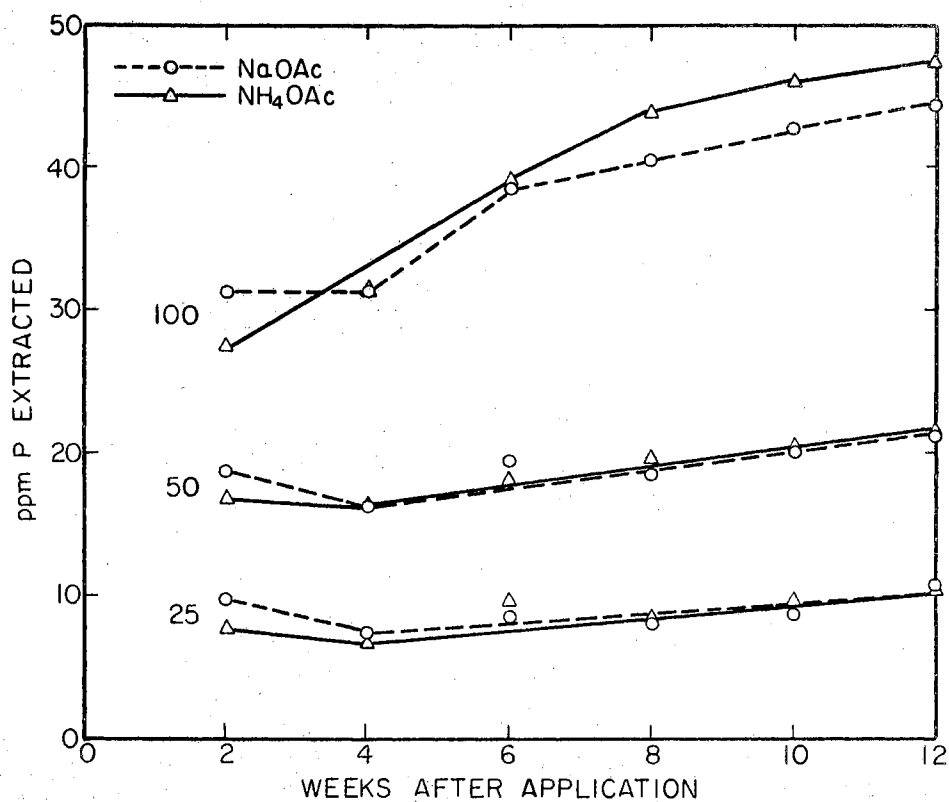


Figure 8. The Amounts of Applied Phosphorus Extracted from Canadian Sandy Loam by the Acetate Reagents.

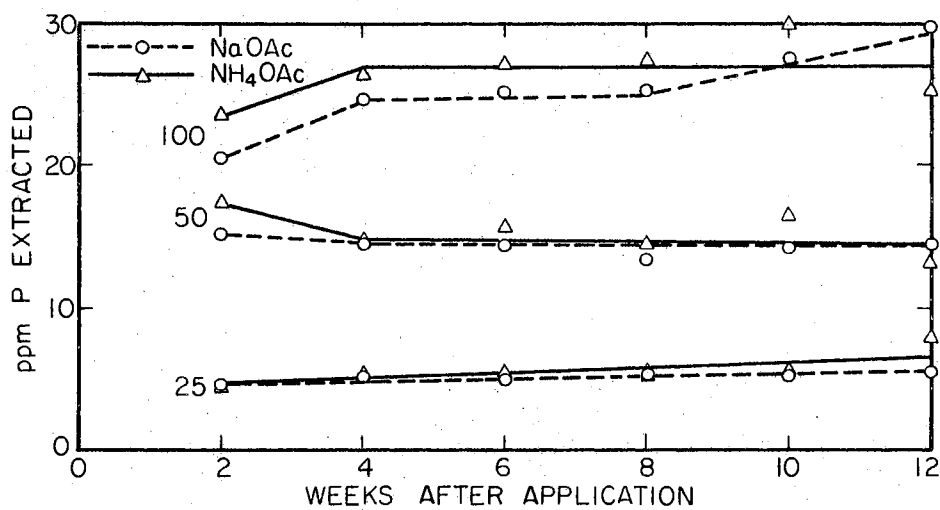


Figure 9. The Amounts of Applied Phosphorus Extracted from Ulysses Silty Clay by the Acetate Reagents.

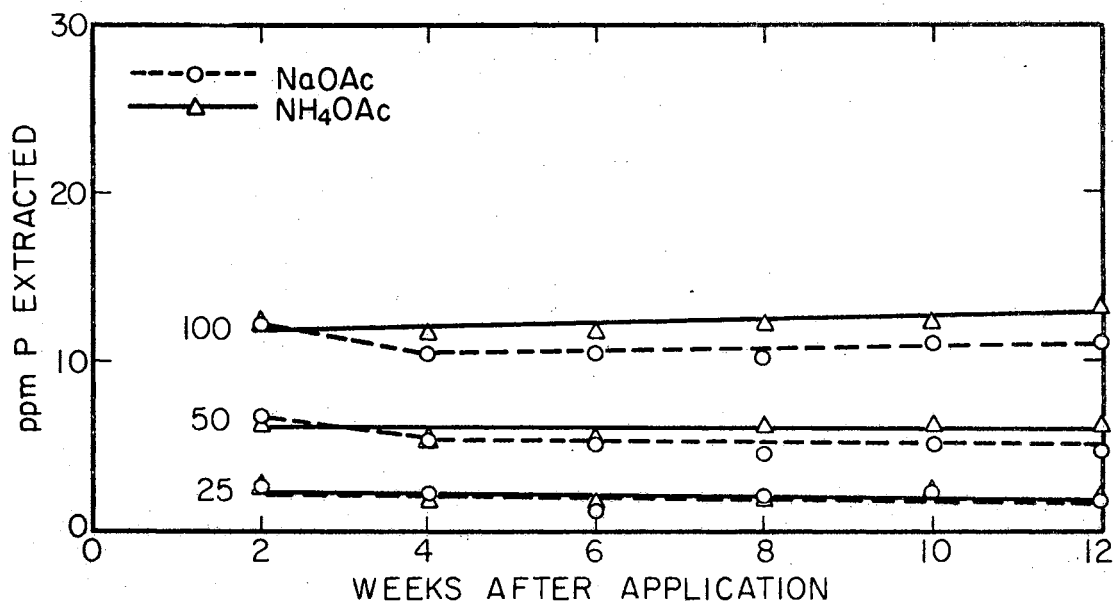


Figure 10. The Amounts of Applied Phosphorus Extracted from Parsons Silt Loam by the Acetate Reagents.

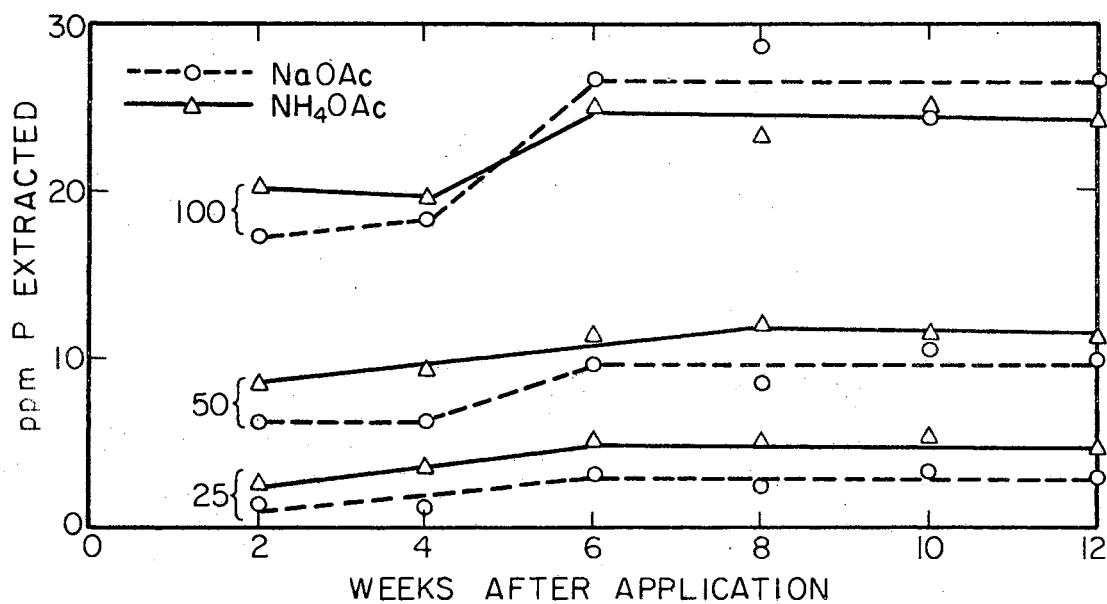


Figure 11. The Amounts of Applied Phosphorus Extracted from Eufaula Loamy Sand by the Acetate Reagents.

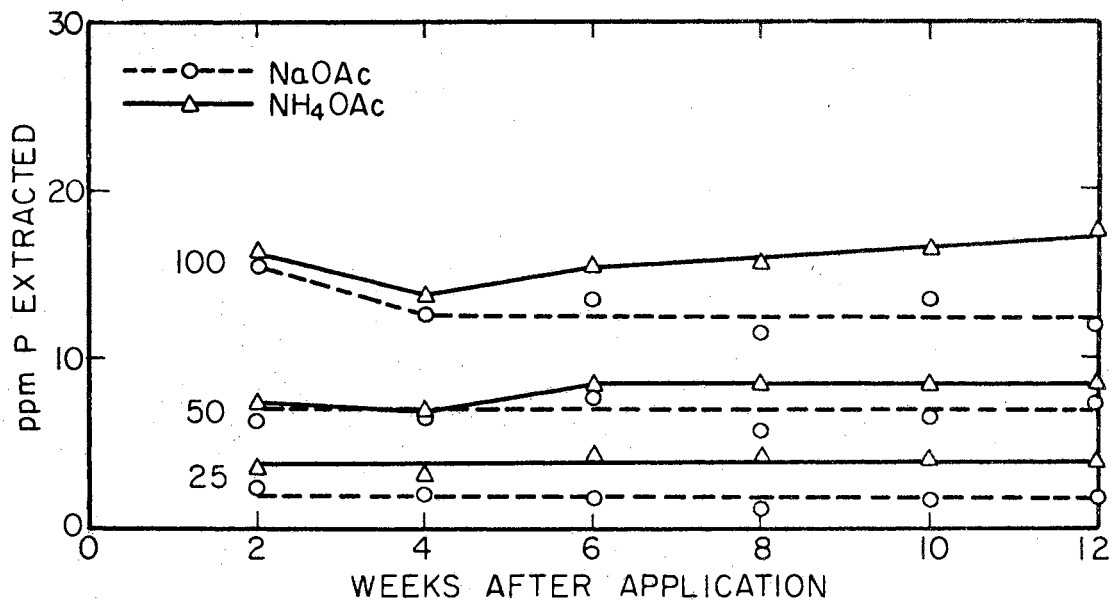


Figure 12. The Amounts of Applied Phosphorus Extracted from Kirkland Loam by the Acetate Reagents.

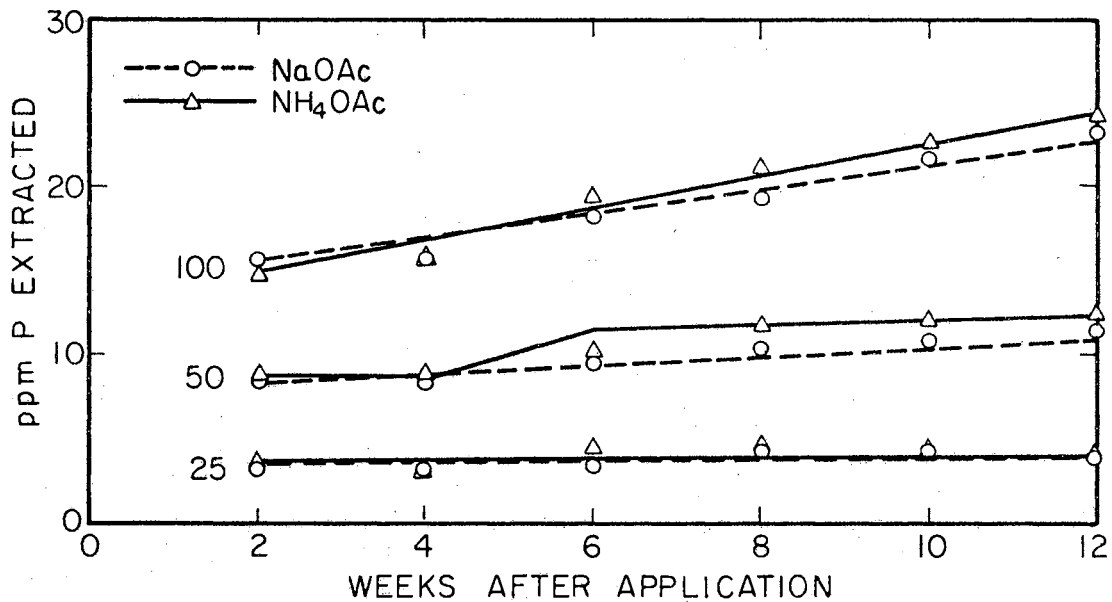


Figure 13. The Amounts of Applied Phosphorus Extracted from Norge Loam by the Acetate Reagents.

amount of phosphorus extracted from Norge (Figure 13) indicates that Norge fixed less phosphorus in insoluble forms than did Parsons or Kirkland.

Eufaula (Figure 11) had considerable Ca-P initially (Table XII). Therefore, some of the applied phosphorus was converted to Ca-P and there was a slight increase in phosphorus extracted with time.

Release of Applied Phosphorus to NaHCO_3 . The amounts of applied phosphorus extracted by NaHCO_3 (Figures 14 through 19) from the soils in this study were intermediate between the amounts extracted by the acetate reagents and the Bray reagents. The single exception was Canadian (Figure 14) from which more phosphorus was extracted by the acetate reagents than by NaHCO_3 because of the Ca-P content of Canadian. Ca-P in Ulysses (Figure 15) apparently was soluble in NaHCO_3 since this reagent extracted more phosphorus from this soil than did the acetate reagents. This contradicts the statement made previously that $\text{NaHCO}_3\text{-P}$ is not correlated with Ca-P. Olsen (19) used NaHCO_3 to remove Ca-P from calcareous soils.

Relation Between the Amount of Applied Phosphorus Extracted and Yield of Sorghum on Similar Soils

This discussion is concerned primarily with the extraction of applied phosphorus by the Bray reagents. Where applicable, references will be made to the other extracting solutions.

The greater response to phosphorus fertilization on Norge opposed to Kirkland can be taken as evidence that the applied phosphorus measured by the Bray reagents is not always proportional to the phosphorus taken up by the plants from these soils. This may be seen in Figures

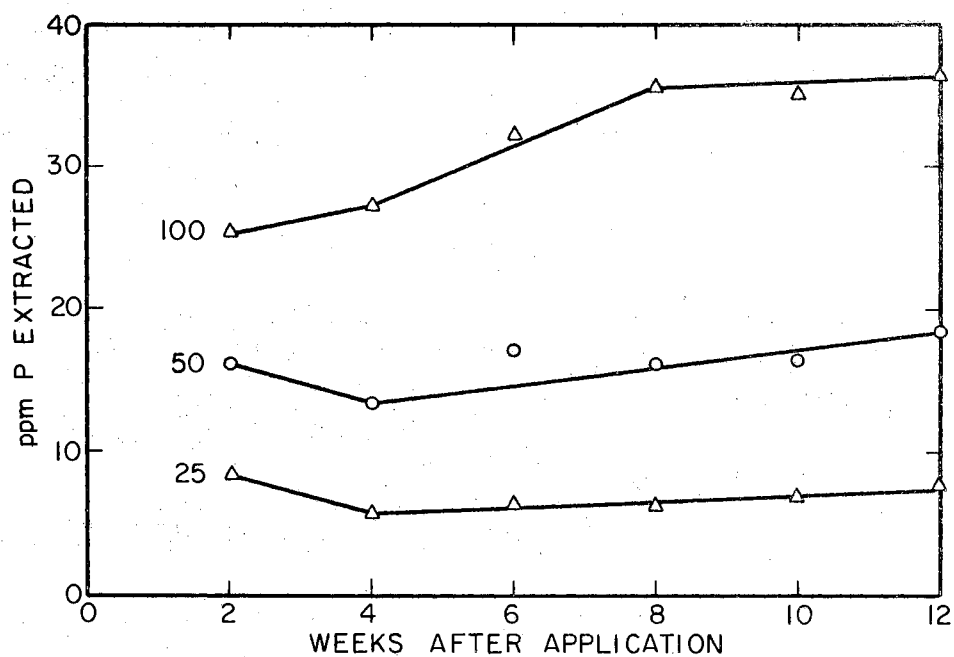


Figure 14. The Amounts of Applied Phosphorus Extracted from Canadian Sandy Loam by NaHCO_3 .

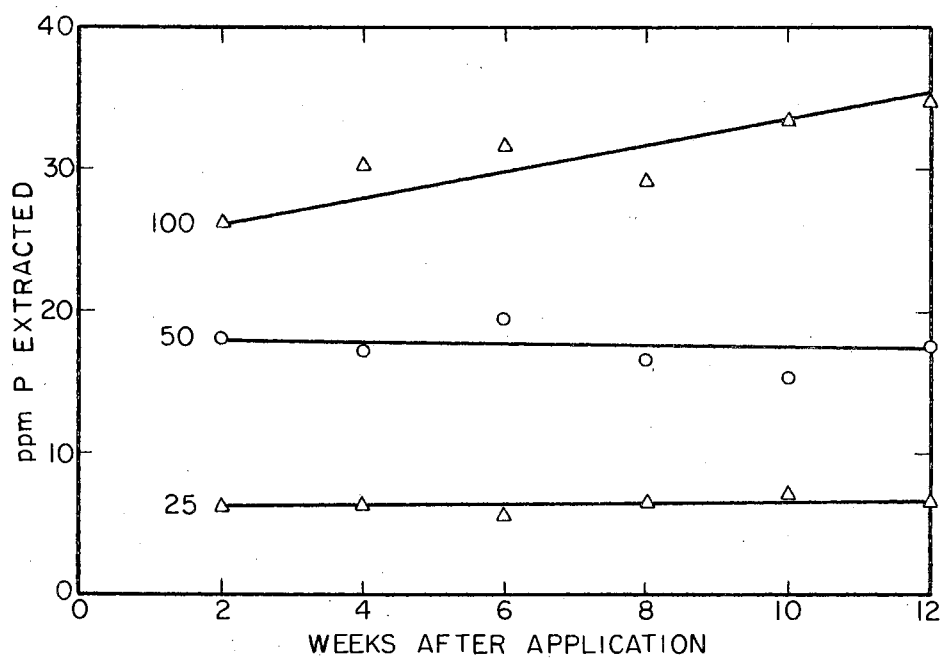


Figure 15. The Amounts of Applied Phosphorus Extracted from Ulysses Silty Clay by NaHCO_3 .

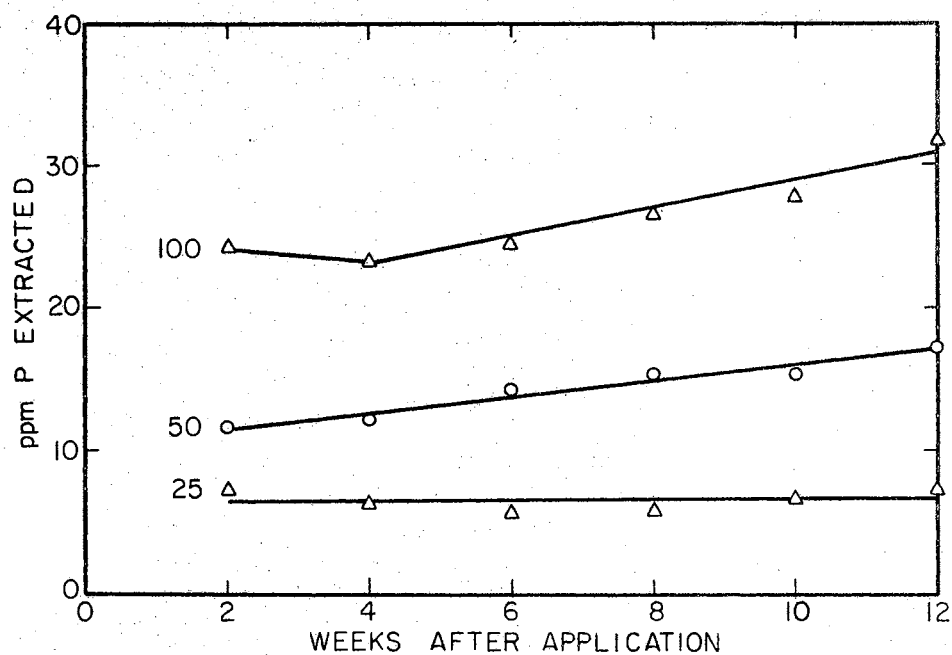


Figure 16. The Amounts of Applied Phosphorus Extracted from Kirkland Loam by NaHCO_3 .

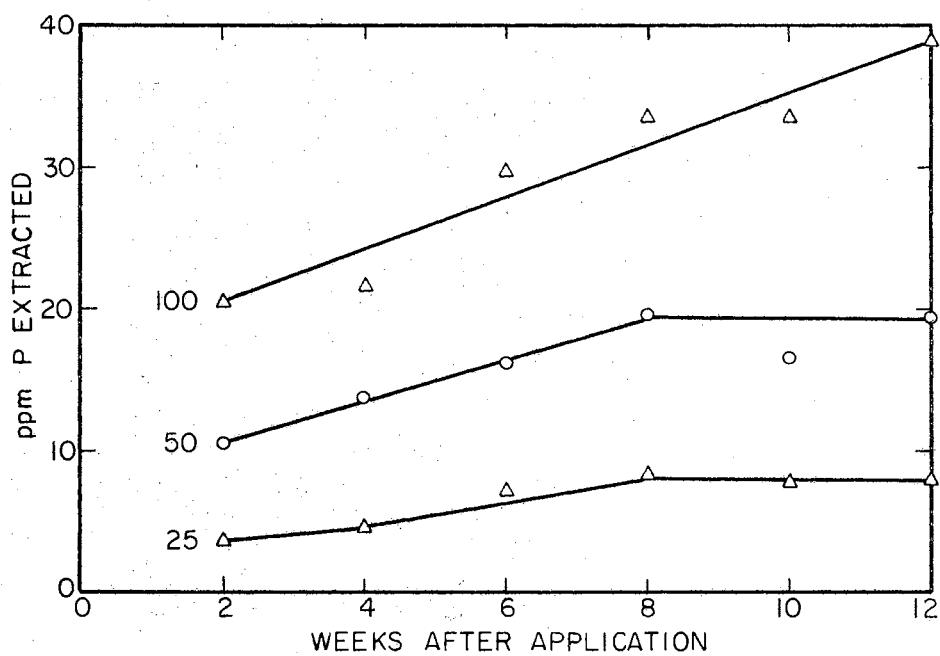


Figure 17. The Amounts of Applied Phosphorus Extracted from Norge Loam by NaHCO_3 .

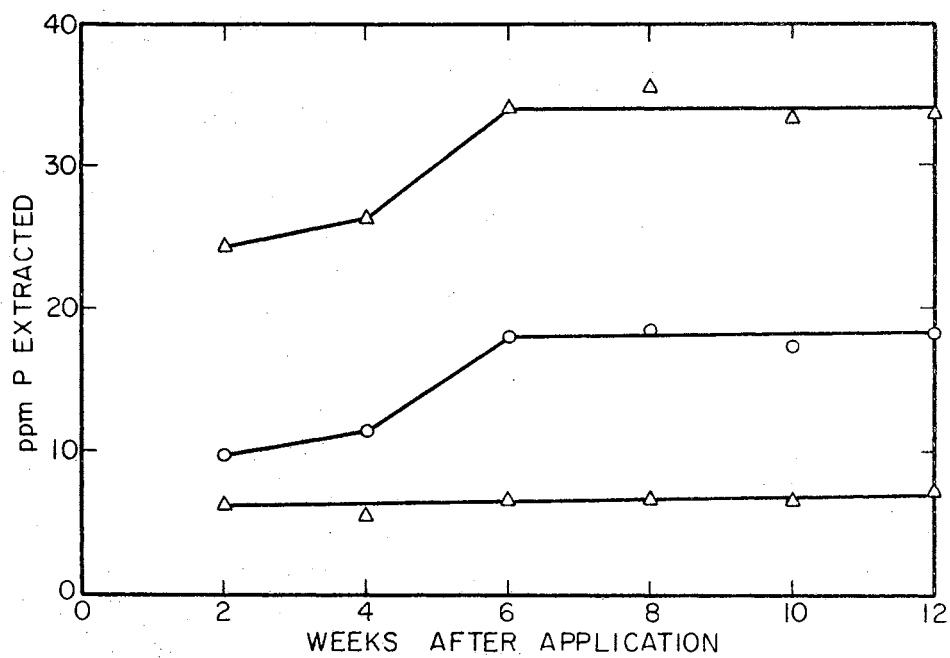


Figure 18. The Amounts of Applied Phosphorus Extracted from Eufaula Loamy Sand by NaHCO_3 .

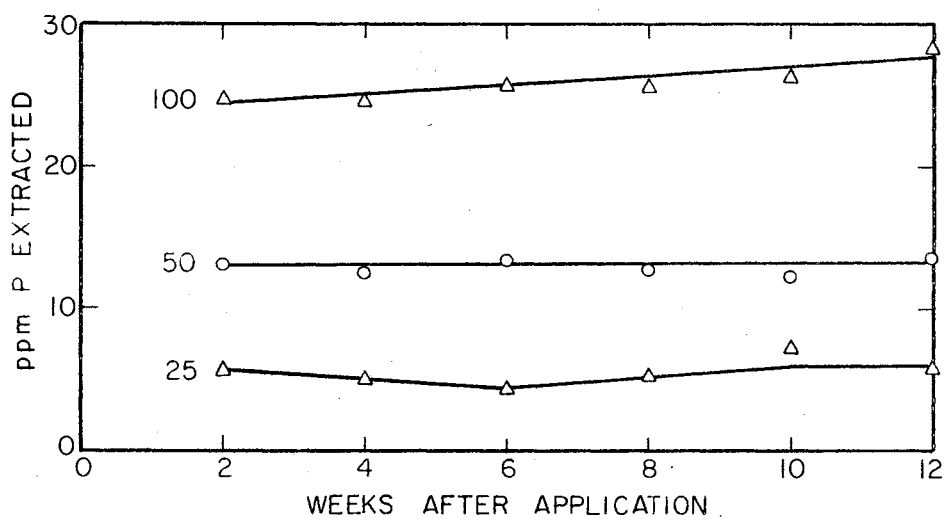


Figure 19. The Amounts of Applied Phosphorus Extracted from Parsons Silt Loam by NaHCO_3 .

3 and 4 and the percentage increase in yield of sorghum from Kirkland and Norge given on Table IX. The growth of the first crop of sorghum corresponds to the phosphorus extracted through week five in Figures 3 and 4, and the growth of the second crop corresponds to phosphorus extracted during weeks seven through twelve. The amounts of phosphorus extracted by the Bray reagents from Norge and Kirkland did not differ by more than five ppm during the period of growth of the first crop, but the increase in yield of sorghum was greater from Norge than from Kirkland. The amounts of phosphorus extracted from Norge at the 50 and 100 ppm fertilization rates, especially the 100 ppm rate, were greater than from Kirkland during the growth period of the second crop and was reflected in a higher increase in yield from Norge. However, the amounts of phosphorus extracted from Norge and Kirkland at the 25 ppm rate did not differ much during either growth period. The increase in yield of sorghum from Norge was greater than from Kirkland at this rate.

When Figures 12 and 13 are compared with the increase in yield in Table IX, it appears that the amounts of phosphorus extracted by NaOAc and NH_4OAc are better related to yield than are amounts extracted by the Bray reagents, at least at the 50 ppm and 100 ppm rates. More phosphorus was extracted from Norge than from Kirkland and the increase in the amount of phosphorus extracted with time was greater for Norge. However, the difference in the amounts of phosphorus extracted from these soils at the 25 and 50 ppm rates was small and it cannot be ascertained that the slightly greater amount and increase of phosphorus extracted from Norge was significantly related to the increased yield from Norge.

TABLE IX
THE PERCENTAGE INCREASE IN THE YIELD OF SUGAR DRIP SORGHUM
ON NORGE LOAM AND KIRKLAND LOAM

Soil	Rate of P Application(ppm)	Total Yield(gms)	Percentage Increase	
			1st Harvest	2nd Harvest
Kirkland	0	12.80	-	-
	25	23.83	203	115
	50	27.04	229	136
	100	29.50	241	186
Norge	0	11.05	-	-
	25	30.30	347	132
	50	37.84	429	174
	100	43.32	483	213

Relationship Between the Increase in Extractable Phosphorus with Time to Yield of Sorghum

Some inferences can be made concerning the relationship between the amount of increase in the extraction of applied phosphorus and the yield of sorghum. A large increase in yield was obtained from those soils that showed a large increase in the amount of phosphorus extracted with time. However, a large increase in yield was not accompanied by a large increase in the amount of phosphorus extracted with time from all soils in this study. This indicates that while a large increase in extractable phosphorus will indicate a large increase in yield, a large increase in yield does not necessarily indicate a large increase in extractable phosphorus.

The amount of phosphorus extracted from Norge and Canadian increased considerably with time, especially when extracted by the Bray reagents (Figures 3 and 5). This increase indicates that applied phosphorus is fixed in a relatively small amount by Norge and Canadian. The increase in extractable phosphorus was accompanied by a large increase in yield on these two soils.

A study of Parsons (Figure 7) revealed a somewhat different pattern between the increase of extractable phosphorus and yield. Parsons gave a high yield increase of sorghum, yet the amount of phosphorus extracted with time did not increase appreciably. Parsons was very low in available phosphorus before fertilization. Thus, application of phosphorus to Parsons resulted in a large increase in yield. The lack of increase in the amount of phosphorus extracted was due to considerable fixation of applied phosphorus. Also, the fixation of phosphorus by Parsons resulted in a lower yield (in grams) than was obtained from

some other soils.

Kirkland (Figure 4) also fixed appreciable quantities of phosphorus, resulting in a lesser increase in the amount of phosphorus extracted with time than was extracted from Norge or Canadian. Kirkland had a rate of increase of extractable phosphorus slightly greater than that of Parsons. The increase in yield of sorghum from Kirkland was lower than from Parsons because Kirkland was higher in phosphorus before fertilization.

Ulysses (Figure 6) was second only to Parsons in yield increase at the higher fertilization rates. It is similar to Kirkland and Parsons in that a large amount of the applied phosphorus was fixed, resulting in a low rate of increase of extractable phosphorus.

On the basis of the rate of increase of extractable phosphorus and the increase in yield of sorghum, the soils in this study can be classified into three categories:

1. Those soils which show a high rate of increase of extractable phosphorus and also a large increase in yield.
2. Those soils which show a lesser increase in the rate of extractable phosphorus and a lower increase in yield.
3. Those soils which show a lesser increase in the rate of extractable phosphorus and a large increase in yield.

Conversion of Applied $\text{Ca}(\text{H}_2\text{PO}_4)_2$

Within the time limits of this study, fertilizer phosphate, applied as $\text{Ca}(\text{H}_2\text{PO}_4)_2$ was converted primarily to the Al-P and Fe-P forms, as determined by the Chang and Jackson fractionation procedure. Relatively little of the applied phosphorus was recovered as Ca-P except

in the case of Ulysses where about 20% of the applied phosphorus was recovered as Ca-P. Table X shows the amount of applied phosphorus in ppm converted to each form of phosphate. Table XI shows the amount of increase or decrease of each phosphorus form.

When the soils were fractionated immediately after adding $\text{Ca}(\text{H}_2\text{PO}_4)_2$ less than five percent of the applied phosphorus was recovered as Ca-P. From 20 to 33 percent was recovered in the $\text{NH}_4\text{Cl-P}$ or easily soluble form. The recovery of a large percentage of applied phosphorus as $\text{NH}_4\text{Cl-P}$ was expected since $\text{Ca}(\text{H}_2\text{PO}_4)_2$ is a more soluble form of phosphorus than any form in the soil. The amount of Al-P recovered immediately and two weeks after application remained essentially constant in all soils except Parsons and Kirkland where a considerable decrease in the amount of Al-P extracted at two weeks occurred. There was also a large increase in the amount of Fe-P extracted at two weeks from these two soils, indicating that the Al-P had probably been converted to the Fe-P form.

It seems that a larger amount of applied phosphorus should have been recovered in the Ca-P fraction. Although very little phosphorus as Ca-P was recovered immediately after application, it seems unlikely that so rapid a conversion to forms other than Ca-P could occur under field conditions. It is possible that fertilizer phosphate was converted to the Al-P form during the extraction process. It is also possible that the fertilizer phosphorus, being more soluble than the phosphorus originally in the soil, was soluble in NH_4F , the extractant for Al-P. A third possibility is that the applied phosphorus extracted in the Al-P fraction is Al-P of a form more soluble than the form originally in the soil. The recovery of fertilizer phosphate as Ca-P from

TABLE X
THE RECOVERY OF 50 ppm PHOSPHORUS APPLIED AS $\text{Ca}(\text{H}_2\text{PO}_4)_2$

Soil, Time After Application (weeks)	Form of Phosphate Recovered (ppm)				
	$\text{NH}_4\text{Cl-P}$	Al-P	Fe-P	Ca-P	Total
Eufaula - initial*	1.87	16.23	11.24	60.28	89.62
0**	33.14	11.57	-0.89	-10.92	32.90
2	4.47	10.96	3.23	-23.61	-4.95
12	1.86	20.63	2.29	-24.67	0.11
Parsons - initial	1.00	6.50	19.49	9.75	36.74
0**	10.68	22.80	9.81	3.97	47.26
2	0.11	14.75	19.36	2.28	36.50
12	-1.00	17.24	25.99	5.70	47.93
Kirkland - initial	1.00	21.23	38.47	18.49	79.19
0**	15.13	25.42	8.78	3.02	52.35
2	2.52	17.75	17.50	2.33	40.10
12	4.24	16.99	19.02	4.19	44.44
Canadian - initial	4.00	15.12	5.88	103.68	128.68
0**	27.52	12.70	4.85	-2.07	43.00
2	8.75	13.21	5.79	-2.27	25.48
12	10.51	20.95	10.87	0.23	42.56
Ulysses - initial	2.56	16.84	2.87	137.89	160.16
0**	15.53	18.20	3.39	-0.48	36.64
2	7.89	21.02	2.04	9.05	40.00
12	4.36	20.25	6.05	9.93	40.59
Norge - initial	2.31	10.50	19.25	13.00	45.06
0**	22.81	19.90	2.52	2.64	47.87
2	1.79	18.91	9.29	4.67	34.66
12	3.50	26.19	14.00	3.79	47.48

* The first row for each soil is the phosphorus content of unfertilized soil as given in Table I.

** Analyzed immediately after application.

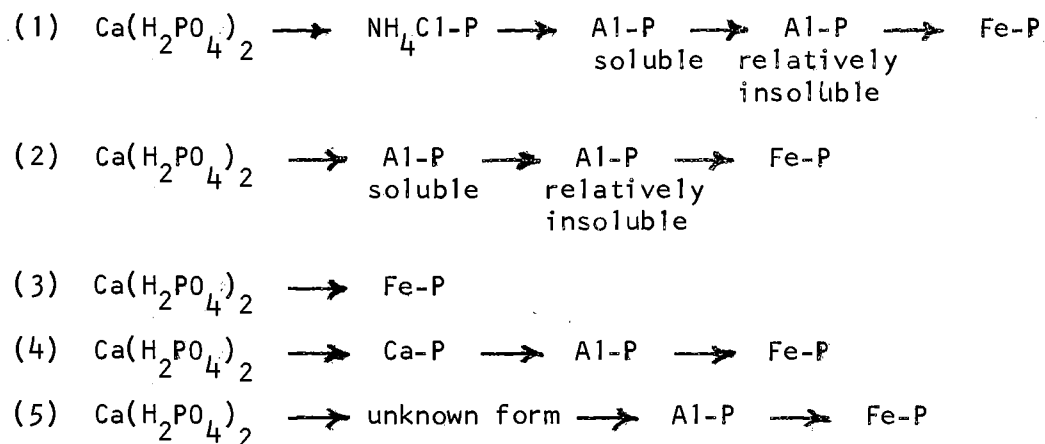
TABLE XI

THE AMOUNT OF CHANGE IN THE FORMS OF PHOSPHATE RECOVERED FROM
50 ppm APPLIED PHOSPHORUS AT TWO AND TWELVE WEEKS

Soil, Time After Application (weeks)	Form of Phosphorus Recovered (ppm)			
	NH ₄ Cl-P	Al-P	Fe-P	Ca-P
Eufaula - 2	-28.67	-0.61	+ 4.12	-12.69
12	-31.28	+9.06	+ 3.18	-13.75
Parsons - 2	-10.57	-8.05	+ 9.55	- 1.69
12	-11.68	-5.56	+16.18	+ 1.73
Kirkland - 2	-12.61	-7.67	+ 8.72	- 0.69
12	-10.89	-8.43	+10.24	+ 1.17
Canadian - 2	-18.77	+0.51	+ 0.94	- 0.20
12	-17.01	+8.25	+ 6.02	+ 1.84
Ulysses - 2	- 7.64	+2.82	- 1.35	+ 9.53
12	-11.17	+2.05	+ 2.66	+10.41
Norge - 2	-21.02	-0.99	+ 6.77	+ 2.03
12	-19.31	+6.29	+11.48	+ 1.15

Ulysses is thought to be due to the amount of CaCO_3 present (Table I). Fertilizer phosphate is precipitated as Ca-P onto CaCO_3 present in the soil, thus reducing the solubility of Ca-P in the extractants for $\text{NH}_4\text{Cl-P}$, Al-P, and Fe-P. The result is that more Ca-P is removed in the extractant for Ca-P from soils containing appreciable CaCO_3 than from soils containing lesser amounts of CaCO_3 .

The possible conversions of $\text{Ca}(\text{H}_2\text{PO}_4)_2$ follow. It is suspected that all reactions occur to some extent.



Reaction (1) shows that the initial reaction is the formation of the more available $\text{NH}_4\text{Cl-P}$, or "surface"-P, with much of this phosphorus being rapidly converted to a soluble form of Al-P and then gradually into relatively insoluble Al-P, with a portion of the applied phosphorus eventually forming Fe-P. Reaction (2) is essentially the same process except that $\text{Ca}(\text{H}_2\text{PO}_4)_2$ is converted directly to soluble Al-P. Reaction (3) probably occurs to a much lesser extent than either (1) or (2). Reaction (3) occurs to the greatest extent in Parsons and Kirkland which fix an appreciable amount of phosphorus as Fe-P (see Table X). Reaction (4) was not observed in this study, although the previous discussion indicates that it probably does occur. This

reaction should essentially terminate with Ca-P in the two alkaline soils, Ulysses and Canadian.

Reaction (5) is given because not all the applied phosphorus was available to the fractionating reagents, as can be seen in Table X. There was a decrease in the amount of total phosphorus extracted at two weeks from Parsons, Kirkland, Canadian and Norge. However, Table XII shows that the summation of Al-P, Fe-P and Ca-P is nearly constant at 0 and 2 weeks in Parsons, Kirkland, and Canadian. There was a decrease in $\text{NH}_4\text{Cl-P}$ and Al-P extracted at two weeks from Parsons and Kirkland, and in $\text{NH}_4\text{Cl-P}$ extracted from Canadian. This loss of phosphorus is not accounted for in any of the other phosphorus fractions. It is concluded, then, that part of the applied phosphorus was converted into some form not soluble in any of the reagents used in the fractionation procedure. The form of this phosphorus remains unknown at this time.

As was expected there was an increase in the amount of Fe-P extracted from all soils with increasing time. It is known that a large portion of applied phosphorus is eventually converted to Fe-P, especially in acid soils, and this is confirmed by the data in Table X. The amount of conversion to Fe-P varies with the soil and depends on the phosphate distribution pattern before fertilization. Unfertilized Parsons is high in Fe-P and a considerable amount of applied phosphorus was recovered in this form. A considerable amount of applied phosphorus was recovered in the Fe-P fraction from the other two soils high in Fe-P, Kirkland and Norge. The conversion to Fe-P occurred to a lesser extent in Canadian and Ulysses which did not contain much Fe-P initially. The conversion to Fe-P took place most rapidly in Kirkland, being essentially

TABLE XII
SUMMATION OF APPLIED PHOSPHORUS RECOVERED AS Al-P + Fe-P + Ca-P

Soil	Time		
	0 weeks	2 weeks	12 weeks
Eufaula	- 0.24	- 9.02	- 1.75
Parsons	36.58	36.39	48.93
Kirkland	37.22	37.58	40.20
Canadian	15.48	16.73	32.05
Ulysses	21.11	32.11	36.23
Norge	25.06	32.87	43.98

complete in two weeks. Parsons and Norge showed an increase in Fe-P at twelve weeks.

Eufaula has been omitted from this discussion because it apparently was not suited to the fractionation process after phosphorus was applied. As the data in Table XI show, there was a considerable loss of Ca-P. This Ca-P was not recovered in any of the other fractions and an explanation for this loss cannot be given on the basis of the data obtained from this study.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Experiment I

Sugar drip sorghum was grown in the greenhouse on six representative Oklahoma soils: Parsons silt loam, Eufaula loamy sand, Ulysses silty clay, Canadian sandy loam, Norge loam, and Kirkland loam. The soils were analyzed for available phosphorus by six extracting procedures. By use of correlation coefficients between the relative yield of sorghum and the amount of phosphorus extracted by each reagent and the forms of phosphorus present in the soil, the following conclusions are suggested:

1. Bray #1 in a 1:20 ratio is best suited for the extraction of "available" phosphorus when all soils are considered.
2. Bray #1 in a 1:50 ratio is probably best suited for Ulysses silty clay since the soil:solution ratio is wide enough to prevent possible neutralization of the reagent by CaCO_3 in the soil.
3. Phosphorus extracted by NH_4OAc and NaOAc is correlated with the Ca-P fraction, and these reagents can be used for the extraction of phosphorus from Ulysses and Canadian soils.
4. NaHCO_3 extracted P correlates well with relative yield, but the correlations are lower than those obtained with the Bray reagents, and also the extraction period is longer, thus, no advantage for the NaHCO_3 reagent over Bray is obtained.

Experiment II

Applied phosphorus was extracted from the soils by the six reagents at biweekly intervals. The amount of phosphorus extracted generally increased with time. The increase was probably due to the conversion of applied phosphorus to various phosphate forms soluble in the extracting reagents. The rate of increase is thought to be dependent on the rate of conversion to the various phosphate forms.

The relationship between yield and the amount of applied phosphorus extracted with time was discussed. While all soils except Eufaula showed a high relative yield, only Norge and Canadian showed a large increase in the amount of applied phosphorus extracted. Eufaula also showed this increase, but sorghum did not respond to phosphate fertilization on Eufaula.

The applied phosphorus in the soils was fractionated and recovered mainly as surface phosphate, aluminum phosphate and iron phosphate. Little phosphate was recovered as calcium phosphate, except from Ulysses where applied phosphate probably precipitated onto calcium carbonate. With time surface phosphate decreased with a corresponding increase in aluminum and iron phosphates. There was a tendency for the phosphate to be converted to forms of phosphates initially present in the soil, with increasing time, except in the case of Canadian where no increase in the dominant form of phosphate, calcium phosphate, was noted. Because of the lack of recovery of applied phosphate as calcium phosphate, it is suggested that the Chang and Jackson fractionation procedure may be of questionable value in determining the conversion of applied phosphate in soils.

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