MINERALIZATION OF ORGANIC PHOSPHORUS IN RELATION TO PHOSPHORUS AVAILABILITY IN SOILS

by

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A Thesis Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major Subject: Soil Fertility

Approved:

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1957

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INTRODUCTION

Several investigators have shown that organic phosphorus undergoes mineralization when soils are incubated. This evidence, however, is not sufficient to establish the importance of organic phosphorus in the phosphorus nutrition of plants. Recently for alkaline soils a fraction of organic phosphorus measured in the laboratory was found to be correlated with estimates of soil phosphorus availability obtained in the greenhouse.

The first objective of the work described in this thesis was to obtain estimates of soil phosphorus availability by applying a new greenhouse technique. The second objective was to find a proper laboratory method to evaluate mineralization of organic phosphorus during incubation. If these measurements of mineralization of soil organic phosphorus during incubation are found to be correlated with estimates of soil phosphorus availability, additional evidence will have been obtained for the importance of soil organic phosphorus to plant growth.

REVIEW OF LITERATURE

Introduction

More than a century ago Mulder (1844) found that a part of soil phosphorus is present in organic form. Since that time research on organic phosphorus has been conducted in several directions. The problem of correctly determining the total amount of organic phosphorus has received much attention in the past and is still attracting the attention of present-day soil analysts. Closely related to this problem is that of separating and identifying different constituents of soil organic phosphorus. The results obtained in this field thus far have not provided a clear picture as to the forms in which soil organic phosphorus exists. At present the only constituents of soil organic phosphorus shown with reasonable certainty are phytin and its derivatives. The lack of consistent information has hampered progress in other phases of research on soil organic phosphorus. If the forms of organic phosphorus in the soil were definitely known, it might be possible to investigate more efficiently the problem of mineralization of soil organic phosphorus.

A comparison of cultivated soils with corresponding virgin soils (Pearson and Simonson, 1940) showed that the quantity of organic phosphorus is lower in the former than in the latter, indicating that organic phosphorus is subject to mineralization. In general, under field conditions mineralization of organic phosphorus appears to proceed more rapidly in alkaline soils (Thompson et al. 1954) than in acid soils at equal levels of organic carbon.

Soil Organic Phosphorus Fractionation

A search for the possible availability of organic phosphorus and an evaluation of this availability, if found, are logical consequences of the aforementioned findings. Pierre and Parker (1927) found organic phosphorus as well as inorganic phosphorus in water extracts of soil, but plants absorbed only the inorganic phosphorus during a 24-hour period. Rogers et al.(1941) grew plants in a culture solution that contained organic phosphorus extracted from soil by 0.5 N ammonium hydroxide. They found that after a 12-hour absorption period the concentration of the ammonium hydroxide-soluble organic phosphorus in the culture solution was reduced from 3.35 to 1.89 p.p.m. The observation that during the same period no increase in inorganic phosphorus was obtained led these investigators to infer that the organic phosphorus compounds were absorbed as such, without being mineralized prior to absorption.

Vincent (1937) reported that the amount of organic phosphorus extracted from the soil by a 2 percent citric acid solution decreased during growth of a crop on the soil. This work provided the first indication of the availability of soil organic phosphorus *in situ*.

Chirikov and Volkova (1941) divided the total soil phosphorus into five fractions on the basis of solubility in different chemical extractants. Three fractions were made up of soil phosphorus soluble in solutions of acids of increasing strength. The fourth fraction, soil phosphorus soluble in 0.2 N sodium hydroxide or ammonium hydroxide, contained most of the organic phosphorus. In none of the experiments, in which oats were used as a test crop, was this fraction of any significance as an indicator of soil phosphorus availability.

Williams (1950) used the same approach but applied different extractants. In none of his experiments could he find a significant decrease in the amount of soil organic phosphorus soluble in 0.1 N sodium hydroxide. This fraction contained a large portion of the total organic phosphorus. Williams' approach involves the assumption that extraction before and after absorption by the crop brings out the same phosphorus with the exception of that which has been absorbed by the plants.

Recently Semb and Uhlen (1955) obtained a significant correlation between plant-response estimates of phosphorus availability and total soil organic phosphorus in soils with a pH higher than 5.5.

The accumulated knowledge of the behavior of soil organic phosphorus is thus conflicting. A better understanding might be obtained if other factors which possibly influence the mineralization of soil organic phosphorus receive proper attention.

Effect of Temperature on Mineralization of Soil Organic Phosphorus

Other workers showed that soil temperature is an important factor in the mineralization of soil organic phosphorus. Knowledge of the change in mineralization with a change in soil temperature might aid in predicting the importance of organic phosphorus to plant growth. Thompson and Black (1947) incubated three virgin Iowa soils for 1 week at temperatures ranging from -14° to 150°C. An increase was found in inorganic phosphorus soluble in 1 N sulfuric acid as a result of incubation at almost all temperatures. Only at temperatures below 50°C, however, was there an agreement between the values obtained for increase in extractable inorganic phosphorus and those for decrease in organic phosphorus. Above 50°C the solubility of the inorganic phosphorus apparently increases during incubation.

Bower (1949) incubated samples of four corresponding cropped and virgin Iowa soils for 30 days. The amount of organic phosphorus mineralized during the incubation period was considerably higher for the virgin soils than for the cropped soils. Samples incubated at 35°C gave a much higher rate of mineralization than samples incubated at 25°C.

In incubation experiments with Prairie soils at ordinary temperatures the major part of the organic phosphorus is resistant to mineralization during even prolonged incubation periods. Thompson and Black (1947) found that soils incubated at 30°C for 7 days released as much inorganic phosphorus as did soils incubated for periods of 30 and 90 days. Different results recently were obtained with peat and muck soil by McCall et al. (1956). In their experiments a steady mineralization of organic phosphorus was found over a period of 4 months. Moreover, the rate of mineralization increased with increasing amounts of monocalcium phosphate added to the samples prior to incubation. The samples were kept at moisture equivalent and 27°C. In some soils no organic phosphorus was left after a 4-month incubation period.

Hayashi and Takijima (1955c) incubated two soils with unusually high amounts of organic phosphorus (1420 p.p.m. and 3950 p.p.m.) for 2 weeks at 27°C. During this incubation period 20 p.p.m. of organic phosphorus were mineralized. To some samples tartrate and citrate were added before incubation. These additions resulted in an increase in organic phosphorus mineralized during incubation. The amounts of organic phosphorus mineralized in samples to which tartrate and citrate had been added were 60 p.p.m. and 80 p.p.m. respectively. In another experiment (1955a) these same investigators found more organic phosphorus mineralized during incubation in flooded soil samples than in corresponding samples held at 60 percent of water-holding capacity.

Importance of Soil Organic Phosphorus to Plant Growth

In none of the aforementioned incubation experiments did the investigators attempt to correlate the amount of organic phosphorus mineralized with the phosphorus available to plants. Working with radioactive phosphorus, Goring and Zoellner (1955) found a significant dependence of phosphorus available to soil organisms on both inorganic phosphorus extracted by the method of Bray and Kurtz (1945) and organic phosphorus synthesized during incubation. They suggested that the significance of organic phosphorus synthesis might result from a correlation between synthesis and mineralization. They found a significant correlation between phosphorus availability according to the technique of Fried and Dean (1952) and inorganic phosphorus extracted by the Bray and Kurtz method.

No significant correlation between phosphorus availability and organic phosphorus synthesized was obtained. They suggested that the greater importance of organic phosphorus in predicting the availability of phosphorus to soil organisms than to plants may have been associated with greater utilization of mineralized phosphorus by soil organisms than by plants.

Eid (1950) and Eid _et al._(1954) attempted to relate various fractions of soil organic phosphorus to soil phosphorus availability. They separated the soil organic phosphorus into three different fractions. The first fraction consisted of the organic phosphorus soluble in 1 percent potassium carbonate solution and hydrolyzed by hypobromite; the second fraction contained the organic phosphorus soluble in the potassium carbonate solution and not hydrolyzed by hypobromite; the third fraction was made up of the organic phosphorus insoluble in the potassium carbonate solution. Besides these three fractions of organic phosphorus they determined the inorganic phosphorus extracted by the method proposed by Bray and Kurtz (1945). Corn was grown in the greenhouse on two series of Iowa soils with a wide range of inorganic and organic phosphorus, at soil temperature of 20°C and 35°C. One series consisted of acid soils, and the other consisted of alkaline soils. The phosphorus availability was estimated in each soil at each temperature from the corn yields by the Mitscherlich equation (1930). Multiple-regression equations were calculated to obtain an estimate of the dependence of soil phosphorus available to plants upon each of the four phosphorus fractions. In most of the experiments a significant correlation between extracted inorganic phosphorus and estimates of soil phosphorus availability was found. For both the acid and alkaline soil series the organic fraction extracted by the potassium carbonate solution and hydrolyzed by hypobromite also was of significance to plants grown on soils with a temperature of 35°C. The other two organic fractions were of no significance.

In an attempt to verify Eid's results the author (1955) failed to find any appreciable amount of the soil organic phosphorus soluble in a 1 percent potassium carbonate solution that could be hydrolyzed by hypobromite. He modified Eid's procedure in such a manner that a 1 percent potassium carbonate -2 percent sodium hydroxide solution was used as an extractant. A part of the organic phosphorus thus removed was hydrolyzed by hypobromite, and this fraction was used for calculating multiple-regression equations similar to those calculated by Eid. The estimates of soil phosphorus availability obtained by Eid were used as dependent variables for the new equations. Additional multiple-regression equations were calculated in which the estimates of soil phosphorus availability were the same as those used above but in which the independent variables were inorganic phosphorus mineralized in moist samples of soil during a 2-day incubation period at 45°C.

The phosphorus availability in the group of alkaline soils was found to be correlated with both fractions of organic phosphorus under consideration. In addition, the fractions were correlated with each other. Since the amount of organic phosphorus mineralized during incubation was smaller than that extracted by the potassium carbonate-sodium hydroxide solution and hydrolyzed by hypobromite, there is some evidence to indicate that the organic phosphorus contained in the former reaction is in fact a part of that contained in the latter.

Soil Organic Phosphorus Mineralization as Affected by Enzymatic Activity

Little is known about the mechanism of mineralization of organic phosphorus and it must be borne in mind that the net mineralization which is measured is the difference between synthesis of organic phosphorus and mineralization of organic phosphorus. There are indications that this mineralization is brought about at least partly by enzymes.

Bower (1949) added enzymes to different fractions of organic phosphorus extracted from soil by a 2 percent sodium hydroxide solution. He observed that the fraction precipitated by calcium hydroxide was readily mineralized by bran extract which contains the phytase enzyme, but not by corn roots, which are free of phytase. On the other hand, the fraction of organic phosphorus which passes into the filtrate from the calcium precipitation was mineralized by bran extract and corn roots, both of which contain the nuclease enzyme.

Hayashi and Takijima (1955a) extracted soils with alkali extractants of increasing strength. Aliquots of the diluted extracts were incubated with and without phosphatase obtained from rice bran. After 21 days of incubation at 27°C, the mineralization in samples without phosphatase ranged from 0 to 17 percent of the total organic phosphorus present initially. After 16 hours of incubation at 27°C the mineralization in samples with phosphatase ranged from 0 to 16 percent of the total organic phosphorus present. In both cases the amounts of organic phosphorus mineralized during incubation increased with the strength of the alkali extractant.

Jackman and Black (1952) determined the hydrolysis of native soil organic phosphorus _in situ_ by added phytase on soils brought from the field and tested without previous drying. Hydrolysis of soil organic phosphorus by added phytase could not be detected, although added phytate phosphorus was hydrolyzed considerably by phytase. The limited solubility of native soil phytates was found to be a more likely factor in limiting the hydrolysis rate of soil phytate phosphorus than phytase activity.

Hayashi and Takijima (1955b) observed that soil organic phosphorus had decreased at a faster rate in samples of soils on which plants had been grown than in samples of the same soils without vegetation. They thus supplied evidence that living roots affect the mineralization of organic phosphorus.

Rovira (1956) grew plants in acid-washed quartz sand to which a complete nutrient solution had been added. After 2 and 3 weeks the roots and sand were rinsed with distilled water. All washings were collected, combined, centrifuged free of root debris and concentrated under vacuum. The concentrated extract was added to soils which, after 14 days at 24°C and field capacity, were analyzed for extractable inorganic phosphorus. No increase in inorganic phosphorus was found in those samples to which the extract had been added. Consequently, if the washings removed any enzymes from the roots and the sand, these enzymes did not bring about any mineralization of organic phosphorus during incubation.

More work will have to be done before any definite statements on the role of enzymes in soil organic phosphorus mineralization can be made. As in other aspects of the problem on mineralization of soil organic phosphorus, experimental conditions approaching the natural ones probably will yield the most nearly valid results.

PRELIMINARY INVESTIGATIONS

Introduction

When soils are incubated to determine the amount of organic phosphorus mineralized during a certain incubation period at a certain temperature, the mineralization of organic phosphorus may be estimated in two different ways. The first one is the difference in inorganic phosphorus extracted from incubated and nonincubated samples. When an increase is found in extractable inorganic phosphorus in incubated samples over that in nonincubated samples, the difference is assumed to be the result of mineralization of a part of the organic phosphorus. A second estimate of organic phosphorus mineralization may be derived from the difference in content of organic phosphorus in soil before and after incubation. A decrease in extractable organic phosphorus in incubated samples compared with nonincubated samples is assumed to be the result of organic phosphorus mineralization during incubation.

In both methods, however, several factors may influence the results so that the estimates of increase in inorganic phosphorus and decrease in organic phosphorus upon incubation may not be unbiased estimates of organic phosphorus mineralization during incubation.

In general, any measurement of the increase in inorganic phosphorus as a result of incubation will be an estimate of the summation of (a) the organic phosphorus mineralized during incubation, (b) the organic phosphorus hydrolyzed during extraotion, and (c) the change in extractability of inorganic phosphorus during incubation. A decrease in organic phosphorus will be an estimate of the summation of the same three factors plus the change in extractability of organic phosphorus during incubation. Since the interest lies in mineralization of organic phosphorus as a factor causing an increase in extractable inorganic phosphorus and a decrease in extractable organic phosphorus, the effects of the other factors should be minimized.

When weak acids and alkalies are used as extractants, the probability that a fraction of the organic phosphorus is hydrolyzed by these extractants is relatively low. On the other hand, the solubility of soil inorganic phosphorus in these extractants might change as a result of incubation. If this change involves an increase in soluble inorganic phosphorus, it will lead to an overestimation of the amount of organic phosphorus mineralized during incubation when the latter is estimated by the increase in extractable inorganic phosphorus upon incubation. However, any change in solubility of soil inorganic phosphorus during incubation will not bias the estimate of the amount of organic phosphorus mineralized during incubation, if the mineralization is estimated by the decrease in extractable organic phosphorus upon incubation. On the other hand, if the solubility of organic phosphorus changes as a result of incubation, this change will not bias the estimate of the amount of inorganic phosphorus mineralized during incubation when the amount mineralized is estimated by the increase in extractable inorganic phosphorus upon incubation. But any increase in solubility of organic phosphorus during incubation would lead to an underestimation of the amount of the organic phosphorus mineralized when the mineralization is estimated by the decrease in extractable organic phosphorus resulting from incubation.

A possible hydrolysis of organic phosphorus during extraction would result in an underestimation of the amount of organic phosphorus mineralized during incubation, provided the hydrolyzed fraction of organic phosphorus is included in the fraction of organic phosphorus mineralized during incubation. Such hydrolysis would affect estimates obtained from measurements of the increase in extractable inorganic phosphorus as well as the decrease in extractable organic phosphorus.

The fractions of both inorganic and organic phosphorus which are not soluble in strong acids and alkalies are not expected to undergo any change in resistance to solution as a result of incubation. Therefore, when strong extractants are being used, the data for mineralization of organic phosphorus are not likely to be affected by changes in solubility of inorganic and organic phosphorus during incubation. On the other hand, the probability that organic phosphorus will be hydrolyzed during extraction increases with the strength of the extracting solutions. Hence on the basis of these considerations it appears that unless some means can be found to obviate the possible sources of error the most suitable extraction procedure will represent a compromise that minimizes the net error.

Methods of Soil Extraction

During the period that a greenhouse experiment was conducted to obtain estimates of phosphorus availability in the soils used in this investigation (see next section), samples of these soils were incubated in the greenhouse. The soil samples and corresponding soils in which the crop grew were thus exposed to the same temperature fluctuations. Estimates of the amount of organic phosphorus mineralized during the growth period of the crop could be obtained by carrying incubated and nonincubated samples through the same extraction procedure after the incubation period. It was decided to extract inorganic phosphorus in the manner described by Mehta et al.(1954) in their method for determining total organic phosphorus in soils. In this procedure 1 - gm. samples of soil are extracted with 10 ml. of concentrated hydrochloric acid on a steam plate in such a way that after 10 minutes the extract has reached a temperature of 70°C. Another 10 ml. of hydrochloric acid are added to the sample bottles, and the latter are allowed to stand at room temperature for 1 hour. After that the content of the bottles is transferred to a Whatman No. 44 filter paper, and the filtrate is collected in a 500 - ml. volumetric flask. The soil on the filter paper is washed several times with 1 N hydrochloric acid, and the washings are collected in the volumetric flask. The extract is made up to volume, and inorganic orthophosphate in the extract is determined colorimetrically as described in the next section.

When the mineralization of organic phosphorus in the samples of soils incubated in the greenhouse was estimated by the concentrated hydrochloric acid extraction method, the apparent mineralization was found to be relatively small and in some instances was negative, as can be seen in Tables 7 and 10. From these results the idea arose that possibly a part of the organic phosphorus which is mineralized during incubation is hydrolyzed by the concentrated hydrochloric acid in nonincubated samples, in which case mineralization of organic phosphorus during incubation is confounded with hydrolysis of organic phosphorus during extraction. If all the organic phosphorus mineralized during incubation were hydrolyzed by the concentrated hydrochloric acid in nonincubated samples, no difference would be found between the amounts of extractable inorganic phosphorus in incubated and nonincubated samples. The frequent negative results can be accounted for on the basis that the experimental error of the mineralization measurements is relatively high because the mineralization is estimated by the difference between two large numbers. The high error will result in the estimation of small positive changes as negative changes in some instances.

As stated before, hydrolysis of organic phosphorus by extractants can probably be minimized by using weak extractants. Bower (1949) and Thompson and Black (1947) used 1 N sulfuric acid and van Diest (1955) used 1 N hydrochloric acid. With both extractants there is a possibility that the solubility of inorganic and organic phosphorus increases as a result of incubation, as was explained before.

To investigate possible changes in phosphorus solubility during incubation, samples of two alkaline soils and two acid soils were selected. One-gm. samples of these soils were incubated for 1 week at 50°C. After this incubation period the amounts of inorganic phosphorus extracted by 1 N sulfuric acid and 1 N hydrochloric acid were determined and compared with the amounts extracted from nonincubated samples (Table 1). After these extractions the soil samples were dried and extracted with concentrated hydrochloric acid and 0.5 N sodium hydroxide, according to Mehta et al. (1954). If the phosphorus solubility in 1 N acids does not change during incubation, the amounts of inorganic phosphorus not extracted by the strong acid and alkali should be the same for incubated and nonincubated

Table 1. Inorganic P extracted from incubated and nonincubated soils by two different weak acid extractants after an incubation period of 1 week at 50°C

			Phosphorus extracted from soil, p.p.m.			
			1 N HCl as extractant		1 N H_2SO_4 as extractant	
Soil No.	Soil type	pH	Inc.	Noninc.	Inc.	Noninc.
F 2863	Grundy s.l.[a]	6.3	517	490	549	524
F 2868	Harpster s.c. loam[b]	7.5	562	477	568	469
F 2880	Ida s.l.	8.0	667	651	678	666
F 2884	Lindley s.l. subsoil	6.5	400	401	424	435

[a]silt loam

[b]silty clay loam

samples of the same soil, provided that (a) the concentrated acid and alkali do not hydrolyze any organic phosphorus not extracted by the weak acid, (b) the extractability of inorganic phosphorus by concentrated hydrocloric acid and 0.5 N sodium hydroxide is not affected by incubation, (c) none of the inorganic phosphorus which originated from mineralization of organic phosphorus during incubation reacts with the soil in such a way that it becomes insoluble in the weak acid extractant.

In respect to the first condition, if a part of the organic phosphorus that is mineralized during incubation is hydrolyzed in nonincubated samples by the strong acid and alkali, then the amount of inorganic phosphorus extracted by the strong acid and alkali will be larger in nonincubated than in incubated samples. Regarding the second condition, a decrease in extractability of inorganic phosphorus by the strong acid and alkali as a result of incubation would have the same effect; that is, it would cause the amount of inorganic phosphorus extracted by the strong acid and alkali in nonincubated samples to exceed that in incubated samples. On the other hand, an increase in extractability of inorganic phosphorus would have the opposite effect. As for the third condition, if a fraction of the inorganic phosphorus which originated from mineralization of organic phosphorus during incubation becomes insoluble in the weak acid, it will probably be extracted by the strong acid and alkali, causing the amount of inorganic phosphorus extracted by the strong acid and alkali from the incubated soil to exceed that extracted from the nonincubated soil. Hence the difference in amount of inorganic phosphorus extracted from incubated and nonincubated samples with the strong acid - alkali treatment after the weak - acid treatment will be the net result of three effects, one of which causes the values for nonincubated soil to exceed those for incubated soils, one of which causes the values for incubated soils to exceed those for nonincubated soils, and one of which may have an effect in either direction.

The results of Table 2 show that in most cases the amount of inorganic phosphorus extracted by the strong acid and alkali was higher in the nonincubated samples than in the incubated samples. With the alkaline soils and 1 N hydrochloric acid as a first extractant, the difference is statistically significant at the 5 percent level. In the case of 1 N sulfuric acid as a first extractant, the difference is significant only for the Harpster silty clay loam. For the acid soils the differences are not significant. Since usually the strong acid and alkali removed more inorganic phosphorus from the nonincubated than from the incubated samples, it appears that an increase in extractability of inorganic phosphorus by the 1 N acids as a result of incubation might occur. A part of the difference might be the result of hydrolysis of organic phosphorus by the strong acid and alkali extractants. This experiment provides no means to differentiate between the two possible causes, but it casts doubt upon the usefulness of weak acid extractants in studies on the mineralization of organic phosphorus during incubation.

Table 2. Inorganic P extracted from incubated and non-incubated soils by concentrated HCl and 0.5 N NaOH after extraction with 1 N HCl or 1 N H_2SO_4

		Phosphorus extracted from soil, p.p.m.			
		1 N as first extractant		1 N H_2SO_4 as first extractant	
Soil No.	Soil type	Inc.	Noninc.	Inc.	Noninc.
F 2863	Grundy s.l.[a]	194	199	158	158
F 2868	Harpster s.c. loam[b]	74	93	75	104
F 2880	Ida s.l.	56	70	44	45
F 2884	Lindley s.l. subsoil	178	185	150	149

[a]silt loam

[b]silty clay loam

Thompson *et al.* (1954) extracted soils with 1 *N* hydrochloric acid followed by 0.5 *N* ammonium hydroxide. They assumed the difference in amounts of inorganic phosphorus in the combined extracts of incubated and nonincubated samples to be the result of mineralization of organic phosphorus. The weak acid extraction was a cold extraction, whereas the alkali extraction consisted of extracting the soil with 0.5 *N* ammonium hydroxide at a temperature of 90°C for 15 hours. During this hot extraction some of the organic phosphorus might be hydrolyzed and if this happens cold ammonium hydroxide might be a better extractant. However, the possibility exists that an extraction with 1 *N* acid followed by a cold extraction with 0.5 *N* ammonium hydroxide is not rigid enough to extract the same fraction of inorganic and organic phosphorus in incubated and nonincubated samples.

To investigate the comparative extractability in incubated and nonincubated samples with cold ammonium hydroxide extraction, 1-gm. samples of Grundy silt loam and Harpster silty clay loam were incubated for 5 days at 45°C. The samples were moistened to saturation and the caps of the sample bottles were screwed on loosely to permit aeration. The water lost by evaporation was replaced daily. (Usually the samples contained about 30 percent water on the dry weight basis at the end of a day's incubation). At the end of the incubation period the samples were extracted with 20 ml. of 1 N sulfuric acid followed by 8 washings with 10-ml. portions of 1 N sulfuric acid. The soil samples then were extracted with two 30-ml. portions of 0.5 N ammonium hydroxide at room temperature for 6 and 10 hours respectively, followed by two washings with 20-ml. portions of 0.5 N ammonium hydroxide. Nonincubated samples were carried through the same extraction procedure. The acid and alkali extracts were combined shortly before analysis.

With both soils the total amount of phosphorus extracted from incubated samples was significantly larger than that extracted from nonincubated samples, as shown in Table 3. These data supply evidence that the extrac-

Table 3. Total P extracted from incubated and nonincubated samples of two soils by 1 N H_2SO_4OH at room temperature after a 5-day incubation period at 45°C

Soil No.	Soil type	Total P extracted, p.p.m.	
		Incubated	Nonincubated
F 2863	Grundy silt loam	920	860
F 2868	Harpster silty clay loam	908	870

tability of either inorganic phosphorus or organic phosphorus or both increases during incubation when this extraction procedure is used, thereby indicating that this procedure is unsuitable for evaluating the amount of organic phosphorus mineralized during incubation.

Subsequently, the comparative extractability of phosphorus was tested in incubated and nonincubated samples of a number of soils with 1 N hydrochloric acid and hot ammonium hydroxide as used by Thompson et al. (1954). Table 4 shows that the total amounts of phosphorus extracted

Table 4. Total P extracted from incubated and nonincubated samples of soil by means of 1 N HCl at room temperature and 0.5 N NH_4OH at 90°C after a 7-day incubation period at 40°C

Soil No.	Soil type	Total P extracted, p.p.m. Incubated	Total P extracted, p.p.m. Nonincubated
F 2868	Harpster silty clay loam	1016	988
F 2869	Harpster silty clay loam	667	668
F 2870	Harpster silty clay loam	656	648
F 2871	Harpster silty clay loam	773	773
F 2872	Harpster silty clay loam	745	742
F 2873	Harpster silty clay loam	712	711
F 2867	Hamburg silt loam	737	737
F 2854	Clarion silt loam	397	392
F 2855	Clarion silt loam	322	327
F 2866	Clarion silt loam	261	260
F 2867	Clarion silt loam	672	682
F 2863	Grundy silt loam	955	954

from incubated and nonincubated samples of soil did not differ significantly. No significant interaction was found between soil series and soil treatment. The procedure in which a hot ammonium hydroxide extraction is used is thus more suitable for evaluating the amount of organic phosphorus mineralized during incubation than the cold ammonium hydroxide extraction procedure. Consequently, the former was used in the subsequent investigations.

Methods of Soil Storage

Jackman and Black (1952) reported that, when phytase activity is to be measured in soils, it appears that the most reliable results will be obtained if the measurements are made immediately after sampling without preliminary drying or storage. The activity of phytase and possibly other enzymes might be an important factor in mineralization of organic phosphorus under field conditions. Therefore, any way in handling soils that might lead to unnatural conditions might bias the interpretation of the findings. It must be recognized that in many ways the greenhouse and incubation experiments conducted in this study involve conditions that deviate from those met in the field. Nevertheless, wherever possible, unnatural conditions should be avoided, and when they are used, tests should be made to study their possible effect upon the validity of the experiments.

After the soils to be used in this investigation had been taken from the field, the main portion of the samples was dried, screened, and stored in air-dry condition. Before drying, however, a small sample of each soil was transferred to a large sample bottle and stored in a cold chamber at a temperature of 7°C. Since these samples, which were not dried, remained in a more natural condition, the results obtained with them in incubation studies might be different and more reliable than those obtained with samples that were dried and stored at room temperature.

To investigate whether the method of storage affects the amount of organic phosphorus mineralized during incubation, samples which had been stored moist and dry for 18 months were incubated for 1 week at a temperature of 40°C. After this incubation period the increase in inorganic phosphorus was measured according to a method introduced by Thompson (1950) and described in the next section. The extractants in this method are 1 N hydrochloric acid and 0.5 N ammonium hydroxide. The alkali extraction is made at 90°C for 15 hours. The results, which are averages of duplicate samples calculated on the oven-dry basis, are listed in Table 5. The average increase in extractable inorganic phosphorus as a result of incubation was 10 p.p.m. for both dry and moist soils. No significant interaction was found between soil series and methods of storage. Consequently, no preference can be given to either method of storage on the basis of this test. Since it is more convenient and time-saving to handle dry soil samples, the subsequent incubation experiments were carried out with soils that had been stored in air-dry condition. The incubation

Table 5. Inorganic P extracted from incubated and nonincubated samples of previously moist and previously dried soils by means of 1 N HCl and 0.5 N NH_4OH

Soil No.	Soil type	Inorganic P, p.p.m. Total extracted Incubated Dry	Incubated Moist	Nonincubated Dry	Nonincubated Moist	Increase upon incubation Dry	Increase upon incubation Moist
F 2848	Albaton silty clay	736	732	727	729	9	13
F 2849	Albaton silty clay	647	648	642	636	5	12
F 2850	Albaton silty clay	767	764	764	769	3	-5
F 2851	Albaton s.c.l.[a]	749	787	738	764	11	23
F 2852	Albaton silt loam	669	672	661	669	8	3
F 2853	Albaton silt loam	1450	1439	1424	1399	26	40
F 2867	Hamburg silt loam	712	709	706	708	6	1
F 2868	Harpster s.c.loam	669	690	619	650	50	40
F 2869	Harpster s.c.loam	391	424	389	423	2	1
F 2871	Harpster s.c.loam	374	365	370	359	4	6
F 2873	Harpster s.c.loam	472	481	465	472	7	9
F 2874	Harpster s.c.loam	463	453	455	450	8	3
F 2875	Harpster s.c.loam	392	391	382	375	10	16
F 2893	Onawa s.c.loam	579	583	575	575	4	8
F 2894	Onawa s.c.loam	606	599	594	594	12	5
F 2895	Onawa s.c.loam	579	575	574	571	5	4
F 2896	Onawa s.c.loam	632	624	627	623	5	1
F 2897	Onawa s.c.loam	1054	1067	1047	1053	7	14
F 2898	Onawa silt loam	736	731	728	724	8	7
F 2899	Onawa v.f.s.loam[b]	624	623	614	615	10	8
F 2901	Sarpy silty clay	674	680	673	674	1	6

[a]silty clay loam

[b]very fine sandy loam

method and extraction procedure used by Thompson (1950) were used with a few modifications which will be described in the next section.

Greenhouse Experiments

The primary objective of this portion of the investigation was to obtain reliable estimates of phosphorus availability in a wide variety of Iowa soils. A new technique was applied to attain this goal in that only a small part of the medium in which plants grew consisted of soil. When a minimum quantity of soil is used, the contact between soil and roots is likely to be more intensive than when ample quantities of soil are present, provided that conditions for development of the root system are favorable.

When a small quantity of soil and a large quantity of quartz sand are added to No. 10 cans, the placement of the soil may affect the intensity of the root-soil contact. In a preliminary experiment the reaction of two crops to different placements of soil and sand were tested. Grain sorghum and rice, two crops with medium-size seeds, were used. The considerable amount of phosphorus in the large seeds of some crops makes these undesirable for the purpose at hand. On the other hand, if the seeds are too small, the plants may not survive during the first few days after emergence when the contact between roots and soil is still limited.

The total amount of soil used in the No. 10 cans was either 200 gm. or 400 gm. The amount of sand with which the soil was mixed varied from 1000 to 2300 gm. In all instances the bottom part was filled with sand, the amount varying with the amount used in the soil-sand mixture.

A few days after emergence the top and root parts of the plants were inspected. Since it was doubtful whether in some of the poorer soils the plants would survive with only 200 gm. of soil present, it was decided to use 400 gm. of soil in the subsequent experiment. Sorghum plants showed the best germination and for that reason were selected for later use.

MATERIALS AND METHODS

Greenhouse Experiment

The soils used in this experiment were all collected in Iowa and are listed in Tables 5 and 8. The containers that were used were No. 10 cans lined with polyethylene bags. To each can, 2300 gm. of quartz sand were added first. Four hundred gm. of soil and 1000 gm. of sand were mixed and placed on the layer of pure sand. Three hundred ml. of distilled water followed by 300 ml. of a Hoagland and Arnon nutrient solution lacking P (1950) were added to the cans. One ml. of a solution containing 36.4 gm. of the sodium-iron salt of ethylenediaminetetraacetic acid per liter was added to each liter of nutrient solution to replace the iron source used by Hoagland and Arnon.

Thirty-five sorghum seeds of the Redbine-60 variety were laid out in a circular pattern on the soil-sand mixture. The seeds were covered with 300 gm. of sand, and 100 ml. of water were added. Shortly after emergence the number of plants was reduced to 30.

Nine replicates of each soil were prepared in the above fashion. They were placed in the greenhouse in a randomized block design. One control, which contained only sand, was added to each block. Pots within blocks were rerandomized regularly. Water losses were estimated daily by weighing a few pots, and losses in weight were adjusted by addition of distilled water. The experiment was started on September 13, 1955. On October 12, 17 mgm. of nitrogen and 47 mgm. of potassium were added to each pot as potassium nitrate, and 5 mgm. of magnesium and 7 mgm. of sulfur were added as magnesium sulfate.

During the experiment the air temperature in the greenhouse ranged from 10°C to 45°C. On sunny days temperatures within the pots were found to be 5-11°C higher than the air temperature. On October 8, a bacterial blight started to develop. Limited watering and cool temperature for a few days aided in checking this disease. Occasionally Nicofume fumigations were applied to control army worms.

Plants were allowed to grow until growth in all pots had almost stopped. For soils low in available phosphorus this stage was reached a few weeks earlier than for soils with an ample supply of available phosphorus.

Harvesting was started on November 7. The plants were cut off at the point where the stalk was connected to the seed. The plant material was dried in paper bags in a forced-air-draft dryer for 48 hours at 65°C. Shortly before weighing, the bags were transferred to a disiccator. After weighing the samples were ground in a Wiley mill and stored in sample bottles for subsequent analysis.

To determine phosphorus the plant material was placed in an oven at 65°C for 2 days. The nine samples of one soil were dried at the same time. Two-gm. samples of replicates of each soil were combined, placed in a milk bottle and mixed in an end-over-end shaker for 2 hours. The combined samples were dried again at 65°C for 24 hours. The oven-dried samples were cooled in a desiccator prior to weighing the analytical sample. Then, following the procedure described by McCants (1955), 1 gm. from each sample was weighed out on an analytical balance and transferred to a 50-ml. beaker. Ten ml. of a 5 percent magnesium acetate solution were added to each beaker. The content of the beakers was evaporated to dryness and the beakers were placed in a cold muffle furnace. The temperature of the furnace was raised gradually to 200°C and the beakers were kept at that temperature until charring was completed. The temperature then was raised to 500°C and the beakers were kept at that temperature for 2 hours. After cooling, the beakers were removed from the furnace, the ash was moistened with 1 _N_ nitric acid, and the acid was evaporated on the steam plate. The beakers were then placed again in the furnace and heated at 500°C for 1 hour. After cooling, the ash was dissolved in 10 ml. of 1 _N_ hydrochloric acid on the steam plate, the content of the beakers was transferred to 500-ml volumetric flasks, the beakers were policed and washed, and the washings were added to the volumetric flasks. After dilution to volume, the content of the flasks was thoroughly mixed and the suspended material was allowed to settle before aliquots were taken for analysis.

To determine the quantity of inorganic phosphorus in the extract, a 10-ml aliquot was transferred to a colorimeter tube. One drop of para-nitrophenol solution was added, and the acidity of the solution was adjusted to about pH 3 by adding 5 N and 1 N hydrochloric acid to the point where the color of the indicator disappeared. The solution was diluted to 40 ml. with water and 5 ml. of ammonium molybdate-hydrochloric acid solution (Mehta et al. 1954) were added. The tube was shaken end over end. In these and all following colorimetric determinations of phosphorus the technique of Dyer and Wrenshall (1938) was used. This technique permits the colorimetric determination of inorganic orthophosphate in the resulting solutions, which were sometimes strongly colored. After the colorimeter had been adjusted to full scale reading upon inserting the photometer tube, 3 drops of stannous chloride-hydrochloric acid solution (Mehta et al. 1954) were added and the tube was shaken end over end. After 10 minutes, during which the blue color developed, the decrease in percentage transmittance was read in the colorimeter. The concentration of inorganic orthophosphate in the solution was calculated from a calibration made using the same reagents as for the unknowns with addition of increasing quantities of potassium dihydrogen phosphate.

Soil Phosphorus Fractionation

The method described by Bray and Kurtz (1945) for determining the inorganic phosphorus soluble in 0.03 N ammonium fluoride and 0.025 N hydrochloric acid was used in a slightly modified form. The modification was the use of 1 ml. of saturated boric acid solution in the colorimetric phosphorus determination to eliminate fluoride interference. The colorimetric determinations of inorganic orthophosphate were made as described before.

As a second laboratory method for estimating inorganic phosphorus availability of soils, the resin method described by Amer et al. (1955) was used. One gm. of soil, which had passed through a 40-mesh screen and 1 gm. of Dowex-2 anion-exchange resin consisting of particles larger than 32 mesh, were transferred to a 250-ml. Erlenmeyer flask. One hundred ml. of water were added and the flasks were shaken for 2 hours. After separating the resin from the soil by washing with water on a 40-mesh screen the resin was dried and transferred to a 250-ml. Erlenmeyer flask. Twenty-five ml. of a 10 percent solution of sodium chloride were added and the flasks were heated on a steam plate for 45 minutes. The content of the flasks was transferred to Whatman No. 44 filter paper, and the filtrate was collected in a 100-ml. volumetric flask. The resin on the filter paper was washed with extra portions of the sodium chloride solution until the volume of the filtrate totaled 100 ml. Twenty-ml. aliquots of the filtrate were transferred to colorimeter tubes and inorganic orthophosphate was determined in the usual manner. All determinations were made in duplicate.

A partial extraction of the organic phosphorus was made by heating 0.5 gm. of soil with 100 ml. of a solution containing 1 percent potassium carbonate and 2 percent sodium hydroxide for 1 hour at 85°C, in a covered flask. After the flask had cooled it was shaken and the suspension was filtered through a Whatman No. 44 filter paper. The organic phosphorus in the alkaline extract was partitioned into two fractions, according to its behaviour toward hypobromite. The quantity of organic phosphorus hydrolyzed by hypobromite was determined by transferring a 10-ml. aliquot of the alkaline solution to a 50-ml.

volumetric flask, to which 1 ml. of bromine-saturated water was added. The solution was boiled for 4 minutes on an electric hot plate. Two ml. of 5 N hydrochloric acid and 0.5 ml. of a 10 percent sodium sulfite solution were added consecutively, and the solution was boiled for 3 minutes on the electric hot plate to expel the bromine and sulphur dioxide. After the flask had cooled, inorganic orthophosphate was determined as before. Determinations were made in duplicate. The difference between the quantities of inorganic phosphorus found after and before the hypobromite treatment was considered to represent the quantity of organic phosphorus hydrolyzed by hypobromite.

Mineralization during Incubation

Ten days after the greenhouse experiment was started, 2-gm. samples of all soils employed in the experiment were incubated in sample bottles. The samples were moistened to saturation, and the lids were screwed on loosely to permit aeration. When the samples were found to have lost much of the moisture, they were moistened again to saturation. The samples were exposed to the same fluctuations in temperature as the soils in the cans. The bottles were protected against direct radiation by a cover of cardboard, in which openings were cut to permit air movement along the sample bottles. Two weeks after harvesting of the plants had started, one replicate of each soil was taken from the greenhouse and analyzed in the laboratory for the amount of organic phosphorus mineralized during the incubation period in the greenhouse.

Ten ml. of concentrated hydrochloric acid were added to sample bottles containing incubated and nonincubated samples of each soil. The bottles were heated on an electric hot plate in such a way that after ten minutes the content of the bottles had reached a temperature of 70°C. Another 10-ml. aliquot of concentrated hydrochloric acid was added and the bottles were kept at room temperature for 1 hour.

After 1 hour the content of the bottles was transferred to a Whatman No. 44 filter paper, and the filtrates were collected in 500-ml. volumetric flasks. The soils on the filter paper were washed with five 20-ml. portions of 1 N hydrochloric acid. The solution in the flasks were made up to volume and shaken. Ten-ml. aliquots were transferred to colorimetric tubes and inorganic orthophosphate was determined as usual.

In a later experiment for evaluating the amount of organic phosphorus mineralized during incubation, 1-gm. samples of soil were weighed on an analytical balance and transferred to sample bottles. The soil in the bottles was moistened to saturation by adding 0.45 - 0.65 ml. of water depending on the soil type and the samples were incubated for 1 week at 40°C. The lids of the sample bottles were screwed on loosely. The daily water loss due to evaporation varied between 40 and 60 percent. The water lost was replaced every day during a period of 15 minutes in which the samples were aerated. Samples which were not incubated were weighed out at the same time. Determinations were made in quadruplicate.

After 1 week of incubation the samples were analyzed according to the method described by Thompson (1950) and Thompson et al. (1954). Since several changes have been made, the procedure will be described in detail. Twenty-five ml. of 1 N hydrochloric acid were added to the sample bottles. The bottles were placed on the steam plate for 5 minutes, after which soil and extract were transferred to a Whatman No. 42 filter paper. The soil was leached with another 25-ml. aliquot of 1 N hydrochloric acid, followed by five consecutive leachings with 10-ml. aliquots of 1 N hydrochloric acid. Finally the soils were washed twice with distilled water. All filtrates were collected in a 500-ml. volumetric flask and made up to volume. The soil and filter paper were transferred to 500-ml. Erlenmeyer flasks graduated at 450 and 500 ml., whereupon 450 ml. of 0.5 N ammonium hydroxide were added to the flasks. These were shaken vigorously and then fitted with Bunsen valves and placed in an oven at 90°C. After 15 hours the ammonia digests were cooled in a water bath and 5.5 gm. of ammonium chloride were added. The solutions were made to a volume of 500 ml., shaken vigorously, and allowed to stand for 10 minutes before filtering through Whatman No. 44 filter paper. Approximately 50 ml. of the ammonia extract were filtered and saved for analysis. The nonincubated samples were carried through the same extraction procedure. Ten-ml. aliquots of both acid and alkali extracts were transferred to a colorimeter tube and inorganic orthophosphate was determined as described before. Using this method, Thompson obtained 100 percent recovery of added inorganic phosphorus.

For the determination of total phosphorus, 5-ml. aliquots of both extracts of the incubated and nonincubated soil samples were transferred to a 50-ml. beaker. One ml. of a 10 percent magnesium nitrate solution was added to the beaker. The solution was evaporated on the steam plate and ignited in the muffle furnace. The temperature of the furnace was raised to 200°C and kept at this temperature for 1 hour, after which the temperature was raised to 500°C. After 2 hours at this temperature the beakers were cooled. The ash was dissolved in 5 ml. of 1 N hydrochloric acid and digested on the steam plate for 10 minutes. The content of the beakers was transferred quantitatively to colorimeter tubes and inorganic orthophosphate was determined as before.

Organic phosphorus mineralization may be estimated in three ways; namely, by the increase in extractable inorganic phosphorus as a result of incubation, by the decrease in extractable organic phosphorus as a result of incubation, or by the average of the increase in extractable inorganic phosphorus and the decrease in extractable organic phosphorus. If, as a result of incubation, the extractability of inorganic and organic phosphorus increases, the mineralization of organic phosphorus, as estimated from the increase in inorganic phosphorus, will be overestimated, whereas the mineralization of organic phosphorus as estimated from the decrease in organic phosphorus will be underestimated. Thus in this case the average of the two estimates will likely be a better estimate of the amount of organic phosphorus mineralized than either one of the two estimates. If, as a result of incubation, the extractability of the inorganic and organic phosphorus decreases, the mineralization of organic phosphorus as estimated from the increase in extractable inorganic phosphorus will be underestimated, whereas the mineralization of organic phosphorus as estimated from the decrease in organic phosphorus will be overestimated. In this case it is also likely that the average is a better estimate of the amount of organic phosphorus mineralized during incubation than either one of the two estimates. If, as a result of incubation, the extractabilities of the inorganic and organic phosphorus go in opposite directions, both estimates will be either overestimated or underestimated depending on the direction of the errors. In such a case the size of the error associated with the average of the two estimates will probably be intermediate between the two errors associated with either one of the two estimates.

The inorganic and organic phosphate radicles in a particular soil are likely to be combined with the same type of cation or types of cations. Therefore, the solubility of both inorganic and organic phosphorus will probably mainly be determined by the solubility of this cation or these cations in an extractant. Consequently, if the extractability of inorganic and organic phosphorus changes during incubation, the change will probably be in the same direction for both kinds of compounds, depending on the change in solubility of the cation or cations with which the inorganic and organic phosphorus radicles are associated. Thus, a change in opposite directions does not seem to be likely and under most circumstances the average of the increase in extractable inorganic phosphorus and the decrease in extractable organic phosphorus as a result of incubation will probably be a better estimate of the amount of organic phosphorus mineralized during incubation than the single values of which the average is composed.

Availability Coefficients

One-gram samples of soil were transferred to 250-ml. Erlenmeyer flasks, after which 0.6-ml. aliquots of a solution containing 100 p.p.m. of phosphorus as potassium dihydrogen phosphate were added to three samples of each soil. To three other samples, which were used as controls, 0.6-ml. aliquots of water were added. The samples were incubated for 1 week at a temperature of 40°C. The stoppers were placed on the Erlenmeyer flasks in such a way that some movement of air could take place. The daily water loss due to evaporation varied between 40 and 70 percent of the quantity added. The water lost was replaced every day during a period of 15 minutes in which the samples were aerated.

After 1 week of incubation, inorganic phosphorus was extracted according to the resin method as described before. The fractional recovery of the added phosphorus was determined by dividing the difference in inorganic phosphorus extracted from samples to which phosphorus had been added and from control samples by the quantity of phosphorus added.

The fractional recovery of the added phosphorus is assumed to be proportional to the availability coefficient of the organic phosphorus mineralized during incubation. Thus by multiplying the total amount of organic phosphorus mineralized during incubation by the fractional recovery of added phosphorus, the resulting figure should be proportional to the availabilities or effective quantities of mineralized organic phosphorus.

For a number of acid soils the fractional recovery was negative. In consequence, the figures entered in Table 9 for the relative availabilities of organic phosphorus in these soils are negative. For these soils, availability of soil inorganic phosphorus would be expected to decrease as a result of organic phosphorus mineralization. For a number of alkaline soils, on the other hand, the fractional recovery exceeded unity and the relative availability of the mineralized organic phosphorus in Table 13 is estimated to exceed the actual quantity.

Statistical Analyses

Multiple linear regression equations were calculated using as dependent variables the data on phosphorus absorbed by the plants in the greenhouse experiment and as independent variables the laboratory data on the quantities of soil phosphorus found in the various chemical fractions or mineralized during incubation (Snedecor, 1956, pp. 431-446). Simple linear regression equations were calculated, using as dependent variables the data on phosphorus absorbed by the plants and as independent variables the estimates of inorganic phosphorus availability according to the Bray and Kurtz method and the resin method (Snedecor, 1956, pp. 122-126), and the difference between the correlation coefficients obtained with both methods was tested (Snedecor, 1956, pp. 178-180). Finally, the difference between the linear regression of yield of phosphorus on inorganic phosphorus extracted by the two methods was tested (Snedecor, 1956, pp. 394-400).

RESULTS

Acid Soils

Table 6 shows the soil number, soil type, and pH of the acid soils, together with the amounts of inorganic phosphorus and organic phosphorus extracted from the soils according to the procedure described by Mehta et al. (1954). In Table 7 the yield-of-phosphorus data as obtained in the greenhouse experiment are listed with two fractions of inorganic phosphorus and one fraction of organic phosphorus. Multiple-regression equations were calculated from these data. The yield-of-phosphorus data are used as dependent variables, and the data on the different fractions of soil phosphorus are used as independent variables.

In the first equation, the data on inorganic phosphorus obtained with the Bray and Kurtz method, and the average result on increase in extractable inorganic phosphorus and decrease in extractable organic phosphorus upon incubation, as obtained with the combined acid and alkali extraction method, are used as independent variables. The equation obtained from these data is as follows:

$$\hat{Y} = \underset{\pm 0.02}{0.29\ f_1} + \underset{\pm 0.06}{0.17\ f_6} - 0.74 \qquad (1)$$

Table 6. Inorganic and organic phosphorus extracted from acid soils by method of Mehta et al. (1954)

Soil No.	Soil type	pH	Inorganic P extracted, p.p.m.	Organic P extracted, p.p.m.
F 2854	Clarion silt loam	6.4	279	257
F 2855	Clarion silt loam	6.2	150	262
F 2856	Clarion silt loam	6.6	160	212
F 2857	Clarion silt loam	6.4	559	225
F 2858	Edina silt loam	6.8	253	291
F 2859	Edina silt loam	6.6	222	238
F 2860	Edina silt loam	6.3	145	231
F 2861	Fayette silt loam, C-hor.	5.4	396	36
F 2862	Fayette silt loam	7.0	389	295
F 2863	Grundy silt loam	6.3	758	366
F 2864	Haig silt loam	5.7	286	278
F 2865	Haig silt loam	6.8	416	204
F 2866	Haig silt loam	6.0	184	272
F 2883	Lindley silt loam	6.8	213	219
F 2884	Lindley silt loam C-hor.	6.5	653	39
F 2886	Nicollet loam	6.6	503	257
F 2887	Nicollet loam	6.4	189	267
F 2888	Nicollet loam	6.7	160	228
F 2889	Nicollet loam	6.7	276	256
F 2901	Seymour silt loam	7.0	161	183
F 2902	Shelby loam	6.0	117	171
F 2903	Shelby loam	5.4	125	143
F 2904	Shelby loam, C-hor.	5.5	222	30
F 2905	Taintor silt loam	6.0	259	329
F 2906	Tama silt loam	5.8	289	167
F 2907	Tama silt loam	6.3	859	285
F 2908	Tama silt loam	6.5	265	235
F 2909	Wabash silty clay loam	6.3	475	265
F 2910	Wabash silty clay loam	7.0	386	306
F 2911	Webster silty clay loam	6.6	253	255
F 2912	Webster silty clay loam	6.8	245	263
F 2913	Webster silty clay loam	6.9	287	261
F 2916	Weller silt loam	6.0	215	209
F 2917	Weller silt loam, C-hor.	6.5	229	39

Table 7. Yield of phosphorus in plants and phosphorus fractions in acid soils

Soil No.	Soil type	Yield of P in plants per culture, mg.	Phosphorus fractions in soils, p.p.m.[a] f_1	f_2	f_6
F 2854	Clarion silt loam	4.94	15.5	13.8	5
F 2855	Clarion silt loam	1.09	4.8	4.3	0
F 2856	Clarion silt loam	2.49	8.2	7.8	9
F 2857	Clarion silt loam	10.29	32.1	25.3	3
F 2858	Edina silt loam	9.17	30.2	25.0	15
F 2859	Edina silt loam	7.26	16.7	12.8	7
F 2860	Edina silt loam	2.88	6.2	5.1	6
F 2861	Fayette silt loam, C-hor.	2.93	23.7	8.0	0
F 2862	Fayette silt loam	7.29	20.7	20.1	33
F 2863	Grundy silt loam	23.91	95.2	76.9	12
F 2864	Haig silt loam	7.60	24.6	22.5	7
F 2865	Haig silt loam	7.30	27.0	22.8	14
F 2866	Haig silt loam	2.86	7.0	7.0	7
F 2883	Lindley silt loam	4.28	7.8	7.8	11
F 2884	Lindley silt loam, C-hor.	8.67	27.3	16.7	1
F 2886	Nicollet loam	5.14	12.1	11.8	6
F 2887	Nicollet loam	2.20	6.6	7.0	5
F 2888	Nicollet loam	0.72	4.2	3.9	1
F 2889	Nicollet loam	4.78	14.6	13.1	8
F 2901	Seymour silt loam	2.36	7.4	7.0	8
F 2902	Shelby loam	1.34	5.9	3.9	4
F 2903	Shelby loam	2.12	5.3	6.6	9
F 2904	Shelby loam, C-hor.	0.43	2.8	2.1	1
F 2905	Taintor silt loam	4.14	11.3	8.5	10
F 2906	Tama silt loam	3.77	9.9	8.0	3
F 2907	Tama silt loam	33.73	73.4	80.1	27
F 2908	Tama silt loam	5.44	13.0	12.3	8
F 2909	Wabash silty clay loam	8.73	22.8	17.5	4
F 2910	Wabash silty clay loam	8.57	27.3	29.9	12
F 2911	Webster silty clay loam	3.99	11.1	10.9	3
F 2912	Webster silty clay loam	1.22	6.6	10.2	4
F 2913	Webster silty clay loam	1.11	5.3	6.4	9
F 2916	Weller silt loam	1.71	5.2	4.6	11
F 2917	Weller silt loam, C-hor.	0.55	3.1	1.7	3

[a] f_1= inorganic phosphorus by Bray and Kurtz method; f_2= inorganic phosphorus by resin method; f_6= average of increase in extractable inorganic P and decrease in extractable organic P upon incubation; 1 N HCl and hot 0.5 N NH_4OH as extractants

The figures directly below the regression coefficients are the standard errors associated with the respective coefficients. The significance of the regression of yield of phosphorus on the individual fractions of soil phosphorus can be found approximately from the ratio of the regression coefficient to its standard error by the use of the "t"-table.

The regression of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, independent of f_6, is significant at the 1 percent level; likewise, the regression of yield of phosphorus on f_6, the average of increase in extractable inorganic phosphorus and decrease in extractable organic phosphorus upon incubation, independent of f_1, is significant at the 1 percent level.

In the second equation, the data on inorganic phosphorus obtained with the resin method and the same values for f_6 are used as independent variables. The equation obtained from these data is as follows:

$$\hat{Y} = \underset{\pm 0.02}{0.36}\, f_2 + \underset{\pm 0.05}{0.03}\, f_6 - 0.02 \qquad (2)$$

The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_6, is significant at the 1 percent level. The regression of yield of phosphorus upon f_6, the average of increase in extractable inorganic phosphorus and decrease in extractable organic phosphorus upon incubation, independent of f_2, is not significant at the 5 percent level.

In the first equation, significant additional information concerning the availability of soil phosphorus to plants beyond that measured with the Bray and Kurtz method can be gained by determining the mineralization of organic phosphorus during incubation. In the second equation, however, for which the available inorganic phosphorus is measured with the resin method, the measurements of mineralization of organic phosphorus during incubation do not yield any significant additional information on the availability of soil phosphorus to plants.

In the third equation, the data on inorganic phosphorus obtained with both the Bray and Kurtz method and the resin method, and the values for f_6 are used as independent variables. The following equation was obtained:

$$\hat{Y} = -0.05\, f_1 + 0.42\, f_2 + 0.01\, f_6 + 0.12 \qquad (3)$$
$$\pm 0.07 \qquad \pm 0.08 \qquad \pm 0.05$$

The negative regression of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, independent of f_2 and f_6, is not significant at the 5 percent level. The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_1 and f_6, is significant at the 1 percent level. The regression of yield of phosphorus on f_6, the average of increase in extractable inorganic phosphorus and decrease in extractable organic phosphorus upon incubation, independent of f_1 and f_2, is not significant at the 5 percent level.

The tests of significance on the foregoing equation show that once the information associated with the resin method has been obtained, no significant additional information of value in predicting the yield of phosphorus is gained from the measurements of either the phosphorus extracted by the Bray and Kurtz method or the mineralization of organic phosphorus during incubation. Because of this evidence that the resin method is more suitable for estimating phosphorus availability in acid soils than the Bray and Kurtz method, the data obtained with the former method are used in the subsequent equations on acid soils.

In Table 8 the yield-of-phosphorus data are listed together with four fractions of organic phosphorus. In equation 4, the data obtained with the resin method and the data on the increase in extractable inorganic phosphorus upon incubation as obtained with the concentrated hydrochloric acid extraction method are used as independent variables. The equation is as follows:

$$Y = \underset{\pm 0.02}{0.37}\, f_2 - \underset{\pm 0.03}{0.04}\, f_3 \quad 0.35 \qquad (4)$$

Table 8. Yield of phosphorus in plants and phosphorus fractions in acid soils

Soil No.	Soil type	Yield of P in plants per culture, mg.	Phosphorus fractions in soils, p.p.m.[a] f_3	f_4	f_5	f_7
F 2854	Clarion silt loam	4.94	7	7	2	41
F 2855	Clarion silt loam	1.09	-8	-3	2	48
F 2856	Clarion silt loam	2.49	6	9	8	48
F 2857	Clarion silt loam	10.29	14	-2	8	50
F 2858	Edina silt loam	9.17	8	7	6	41
F 2859	Edina silt loam	7.26	1	7	6	41
F 2860	Edina silt loam	2.88	0	6	5	46
F 2861	Fayette silt loam, C-hor.	2.93	-2	0	-1	10
F 2862	Fayette silt loam	7.29	5	33	33	36
F 2863	Grundy silt loam	23.91	4	12	11	53
F 2864	Haig silt loam	7.60	1	5	9	39
F 2865	Haig silt loam	7.30	8	13	14	38
F 2866	Haig silt loam	2.86	9	5	8	45
F 2883	Lindley silt loam	4.28	9	10	11	43
F 2884	Lindley silt loam, C-hor.	8.67	-4	1	1	5
F 2886	Nicollet loam	5.14	6	6	6	32
F 2887	Nicollet loam	2.20	14	1	8	35
F 2888	Nicollet loam	0.72	1	-1	2	46
F 2889	Nicollet loam	4.78	-7	8	7	44
F 2901	Seymour silt loam	2.36	1	7	9	42
F 2902	Shelby loam	1.34	4	1	6	50
F 2903	Shelby loam	2.12	4	6	11	67
F 2904	Shelby loam, C-hor.	0.43	-4	-1	2	7
F 2905	Taintor silt loam	4.14	11	10	9	67
F 2906	Tama silt loam	3.77	3	2	4	42

[a] f_3 = increase in extractable inorganic P upon incubation; conc. HCl as extractant; f_4 = increase in extractable inorganic P upon incubation; 1 N HCl and hot 0.5 N NH_4OH as extractants; f_5 = decrease in extractable organic P upon incubation; 1 N HCl and hot 0.5 N NH_4OH as extractants; f_7 = organic P soluble in K_2CO_3 and NaOH and hydrolyzed by hypobromite

Table 8. (continued)

Soil No.	Soil type	Yield of P in plants per culture, mg.	Phosphorus fractions in soils, p.p.m.			
			f_3	f_4	f_5	f_7
F 2907	Tama silt loam	33.73	7	37	17	47
F 2908	Tama silt loam	5.44	24	7	9	35
F 2909	Wabash silty clay loam	8.73	-5	4	3	40
F 2910	Wabash silty clay loam	8.57	7	11	12	42
F 2911	Webster silty clay loam	3.99	7	2	4	42
F 2912	Webster silty clay loam	1.22	35	11	-4	45
F 2913	Webster silty clay loam	1.11	21	7	11	36
F 2916	Weller silt loam	1.71	9	8	14	44
F 2917	Weller silt loam, C-hor.	0.55	0	1	5	8

The regression of yield phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_3, is significant at the 1 percent level. The negative regression of yield of phosphorus on f_3, the increase in inorganic phosphorus extractable by concentrated hydrochloric acid upon incubation, independent of f_2, is not significant at the 5 percent level.

The data obtained with the resin method and the data on the increase in extractable inorganic phosphorus upon incubation obtained with the combined acid and alkali extraction method are used as independent variables in equation 5:

$$\hat{Y} = \underset{\pm 0.02}{0.35}\, f_2 + \underset{\pm 0.04}{0.05}\, f_4 - 0.01 \qquad (5)$$

The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_4, is significant at the 1 percent level. The regression of yield of phosphorus on f_4, the increase in inorganic phosphorus extracted upon incubation by the combined acid and alkali extraction method, independent of f_2, is not significant at the 5 percent level.

The results obtained with the resin method and the data on the decrease in extractable organic phosphorus upon incubation obtained with the combined acid and alkali extraction method are the independent variables in equation 6:

$$\hat{Y} = \underset{\pm 0.02}{0.37}\, f_2 + \underset{\pm 0.05}{0.01}\, f_5 + 5.63 \qquad (6)$$

The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_5, is significant at the 1 percent level. The regression of yield of phosphorus on f_5, the decrease in extractable organic phosphorus upon incubation as obtained with the combined acid and alkali extraction method, is not significant at the 5 percent level.

The data on inorganic phosphorus obtained with the resin method and the fraction of organic phosphorus soluble in a 1 percent potassium caronate-2 percent sodium hydroxide solution and hydrolyzed by hypobromite are used as independent variables in equation 7:

$$\hat{Y} = \underset{\pm 0.02}{0.37}\, f_2 - \underset{\pm 0.02}{0.01}\, f_7 + 0.62 \qquad (7)$$

The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_7, is significant at the 1 percent level. The negative regression of the yield of phosphorus on f_7, the organic phosphorus soluble in the potassium carbonate-sodium hydroxide solution and hydrolyzed by hypobromite, independent of f_2, is not significant at the 5 percent level.

Thus for the acid soils it appears that the availability of soil phosphorus to plants is not correlated with any fraction of organic phosphorus as determined in this experiment, independent of correlation of any of these fractions with a fraction of inorganic phosphorus designed to estimate availability of soil inorganic phosphorus.

In Table 9, the fractional recoveries of added soluble inorganic phosphorus for acid soils, as determined in the incubation experiment described in the previous section, are listed together with the amounts of organic phosphorus mineralized during incubation. The figures for mineralization are derived from the average of the increase in extractable inorganic phosphorus and the decrease in extractable organic

Table 9. Estimated relative availability of organic phosphorus as derived from the fractional recovery of added inorganic P and the organic P mineralized during a 1-week incubation at 40°C

Soil No.	Soil type	Fractional recovery of added inorganic P	Organic P mineralized during incubation, p.p.m.	Estimated relative availability of organic P mineralized during incubation, p.p.m.
F 2854	Clarion s.l.[a]	0.147	5	0.74
F 2855	Clarion s.l.	0.012	0	0.00
F 2856	Clarion s.l.	0.040	9	0.36
F 2857	Clarion s.l.	0.828	3	2.48
F 2858	Edina s.l.	-0.007	15	-0.10
F 2859	Edina s.l.	0.025	7	0.17
F 2860	Edina s.l.	0.015	6	0.09
F 2861	Fayette s.l., C-hor.	-0.093	0	0.00
F 2862	Fayette s.l.	0.072	33	2.38
F 2863	Grundy s.l.	0.197	12	2.36
F 2864	Haig s.l.	-0.003	7	-0.02
F 2865	Haig s.l.	0.002	14	0.28
F 2866	Haig s.l.	0.027	7	0.19
F 2883	Lindley s.l.	-0.015	11	-0.17
F 2884	Lindley s.l. C-hor.	-0.022	1	-0.02
F 2886	Nicollet loam	0.903	6	5.42
F 2887	Nicollet loam	0.133	5	0.67
F 2888	Nicollet loam	0.067	1	0.07
F 2889	Nicollet loam	0.412	8	3.30
F 2901	Seymour s.l.	0.163	8	1.30
F 2902	Shelby loam	0.000	4	0.00
F 2903	Shelby loam	-0.055	9	-0.50
F 2904	Shelby loam, C-hor.	-0.002	1	0.00
F 2905	Taintor s.l.	0.187	10	1.87
F 2906	Tama s.l.	-0.038	3	-0.11

[a]silt loam

Table 9. (continued)

Soil No.	Soil type	Fractional recovery of added inorganic P	Organic P mineralized during incubation, p.p.m.	Estimated relative availability of organic P mineralized during incubation, p.p.m.
F 2907	Tama s.l.	0.447	27	12.07
F 2908	Tama s.l.	0.307	8	2.46
F 2909	Wabash s.c.l.[b]	0.235	4	0.94
F 2910	Wabash s.c.l.	0.122	12	1.46
F 2911	Webster s.c.l.	0.362	3	1.09
F 2912	Webster s.c.l.	0.250	4	1.00
F 2913	Webster s.c.l.	0.633	9	5.70
F 2916	Weller s.l.	0.012	3	0.04
F 2917	Weller s.l., C-hor.	0.040	8	0.32

[b]silty clay loam

phosphorus upon incubation, according to the combined acid and alkali extraction method. Multiplication of these two data for every soil yields a third figure, which is assumed to be proportional to the availability of the mineralized organic phosphorus. For want of a better term these figures will be designated as estimated relative availabilities of the organic phosphorus mineralized during incubation, and they will be referred to more briefly as the estimated availabilities of organic phosphorus. The estimated availabilities of organic phosphorus are used as independent variables in the subsequent equations.

In equation 8, the data on inorganic phosphorus obtained with the Bray and Kurtz method and the data on estimated availabilities of organic phosphorus, designated as f_8, are used as independent variables. The following equation was calculated:

$$\hat{Y} = \underset{\pm 0.02}{0.27}\, f_1 + \underset{\pm 0.15}{0.76}\, f_8 - 0.09 \qquad (8)$$

The regression of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, independent of f_8, is significant at the 1 percent level. Likewise, the regression of yield of phosphorus on f_8, the estimated availability of organic phosphorus, independent of f_1, is significant at the 1 percent level.

In equation 9, the data on inorganic phosphorus obtained with the resin method and the same values of f_8 are used as independent variables. The following equation was obtained:

$$\hat{Y} = \underset{\pm 0.02}{0.34}\, f_2 + \underset{\pm 0.14}{0.31}\, f_8 + 0.10 \qquad (9)$$

The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_7, is significant at the 1 percent level. The regression of yield of phosphorus on f_7, the estimated availability of organic phosphorus, independent of f_2, is significant at the 5 percent level.

In equation 10, the data on inorganic phosphorus obtained with both the Bray and Kurtz method and the resin method and the estimated availabilities of organic phosphorus are used as independent variables. The following equation was obtained:

$$\hat{Y} = 0.01\,f_1 + 0.32\,f_2 + 0.33\,f_8 + 0.09 \qquad (10)$$
$$\pm 0.07 \qquad \pm 0.08 \qquad \pm 0.17$$

The regression of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, independent of f_2 and f_8, is not significant at the 5 percent level. The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_1 and f_8, is significant at the 1 percent level. The regression of yield of phosphorus on f_8, the estimated availability of organic phosphorus, independent of f_1 and f_2, is significant at a level slightly above that of 5 percent probability.

Alkaline Soils

In Table 10 the soil number, soil type and pH of the alkaline soils are listed together with the total amounts of inorganic and organic phosphorus extracted from the soils according to the procedure described by Mehta et al. (1954). In Table 11 the yield-of-phosphorus data as obtained in the greenhouse experiment are listed with two fractions of inorganic phosphorus and one fraction of organic phosphorus.

Table 10. Inorganic and organic phosphorus extracted from alkaline soils by the method of Mehta *et al.* (1954)

Soil No.	Soil type	pH	Inorganic P extracted, p.p.m.	Organic P extracted, p.p.m.
F 2848	Albaton silty clay	7.9	827	81
F 2849	Albaton silty clay	8.1	698	98
F 2850	Albaton silty clay	7.7	830	94
F 2851	Albaton silty clay loam	7.5	827	81
F 2852	Albaton silt loam	7.9	731	77
F 2853	Albaton silt loam	7.1	1506	360
F 2867	Hamburg silt loam	8.1	764	28
F 2868	Harpster silty clay loam	7.5	614	550
F 2869	Harpster silty clay loam	7.8	419	341
F 2870	Harpster silty clay loam	7.9	411	361
F 2871	Harpster silty clay loam	7.8	392	360
F 2872	Harpster silty clay loam	7.5	369	375
F 2873	Harpster silty clay loam	7.8	475	337
F 2874	Harpster silty clay loam	7.7	486	362
F 2875	Harpster silty clay loam	7.6	415	365
F 2876	Ida silt loam	7.8	685	171
F 2877	Ida silt loam.	7.7	639	141
F 2878	Ida silt loam	8.1	694	98
F 2879	Ida silt loam	8.1	712	84
F 2880	Ida silt loam	8.0	714	74
F 2881	Ida silt loam	8.1	745	59
F 2882	Ida silt loam	7.5	491	237
F 2885	Loess	8.3	735	5
F 2890	Onawa silty clay loam	7.8	646	82
F 2891	Onawa silty clay loam	7.9	626	102
F 2892	Onawa silty clay loam	7.9	687	145
F 2893	Onawa silty clay loam	7.9	645	155
F 2894	Onawa silty clay loam	7.7	712	100
F 2895	Onawa silty clay loam	7.9	639	73
F 2896	Onawa silty clay loam	8.0	675	105
F 2897	Onawa silty clay loam	7.7	1118	170
F 2898	Onawa silt loam	7.8	822	114
F 2899	Onawa very fine sandy loam	8.3	668	68
F 2900	Sarpy silty clay	7.8	705	47
F 2914	Webster silty clay loam	7.4	355	273
F 2915	Webster silty clay loam	7.1	587	245

Table 11. Yield of phosphorus in plants and phosphorus fractions in alkaline soils

Soil No.	Soil type	Yield of P in plants per culture, mg.	Phosphorus fractions in soils, p.p.m.[a]		
			f_1	f_2	f_6
F 2848	Albaton silty clay	6.71	24.3	27.4	9
F 2849	Albaton silty clay	5.68	11.9	13.1	4
F 2850	Albaton silty clay	6.65	29.1	26.2	8
F 2851	Albaton silty clay	6.53	25.2	34.2	8
F 2852	Albaton silt loam	2.95	11.2	6.8	5
F 2853	Albaton silt loam	33.80	123.4	133.4	40
F 2867	Hamburg silt loam	0.89	2.4	2.4	1
F 2868	Harpster silty clay loam	23.59	12.3	48.0	45
F 2869	Harpster silty clay loam	2.95	12.4	22.0	12
F 2870	Harpster silty clay loam	5.77	13.5	23.5	6
F 2871	Harpster silty clay loam	2.78	6.3	11.8	9
F 2872	Harpster silty clay loam	1.84	4.1	9.2	8
F 2873	Harpster silty clay loam	5.67	0.4	8.0	7
F 2874	Harpster silty clay loam	1.58	0.6	5.6	8
F 2875	Harpster silty clay loam	3.81	2.3	9.4	10
F 2876	Ida silt loam	9.85	2.5	2.6	3
F 2877	Ida silt loam	6.53	18.8	17.5	9
F 2878	Ida silt loam	1.21	3.1	3.1	2
F 2879	Ida silt loam	0.40	1.3	1.5	0
F 2889	Ida silt loam	0.29	1.2	1.9	1
F 2881	Ida silt loam	1.54	4.6	3.4	6
F 2882	Ida silt loam	5.87	16.5	17.7	10
F 2885	Loess	0.25	1.3	1.9	0
F 2890	Onawa silty clay loam	4.32	8.5	9.0	4
F 2891	Onawa silty clay loam	2.38	9.5	8.0	4

[a]f_1 = inorganic phosphorus by Bray and Kurtz method; f_2 = inorganic phosphorus by resin method; f_6 = average of increase in extractable inorganic phosphorus and decrease in extractable organic P upon incubation; 1 N HCl and hot 0.5 N NH_4OH as extractants

Table 11. (continued)

Soil No.	Soil type	Yield of P in plants per culture, mg.	Phosphorus fractions in soils, p.p.m. f_1	f_2	f_6
F 2892	Onawa silty clay loam	2.17	6.2	5.9	2
F 2893	Onawa silty clay loam	2.92	7.0	8.3	8
F 2894	Onawa silty clay loam	3.97	11.8	9.9	5
F 2895	Onawa silty clay loam	0.88	3.5	2.9	3
F 2896	Onawa silty clay loam	2.78	7.2	6.8	5
F 2897	Onawa silty clay loam	17.25	79.9	62.3	16
F 2898	Onawa silt loam	7.79	24.9	20.1	10
F 2899	Onawa very fine silt loam	3.16	9.5	6.1	5
F 2900	Sarpy silty clay	4.10	8.6	10.7	5
F 2914	Webster silty clay loam	4.05	12.7	13.6	9
F 2915	Webster silty clay loam	4.78	13.6	13.6	11

The yield of phosphorus in the plant is used as the dependent variable, and the data on the different fractions of soil phosphorus are used as independent variables.

In equation 11, the data on inorganic phosphorus obtained with the Bray and Kurtz method and the average of the increase in extractable inorganic phosphorus and decrease in extractable organic phosphorus, as obtained with the combined acid and alkali extraction method, are used as independent variables. The following equation was calculated:

$$\hat{Y} = \underset{\pm 0.01}{0.13}\, f_1 + \underset{\pm 0.04}{0.45}\, f_6 - 0.38 \qquad (11)$$

The regression of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, indedependent of f_6, is significant at the 1 percent level. Likewise, the regression of yield of phosphorus on f_6, the average increase in extractable inorganic phosphorus and decrease in extractable organic phosphorus upon incubation, independent of f_1, is significant at the 1 percent level.

In equation 12, the data on inorganic phosphorus obtained with the resin method and the same values for f_6 are used as independent variables. The following equation was obtained:

$$\hat{Y} = \underset{\pm 0.02}{0.17}\, f_2 + \underset{\pm 0.04}{0.31}\, f_6 - 0.09 \qquad (12)$$

The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_6, is significant at the 1 percent level. The regression of yield of phosphorus on f_6, the average of increase in extractable organic phosphorus upon incubation, independent of f_1, also is significant at the 1 percent level.

In equation 13, the data on inorganic phosphorus obtained with both the Bray and Kurtz method and the resin method and the average of increase in extractable inorganic phosphorus and decrease in extractable organic phosphorus upon incubation are used as independent variables. The following equation was obtained:

$$\hat{Y} = 0.09\, f_1 + 0.06\, f_2 + 0.40\, f_6 - 0.28 \qquad (13)$$
$$\pm 0.05 \qquad \pm 0.06 \qquad \pm 0.07$$

The regressions of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, and on f_2, the inorganic phosphorus according to the resin method, independent of each other and of f_6, are not significant at the 5 percent level. The regression of yield of phosphorus on f_6, the average of increase in extractable inorganic phosphorus and decrease in extractable organic phosphorus upon incubation, independent of f_1 and f_2, is significant at the 1 percent level.

The tests of significance on equations 11 and 12 show that significant information of value in predicting the yield of phosphorus is gained from both the mineralization of organic phosphorus during incubation and the Bray and Kurtz method in equation 11 and the resin method in equation 12. However, tests of significance in equation 13 indicate that, when all three fractions are tested in one equation, once the information on the mineralization of organic phosphorus during incubation has been obtained, no significant additional information of value in predicting the yield of phosphorus is gained from the phosphorus extracted by either the Bray and Kurtz method or the resin method. Hence the Bray and Kurtz method and the resin method appear to give much the same information with this group of soils.

Since in equations 11 and 12 the regression of yield of phosphorus on the inorganic phosphorus according to the Bray and Kurtz method and the resin method, respectively, was found to be significant at the 1 percent level, the data obtained with both methods are used in the subsequent calculations. That is to say, in these calculations sets of two equations will be obtained, in which one fraction of organic phosphorus is tested with each fraction of inorganic phosphorus separately. In all these equations f_1 will designate the fraction of inorganic phosphorus obtained with the Bray and Kurtz method and f_2 will designate the fraction of inorganic phosphorus obtained with the resin method.

In Table 12 the yield-of-phosphorus data for alkaline soils are listed together with four fractions of organic phosphorus. In equations 14 and 15 the two fractions of inorganic phosphorus and the data on the increase in extractable inorganic phosphorus upon incubation as obtained with the concentrated hydrochloric acid extraction method are used as independent variables. The equations are as follows:

$$\hat{Y} = \underset{\pm 0.03}{0.22}\, f_1 + \underset{\pm 0.04}{0.08}\, f_3 + 1.36 \qquad (14)$$

$$\hat{Y} = \underset{\pm 0.02}{0.25}\, f_2 + \underset{\pm 0.03}{0.05}\, f_3 + 0.63 \qquad (15)$$

The regression of yield of phosphorus on f_1, independent of f_3, is significant at the 1 percent level. The regression

Table 12. Yield of phosphorus in plants and phosphorus fractions in alkaline soils

Soil No.	Soil type	Yield of P in plants per culture, mg.	Phosphorus fractions in soils, p.p.m.[a]			
			f_3	f_4	f_5	f_7
F 2848	Albaton s.c.[b]	6.71	1	9	9	18
F 2849	Albaton s.c.	5.68	6	3	4	20
F 2850	Albaton s.c.	6.65	18	3	12	26
F 2851	Albaton s.c.l.[c]	6.53	28	10	6	29
F 2852	Albaton s.l.[d]	2.95	-20	5	4	18
F 2853	Albaton s.l.	33.80	21	37	42	52
F 2867	Hamburg s.l.	0.89	4	1	1	9
F 2868	Harpster s.c.l.	23.59	40	59	31	83
F 2869	Harpster s.c.l.	2.95	-9	12	11	49
F 2870	Harpster s.c.l.	5.77	2	4	8	47
F 2871	Harpster s.c.l.	2.78	20	13	5	53
F 2872	Harpster s.c.l.	1.84	0	9	7	48
F 2873	Harpster s.c.l.	5.67	5	7	7	39
F 2874	Harpster s.c.l.	1.58	-6	9	6	40
F 2875	Harpster s.c.l.	3.81	21	10	9	56
F 2876	Ida s.l.	0.85	4	1	4	31
F 2877	Ida s.l.	6.53	-1	5	13	23
F 2878	Ida s.l.	1.21	3	4	-1	15
F 2879	Ida s.l.	0.40	10	0	0	13
F 2880	Ida s.l.	0.29	9	0	1	16

[a] f_3 = increase in extractable inorganic P upon incubation; conc. HCl as extractant; f_4 = increase in extractable inorganic P upon incubation; 1 N HCl and hot 0.5 N NH_4OH as extractants; f_5 = decrease in extractable organic P upon incubation; 1 N HCl and hot 0.5 N NH_4OH as extractants; f_7 = organic P soluble in K_2CO_3 and NaOH and hydrolyzed by hypobromite

[b] silty clay

[c] silty clay loam

[d] silt loam

Table 12. (continued)

Soil No.	Soil type	Yield of P in plants per culture, mg.	Phosphorus fractions in soils, p.p.m.[a]			
			f_3	f_4	f_5	f_7
F 2881	Ida s.l.	1.54	7	6	5	9
F 2882	Ida s.l.	5.87	2	5	15	41
F 2885	Loess	0.25	-1	1	-1	0
F 2890	Onawa s.c.l.	4.32	3	4	4	23
F 2891	Onawa s.c.l.	2.38	0	4	3	9
F 2892	Onawa s.c.l.	2.17	4	0	3	18
F 2893	Onawa s.c.l.	2.92	-7	8	8	28
F 2894	Onawa s.c.l.	3.97	27	4	5	18
F 2895	Onawa s.c.l.	0.88	1	-3	8	14
F 2896	Onawa s.c.l.	2.78	8	5	5	25
F 2897	Onawa s.c.l.	17.25	69	16	15	30
F 2898	Onawa s.l.	7.97	9	8	11	22
F 2899	Onawa v.f.s.l.[e]	3.16	0	4	5	11
F 2900	Sarpy s.c.	4.10	5	4	5	11
F 2914	Webster s.c.l.	4.05	16	9	8	41
F 2915	Webster s.c.l.	4.78	12	8	14	33

[e]very fine sandy loam

of yield of phosphorus on f_2, independent of f_3, also is significant at the 1 percent level. The regressions of yield of phosphorus on f_3, the increase in extractable inorganic phosphorus by concentrated hydrochloric acid upon incubation, independent of f_1, in equation 14 and of f_2 in equation 15, are not significant at the 5 percent level.

In equations 16 and 17, the two fractions of inorganic phosphorus and the data on increase in extractable inorganic phosphorus upon incubation by the combined acid and alkali extraction method are used as independent variables. The equations are:

$$\hat{Y} = \underset{\pm 0.01}{0.17}\, f_1 + \underset{\pm 0.03}{0.33}\, f_4 + 0.16 \qquad (16)$$

$$\hat{Y} = \underset{\pm 0.01}{0.20}\, f_2 + \underset{\pm 0.03}{0.20}\, f_4 + 0.30 \qquad (17)$$

The regressions of yield of phosphorus on f_1, independent of f_3 in equation 16, and on f_2, independent of f_3 in equation 17, are significant at the 1 percent level. The regressions of yield of phosphorus on f_4, the increase in extractable inorganic phosphorus upon incubation, independent of f_1 in equation 16 and of f_2 in equation 17, also are significant at the 1 percent level.

The two fractions of inorganic phosphorus and the decrease in extractable organic phosphorus upon incubation as determined with the combined acid and alkali extraction method are the independent variables in the following equations:

$$\hat{Y} = \underset{\pm 0.02}{0.09}\, f_1 + \underset{\pm 0.06}{0.55}\, f_5 - 0.53 \qquad (18)$$

$$\hat{Y} = \underset{\pm 0.02}{0.15}\, f_2 + \underset{\pm 0.08}{0.36}\, f_5 - 0.20 \qquad (19)$$

The regressions of yield of phosphorus on f_1, independent of f_5 in equation 18, and on f_2, independent of f_5 in equation 19, are significant at the 1 percent level. The regressions of yield of phosphorus on f_5, the decrease in extractable organic phosphorus upon incubation, independent of f_1 in equation 18 and of f_2 in equation 19, also are significant at the 1 percent level.

The two fractions of inorganic phosphorus and the fraction of organic phosphorus soluble in a 1 percent potassium carbonate-2 percent sodium hydroxide solution and hydrolyzed by hypobromite are the dependent variables in equations 20 and 21:

$$\hat{Y} = \underset{\pm 0.02}{0.22}\, f_1 + \underset{\pm 0.03}{0.13}\, f_7 - 1.83 \qquad (20)$$

$$\hat{Y} = \underset{\pm 0.02}{0.25}\, f_2 + \underset{\pm 0.02}{0.05}\, f_7 - 0.35 \qquad (21)$$

The regressions of yield of phosphorus on f_1, independent of f_7 in equation 20, and on f_2, independent of f_7 in equation 21, are significant at the 1 percent level. The regressions of yield of phosphorus on f_7, independent of f_1 in equation 20 and of f_2 in equation 21, also are significant at the 1 percent level.

Thus for the alkaline soils there is evidence that the yield of phosphorus and hence the availability of soil phosphorus to plants is correlated with most of the fractions of organic phosphorus measured in this experiment, independent of correlation of any of these fractions with fractions of inorganic phosphorus designed to estimate availability of soil inorganic phosphorus. Only for the fraction of organic phosphorus mineralized during incubation, as measured by the increase in inorganic phosphorus extractable upon incubation by concentrated hydrochloric acid, is no such independent correlation found.

In Table 13, the fractional recoveries of soluble inorganic phosphorus added to alkaline soils are listed, together with the total amounts of organic phosphorus mineralized during incubation, as estimated from the average of the increase in extractable inorganic phosphorus and the decrease in extractable organic phosphorus upon incubation according to the combined acid and alkali extraction method. The estimated availabilities of organic phosphorus acquired by multiplying the data on organic phosphorus mineralized during incubation with the corresponding fractional recoveries are used as independent variables in the subsequent equations.

In equation 22, the data on inorganic phosphorus obtained with the Bray and Kurtz method and the data on estimated availability of organic phosphorus, designated as f_8,

Table 13. Estimated relative availability of organic P as derived from the fractional recovery of added inorganic P and the organic P mineralized during a 1-week incubation at 40°C

Soil No.	Soil type	Fractional recovery of added inorganic P	Organic P mineralized during incubation, p.p.m.	Estimated relative availability of organic P mineralized during incubation, p.p.m.
F 2848	Albaton s.c.[a]	1.22	9	11.0
F 2849	Albaton s.c.	1.40	4	5.6
F 2850	Albaton s.c.	1.35	8	10.8
F 2851	Albaton s.c.l.[b]	1.29	8	10.3
F 2852	Albaton s.l.[c]	1.46	5	7.3
F 2853	Albaton s.l.	1.10	40	44.0
F 2867	Hamburg s.l.	1.32	1	1.3
F 2868	Harpster s.c.l.	0.20	45	9.0
F 2869	Harpster s.c.l.	0.75	12	9.0
F 2870	Harpster s.c.l.	0.85	6	5.1
F 2871	Harpster s.c.l.	0.82	9	7.4
F 2872	Harpster s.c.l.	0.39	8	3.1
F 2873	Harpster s.c.l.	0.21	7	1.5
F 2874	Harpster s.c.l.	0.25	8	2.0
F 2875	Harpster s.c.l.	0.22	10	2.2
F 2876	Ida s.l.	0.48	3	1.4
F 2877	Ida s.l.	0.37	9	3.3
F 2878	Ida s.l.	1.07	2	2.1
F 2879	Ida s.l.	0.55	0	0.0
F 2980	Ida s.l.	0.85	1	0.9

[a]silty clay

[b]silty clay loam

[c]silt loam

Table 13. (continued)

Soil No.	Soil type	Fractional recovery of added inorganic P	Organic P mineralized during incubation, p.p.m.	Estimated relative availability of organic P mineralized during incubation, p.p.m.
F 2881	Ida s.l.	1.29	6	7.7
F 2882	Ida s.l.	0.70	10	7.0
F 2885	Loess	0.37	0	0.0
F 2890	Onawa s.c.l.	1.07	4	4.3
F 2891	Onawa s.c.l.	1.18	4	4.7
F 2892	Onawa s.c.l.	1.21	2	2.4
F 2893	Onawa s.c.l.	1.48	8	11.8
F 2894	Onawa s.c.l.	1.46	5	7.3
F 2895	Onawa s.c.l.	1.32	3	4.0
F 2896	Onawa s.c.l.	1.45	5	7.3
F 2897	Onawa s.c.l.	0.92	16	14.7
F 2898	Onawa s.l.	1.30	10	13.0
F 2899	Onawa v.f.s.l.[d]	1.34	5	6.7
F 2900	Sarpy s.c.	1.02	5	5.1
F 2914	Webster s.c.l.	0.89	9	8.0
F 2915	Webster s.c.l.	1.65	11	18.2

[d]very fine sandy loam

are used as independent variables. The following equation was obtained:

$$\hat{Y} = \underset{\pm 0.05}{0.18}\, f_1 + \underset{\pm 0.16}{0.21}\, f_8 + 1.02 \qquad (22)$$

The regression of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, independent of f_8, is significant at the 1 percent level. The regression of yield of phosphorus on f_8, the estimated availability of organic phosphorus, independent of f_1, is not significant at the 5 percent level.

In equation 23, the data on inorganic phosphorus obtained with the resin method and the same values of f_8 are used as independent variables. The following equation was calculated:

$$\hat{Y} = \underset{\pm 0.03}{0.30\, f_2} - \underset{\pm 0.10}{0.13\, f_8} + 1.11 \qquad (23)$$

The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_8, is significant at the 1 percent level. The negative regression of yield of phosphorus on f_8, the estimated availability of organic phosphorus, independent of f_2, is not significant at the 5 percent level.

In equation 24, the data on inorganic phosphorus obtained with both the Bray and Kurtz and resin methods and the data on estimated availabilities of organic phosphorus are used as independent variables. The following equation was obtained:

$$\hat{Y} = -\underset{\pm 0.05}{0.12\, f_1} + \underset{\pm 0.05}{0.39\, f_2} - \underset{\pm 0.10}{0.06\, f_8} + 0.83 \qquad (24)$$

The negative regression of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, independent of f_2 and f_8, is significant at the 5 percent level. The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_1 and f_8, is significant at the 1 percent level. The regression of yield of phosphorus on f_8, the estimated availability of organic phosphorus, independent of f_1 and f_2, is not significant at the 5 percent level.

In the following equations, the data on estimated availability of mineralized organic phosphorus are used for soils with a fractional recovery coefficient less than unity. For soils with a fractional recovery coefficient greater than unity, the data on total amounts of organic phosphorus mineralized during incubation as estimated from the average of increase in extractable inorganic phosphorus and decrease in extractable organic phosphorus upon incubation are used.

In equation 25, the data on inorganic phosphorus obtained with the Bray and Kurtz method and the data on estimated availability of organic phosphorus or on estimated total organic phosphorus mineralized during incubation, designated as f_9, are used as independent variables. The following equation was obtained:

$$\hat{Y} = \underset{\pm 0.6}{0.12}\, f_1 + \underset{\pm 0.22}{0.47}\, f_9 + 0.47 \qquad (25)$$

The regression of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, independent of f_9, is significant at a level slightly higher than that for 5 percent probability. The regression of yield of phosphorus on f_9, the estimated availability of organic phosphorus or the estimated total organic phosphorus mineralized during incubation, independent of f_1, is significant at the 5 percent level.

In equation 26, the data on inorganic phosphorus obtained with the resin method and the same values of f_9 are used as independent variables. The following equation was calculated:

$$\hat{Y} = \underset{\pm 0.04}{0.33}\, f_2 - \underset{\pm 0.15}{0.25}\, f_9 + 1.30 \qquad (26)$$

The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_9, is significant at the 1 percent level. The negative regression of yield of phosphorus on f_9, the estimated availability of organic phosphorus or the estimated total organic phosphorus mineralized during incubation, independent of f_2, is not significant at the 5 percent level.

In equation 27, the data on inorganic phosphorus obtained with both the Bray and Kurtz and resin methods and the data on estimated availability of organic phosphorus or on estimated total organic phosphorus mineralized during incubation are used as independent variables. The following equation was obtained:

$$\hat{Y} = -0.12\ f_1 + 0.41\ f_2 - 0.15\ f_9 + 0.99 \qquad (27)$$
$$\pm 0.05 \qquad \pm 0.05 \qquad \pm 0.14$$

The negative regression of yield of phosphorus on f_1, the inorganic phosphorus according to the Bray and Kurtz method, independent of f_2 and f_9, is significant at the 5 percent level. The regression of yield of phosphorus on f_2, the inorganic phosphorus according to the resin method, independent of f_1 and f_9, is significant at the 1 percent level. The negative regression of yield of phosphorus on f_9, the estimated availability of organic phosphorus or the estimated total organic phosphorus mineralized during incubation, independent of f_1 and f_2, is not significant at the 5 percent level.

Soil Inorganic Phosphorus Availability

The data obtained in this experiment yield an opportunity to compare the suitability of the Bray and Kurtz method and the resin method for estimating inorganic phosphorus availability in Iowa soils. Simple correlation coefficients were determined for yield-of-phosphorus data as obtained in the greenhouse experiment and inorganic phosphorus availability as estimated by the two laboratory methods, on both the acid and alkaline soils.

With the group of acid soils the correlation coefficient for yield of phosphorus in the plants and the soil phosphorus extracted by the Bray and Kurtz method is 0.93; for yield of phosphorus in the plants and the soil phosphorus extracted by the resin method the correlation coefficient is 0.97. Both correlation coefficients are significant at the 1 percent level; the difference between them is not significant. With the group of alkaline soils the correlation coefficient for yield of phosphorus in the plants and phosphorus extracted by the Bray and Kurtz method is 0.85; for yield of phosphorus in the plants and phosphorus extracted by the resin method the correlation coefficient is 0.95; both correlation coefficients are significant at the 1 percent level. The difference between them is significant at the 5 percent level.

It is of interest to know further if the linear regression of yield of phosphorus on inorganic phosphorus extracted by the two methods is the same for acid and alkaline soils. A covariance analysis made to test the similarity shows that for the Bray and Kurtz method the difference in slope between the two regression lines for acid and alkaline soils is significant at the 5 percent level. For the resin method the difference in slope between the two lines is significant at the 1 percent level.

DISCUSSION

The role that organic phosphorus plays in phosphorus nutrition of plants is still largely unknown. However, in the last 2 decades, investigators have made efforts to gain information on the importance of soil organic phosphorus to plant growth, and some progress has been made in this field. Eid *et al.* (1954) found that at a high soil temperature a fraction of organic phosphorus hydrolyzed by hypobromite was significantly correlated with soil phosphorus availability as estimated from plant response measurements, whereas at a low soil temperature no significant correlation could be found. They postulated that soil organic phosphorus *per se* is without importance to plant growth and that it becomes of importance only after having been mineralized. Van Diest (1955) reported that for alkaline soils a fraction of organic phosphorus mineralized during incubation was significantly correlated with yield of phosphorus in plants, thereby supplying more evidence that only after mineralization organic phosphorus plays a role in phosphorus nutrition of plants.

To evaluate the possible relationship between organic phosphorus and phosphorus uptake by plants, it appears that estimates of both mineralization of organic phosphorus and the response of plants to the increase in soil inorganic phosphorus resulting from mineralization of organic phosphorus must be obtained. The possibility exists that in some instances the relationship is present but remains unnoticed owing to large errors made in estimating either the mineralization of organic phosphorus or the response of plants to this mineralization process or both.

The first objective of this study was to find a plant-response method for estimating soil phosphorus availability that could be expected to reflect most sensitively any change in soil phosphorus availability as a result of mineralization of organic phosphorus. Dos Santos et al. (1957) found that in soil-culture experiments the absolute yields of the control plants that received no phosphorus fertilization yielded lower coefficients of variation and higher coefficients of correlation with chemical estimates of soil phosphorus availability than three other plant response methods examined. The difference in magnitude of the coefficients of correlation appeared to be attributable primarily to differences in experimental error associated with the various plant-response methods. As a result of these findings, a plant-response method in which the absolute yields of phosphorus in plants that received no phosphorus fertilization were measured, as described in a previous section, was adopted for the present investigation.

It was originally intended to estimate in the different soils the mineralization of organic phosphorus taking place during the growth period of the crop and at temperature fluctuations equal to those to which the crop was subjected by measuring the increase in inorganic phosphorus and the decrease in organic phosphorus extracted by concentrated hydrochloric acid as a result of incubation. As was described before, the results obtained with this extraction technique made it necessary to investigate other possible methods for measuring the amounts of organic phosphorus mineralized during incubation. Samples of all soils were incubated for 1 week at 40°C, and the estimates of mineralization of organic phosphorus obtained when using this incubation technique and a combined 1 N hydrochloric acid-0.5 N hot ammonium hydroxide extraction method were used in the calculations.

When for acid soils the phosphorus extracted by the resin and Bray and Kurtz methods and the theoretically most reliable estimates of organic phosphorus mineralized during incubation were all used as independent variables in one equation, the resin method was found to be superior to the Bray and Kurtz method (equation 3). In subsequent equations the other estimates of organic phosphorus mineralized during incubation and the fraction of organic phosphorus hydrolyzed by hypobromite were used as independent variables together with the resin method data (equations 4-10). In no case could any significant independent correlation be found between yield-of-phosphorus data and the estimates of mineralized organic phosphorus or the fraction of organic phosphorus hydrolyzed by hypobromite.

A major problem in phosphorus fertilization is the speed at which and the extent to which phosphate fertilizers applied to soil react with the soil in such a way that the availability of the added phosphorus to plants is reduced. The phosphorus fixation capacities of different soils vary widely, and consequently the effective quantities of phosphorus that remain in different soils after addition of a fixed quantity of a soluble form of phosphorus are subject to large variation.

Mineralization of organic phosphorus can, to a certain extent, be compared with phosphate fertilization. In both cases the quantity of inorganic phosphorus is raised, and the newly added inorganic phosphorus will gradually react with the soil. In the case of mineralization of organic phosphorus, the increase in inorganic phosphorus content of the soil will proceed more gradually and the distribution of the newly gained inorganic phosphorus will be more even throughout the soil than in the case of phosphorus fertilization.

In the experiment in which the fractional recovery of added inorganic phosphorus was studied, the inorganic phosphorus was dissolved in water and the concentration was made such that 60 μgm. of inorganic phosphorus were added to 1-gm. samples of soil in the 0.6 ml. of solution needed to saturate the samples before they were incubated. This technique ensured an even distribution of the added phosphorus throughout the sample and thus aided in approaching the condition of increase in soil inorganic phosphorus as a result of mineralization of organic phosphorus.

After 1 week of incubation the recovery of added inorganic phosphorus was determined, and for each soil the resulting fractional recovery coefficient was multiplied by the quantity of organic phosphorus mineralized (as estimated from the average of the increase in inorganic phosphorus and the decrease in organic phosphorus upon incubation). The resulting new estimates for availability of organic phosphorus were used as independent variables,along with the estimates of inorganic phosphorus availability, and new multiple-regression equations were calculated (equations 8-10). In all cases a significant independent effect of availability of organic phosphorus of value in predicting phosphorus availability to plants could now be found.

These results might explain why in the past some investigators failed to find a significant correlation between yield of phosphorus in plants and estimates of mineralized organic phosphorus in acid soils, while they did find a correlation in alkaline soils. Just as with some groups of soils the total amount of phosphorus applied in fertilizer form is a poor estimate of the increase in phosphorus availability, so with some groups of soils the total amount of organic phosphorus mineralized is a poor estimate of the availability of organic phosphorus.

For alkaline soils all estimates of organic phosphorus mineralized during incubation, except the increase in in-inorganic phosphorus extractable by concentrated hydrochloric acid, and the fraction of organic phosphorus hydrolyzed by hypobromite showed a significant independent effect of value in predicting soil phosphorus availability to plants (equations 11-21).

When fractional recovery coefficients were determined for alkaline soils it was found that for more than 50 percent of the soils the difference in extractable inorganic phosphorus between samples treated with inorganic phosphorus and control samples was more than the amount of phosphorus added to the treated samples. This finding obviated a clear-cut interpretation of the recovery coefficients. Nevertheless, the estimated availability of organic phosphorus calculated with these coefficients were used as independent variables, along with the estimates of inorganic phosphorus availability and new multiple-regression equations were calculated. It was found that no significant independent effect of value in predicting phosphorus availability to plants could be assessed to the estimated availabilities of organic phosphorus (equations 22-24), contrary to the significant effect obtained with the estimates of total organic phosphorus mineralized during incubation.

The combined acid-alkali extraction method used for estimating the amounts of organic phosphorus mineralized during incubation yields 100 percent recovery of added phosphorus, as was reported by Thompson (1950). Thus it can be expected that all organic phosphorus mineralized during the incubation period will be extracted by the acid and alkali. This being the case, application of fractional recovery coefficients greater than unity will lead to figures for availability of organic phosphorus mineralized which exceed the actual amounts mineralized as estimated by the use of the acid-alkali extraction method. There is some reason to believe that for soils with fractional recovery coefficients greater than one the use of the estimates of the total amounts of organic phosphorus mineralized is preferable to the estimated availabilities of organic phosphorus. Multiple-regressions equations were calculated, using the former estimates for those soils for which the fractional recovery coefficients exceeded unity and the latter estimates for those soils for which the fractional recovery coefficients were smaller than unity. The equations showed that these estimates were of significant independent value in predicting soil phosphorus availability to plants only when tested in connection with the data obtained with the Bray and Kurtz method (equations 25-27).

As a result of the findings reported in the above discussion, the following speculations can be made. When inorganic phosphorus is added to soils either by application of fertilizers or by mineralization of organic phosphorus, at least two processes will take place. A part of the added inorganic phosphorus will be fixed in either chemical or biological form in such a way that it can no longer be extracted by extractants used for estimating inorganic phosphorus availability. Simultaneously, the addition of inorganic phosphorus will touch off mineralization of soil organic phosphorus, whereupon a fraction of this inorganic phosphorus resulting from mineralization will be fixed.

In acid soils the fixation process is probably predominant to such an extent that it masks any mineralization of organic phosphorus that may be induced by addition of inorganic phosphorus, whereas in many alkaline soils little fixation of inorganic phosphorus takes place and mineralization of organic phosphorus caused by addition of inorganic phosphorus can be brought to light. Since fixation of inorganic phosphorus is quantitatively of more importance in acid soils than in alkaline soils, the use of fractional recovery coefficients in connection with estimates of mineralized organic phosphorus in the former might be more meaningful than when used in connection with the latter. If such is the case, it is reasonable to expect that the correlation between yield of phosphorus in plants and organic phosphorus mineralized in acid soil will be improved by the use of fractional recovery coefficients, whereas the opposite will take place with the alkaline soils. The results of the foregoing experiments are in accordance with this theory.

As a whole, the results of the experiments show that, in acid soils, estimates of availability of organic phosphorus and, in alkaline soils, estimates of total amounts of organic phosphorus mineralized during incubation are of significant value in predicting phosphorus availability to plants. Further work will be needed to examine more exhaustively the fixation of inorganic phosphorus added to soils and the possible mineralization of organic phosphorus brought about by the added inorganic phosphorus.

SUMMARY

Experiments were conducted to test the hypothesis that soil organic phosphorus may be of significance in the phosphorus nutrition of plants. Seventy Iowa soils representing a wide range in soil phosphorus availability were selected for this purpose.

A plant-response method was developed in which the absolute yields of phosphorus in plants that received no phosphorus fertilization were measured. Mineralization of organic phosphorus was estimated by measuring the increase in inorganic phosphorus and the decrease in organic phosphorus removed from soil by different extractants as a result of incubation, and also by measuring the amount of organic phosphorus hydrolyzed by hypobromite in an alkali soil extract.

Multiple-regression equations were calculated in which the estimates of yield of phosphorus obtained with the plant-response method were used as the dependent variable. The independent variables were inorganic phosphorus extracted by the Bray and Kurtz method and the resin method and the estimates of organic phosphorus mineralized during incubation or hydrolyzed by hypobromite.

With acid soils no significant independent correlation was found between yield-of-phosphorus data and the estimates of organic phosphorus mineralized during incubation or the fraction of organic phosphorus hydrolyzed by hypobromite. Subsequently, the availability of organic phosphorus mineralized was estimated by determining for each soil the fractional recovery of added inorganic phosphorus in an incubation experiment. When the estimates of organic phosphorus mineralized during incubation were multiplied by the corresponding fractional recovery coefficients, the resulting estimates of availability of organic phosphorus mineralized were of significant independent effect of value in predicting phosphorus availability to plants.

With alkaline soils significant independent correlation could be found between yield-of-phosphorus data and the estimates of organic phosphorus mineralized during incubation or the fraction of organic phosphorus hydrolyzed by hypobromite. However, when the estimates of organic phosphorus mineralized during incubation were multiplied by the corresponding fractional recovery coefficients, the resulting estimates of availability of organic phosphorus mineralized showed no significant independent effect of value in predicting phosphorus availability to plants.

On the basis of the much higher fractional recoveries of the added inorganic phosphorus in alkaline than in acid soils (with a number of alkaline soils the fractional recovery exceeded unity), it was speculated that the improvement in prediction of yield of phosphorus associated with the use of the fractional recovery data on acid soils resulted because in these soils the phosphorus fixation was of considerable importance. The lack of improvement in prediction with the alkaline soils, on the other hand, resulted because in them phosphorus fixation was of relatively less importance and also because the fractional recovery was affected strongly by processes other than fixation. In consequence of the latter, the theoretical meaning of the fractional recovery was not the same in the alkaline soils as in the acid soils.

As a whole, the results of the experiments show that, in acid soils, estimates of availability of organic phosphorus and, in alkaline soils, estimates of total amounts of organic phosphorus mineralized during incubation are of significant value in predicting phosphorus availability to plants.

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ACKNOWLEDGMENTS

The author wishes to express his sincere gratitude to Dr. C. A. Black under whose guidance this work was undertaken; for the encouragement and assistance during the investigation and constructive criticism during the preparation of this manuscript.

The author is deeply indebted to his wife, Anna V. Schophuys van Diest, for moral and material support during the author's years of graduate study.