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The Relationship Between Forms of Soil Phosphorus and Uptake of Phosphorus by Barley

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THE RELATIONSHIP BETWEEN FORMS OF SOIL PHOSPHORUS
AND UPTAKE OF PHOSPHORUS BY BARLEY

BY

TIMOTHY OKUNOLA FADAYOMI

A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Major in
Agronomy, South Dakota
State University

1967

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THE RELATIONSHIP BETWEEN FORMS OF SOIL PHOSPHORUS
AND UPTAKE OF PHOSPHORUS BY BARLEY

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser

Head, Agronomy Department

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INTRODUCTION

The present investigation was suggested by the evidence that results obtained from some fertilizer experiments in the northern half of South Dakota related poorly to the soil test values. The yield increases from added phosphorus on fallowed land have not been as well correlated with soil tests as on non-fallowed land. A greater yield increase due to added phosphorus was obtained on fallowed soils having a high phosphorus test than on those having a medium test. Continued study was needed to determine the relationship between crop response to applied phosphorus, phosphorus uptake by plants, and the phosphorus fertility status of these soils as revealed by chemical methods.

The availability of soil phosphorus to plants during the growing season may be a function of the solubility and amounts of all or certain forms of the phosphorus present in the soil. Variation in the tests between different groups of soils might also be due to the variation in the forms of phosphorus present in these soils.

The objective of this investigation, therefore, was to study the relationship between the various forms of soil phosphorus and plant-available phosphorus. The plant-available phosphorus is taken to be the amount of phosphorus taken up by barley plants grown on these soils in the greenhouse. It was hoped that by separately determining the amounts of the different forms of soil phosphorus and

relating each of them to plant phosphorus availability a more rational basis for future development or selection of a soil test might be provided.

LITERATURE REVIEW

Soil tests are one of the means of characterizing soil fertility. Even though advances in developing soil tests have been made in recent years, there is yet a diversity of methods used. The development of better criteria for interpreting soil test results is therefore an important need of soil testing programs.

General Review

The reliability of various methods for estimating the so-called available phosphorus in soils has received considerable study. The use of 0.03N NH_4F plus 0.025N HCl proposed by Bray and Kurtz (13) has been the object of many correlation studies (11, 32, 37, 45, 47, 52). Several other studies have employed Truog's 0.002N H_2SO_4 (23, 53), Olsen's 0.5N NaHCO_3 (40), water (12), Morgan's solution of sodium acetate in acetic acid (38) and, of late, Barber's 0.3N NaOH plus 0.5N $\text{Na}_2\text{C}_2\text{O}_4$ solution (2). These methods have been developed in an attempt to assess the ability of soils to supply phosphate to the crop in the field during the growing season. They are therefore empirical and must be correlated with field experiments before useful information can be obtained from them. These tests usually give satisfactory results within restricted soil groups but not for combinations of groups (49).

Numerous studies have indicated that the availability of soil phosphorus to plants is determined by a combination of factors.

Olsen and Fried (41) summarized a number of these factors which include: (1) forms and solubilities of soil inorganic phosphates in acid and calcareous soils, (2) effects of particle size and surface area of inorganic phosphorus compounds on solubility and availability, and (3) influence of plant species and root environment on phosphorus uptake (24). To the above should be added climatic fluctuations, such as amount and distribution of rainfall during the growing season, and the related effects on reserve supplies of available subsoil moisture (4, 39).

Some Chemistry of Phosphorus Availability

The absorption of phosphates by plants is a function of the solution concentration of the phosphate ion (46). The solution concentration of the phosphate ion is related to the phosphorus associated with the reactive surfaces of soil materials (61). The reactive surfaces of soil materials are found to retain a large proportion of added or mineralized phosphate when they are coated with iron or aluminum, the amount retained increasing as the concentration of phosphorus in solution is increased (25). Thus a much higher concentration of phosphorus is needed on the reactive surfaces of soils having a high saturation of exchangeable aluminum in order to obtain maximum yields, because neutralization of exchangeable aluminum markedly reduces the phosphorus adsorption maximum for soils with a

wide range in chemical properties (61). Adsorbed phosphates, however, are either hydrolytically displaced or displaced by other anions (46).

Both the intensity of soil phosphate supply -- defined as the amount of phosphate in solution at any given time -- and the capacity of the soil to rapidly renew this supply -- upon fixation in the soil or uptake by the plant -- should be evaluated in order to adequately describe plant-available phosphorus in the soil. Although some of the various acid and alkaline extractants used in soil tests for available phosphorus do involve an intensity as well as a capacity factor -- since they are single extracts and inasmuch as they either dissolve or desorb some of the phosphorus on the soil particle surfaces -- the relative importance of the two factors differ among soils (26).

Crop Response to Applied Phosphate

The capacity of certain Minnesota soils to "fix" phosphorus from added KH_2PO_4 was observed by Chai and Caldwell (16). They found that the phosphorus-fixing capacity of the soils increased with departure from a pH near neutrality. Olson (42) also showed that both sulfur and lime affect crop response to applied phosphate. Lime, for example, depressed yields when added to near neutral soils with high phosphate levels but increased yields in acid soils with low phosphate levels. Even though applied phosphate resulted in highly significant increases in yield and percentage of phosphorus in the crop on all soils in greenhouse investigations, MacClean et al.

(36) found that the degree of response was, however, not the same on all soil types. The higher the phosphorus content of the crop grown without phosphorus fertilizer the lower the increase in yield from applied phosphorus. Carson et al. (15) and Salami (45) indicated that the higher the estimate of available phosphorus in some non-fallowed South Dakota soils as determined by chemical soil tests the lower the increase in yield from applied phosphorus.

Phosphorus Solubility Curves

Stelly and Pierre (50) compared the phosphorus solubility curves of some Iowa soils and of some phosphate minerals and suggested that the forms of phosphorus are quite different in various soils. Their findings were confirmed by the report of Bishop and Barber (8).

Fractionation of Soil Phosphorus

The relative amounts of soil phosphorus compounds present in any soil vary because of weathering, pH, organic matter content, parent material, cropping and fertilizer practice (3, 9, 29, 34, 39).

Two of the earliest attempts at fractionation of soil phosphates were by Fisher and Thomas (22) in 1935 and Dean (19) in 1938. During this period and in the several years which followed, many attempts were made to completely fractionate soil phosphorus but an insoluble fraction always remained (59). It was not until Bauwin and Tyner

(5), working with selected soils from Illinois, combined the earlier methods and those of Bray and Kurtz (13) into a workable fractionation procedure that solution and fractionation of the so-called insoluble soil phosphorus was accomplished.

Chang and Jackson (17) reported a procedure for fractionation of soil phosphorus into the discrete chemical forms: aluminum, iron, calcium, and occluded iron and aluminum phosphates. Their procedure, like most previous procedures, was based on the differential solubilities of the various inorganic phosphates in various extractants. However, they reported essentially complete fractionation of the total phosphorus in the soils and other materials investigated. This procedure has recently been modified by Petersen and Corey (43) with a view to increasing the speed of the phosphorus determinations in routine laboratory analysis.

Fractionation of inorganic soil phosphates has been used in soil fertility and genesis studies. An investigation conducted by Bauwin and Tyner (6) indicated that the occluded phosphates were generally highest in the B horizons of Gray-Brown Podzolic soils and lowest in the C. They reported significant increases in the B horizons with increasing profile maturity, particularly from early through medial stages of development. Their observations were in general agreement with those of other researchers (3, 27, 28) regarding the decline in soil phosphorus solubility with increasing profile development or weathering. Iron phosphates were reported to increase

with weathering, at the expense of calcium and aluminum phosphates, with eventual occluding of some aluminum and aluminum-iron phosphates with iron oxide coatings (18, 30).

Chai and Caldwell (16), using several Minnesota soils, showed that iron and aluminum phosphates were abundant in acid soils while calcium phosphate was abundant in alkaline soils, and that the aluminum, iron, and calcium phosphates were about equally distributed in neutral soils. The presence of relatively higher contents of iron and aluminum phosphates in neutral soils have also been reported by Bhangoo and Smith (7) and Chang and Jackson (18). Carlson (14), in a similar study, characterized the phosphorus content of four acid to neutral South Dakota surface soils and found that, among the three forms, the calcium phosphate was the highest followed by the iron and aluminum phosphates respectively. His findings are in general agreement with the fractionation data obtained by Westin and Buntley (56).

The relationship between the soil phosphorus fractions and the available phosphorus as determined by chemical methods has also been the object of correlation studies by Pratt and Garber (44) and Westin and Buntley (57). However, correlation studies between the soil phosphorus fractions and the available phosphorus as determined from plant growth experiments seemed to be a more rational approach to development of a soil test. Williams (60), in pot-culture experiments with a wide range of South Australian soils, separated the soil phosphates into two fractions, namely, inorganic and organic

and indicated that there was a significant correlation between inorganic soil phosphate and phosphorus uptake by plants. Bishop and Barber (8), using acid and alkaline extractants on soils of the upland and lake catenas in Indiana, indicated that the use of both the alkali-soluble phosphorus and acid-soluble phosphorus was required to explain the contribution of the different soil phosphorus compounds to variation in yield. Al Abbas and Barber (1), working with 24 Indiana soils, reported that iron phosphate gave the best correlation of any form of soil phosphate with plant uptake of phosphorus in the greenhouse, and used their findings as a basis for developing a soil test (2). In contrast to the above findings Susuki et al. (51), in a similar study, indicated that only calcium and aluminum phosphates contributed significantly to the phosphorus removed by plants on Michigan soils.

Inasmuch as the reasons why these results differ are yet obscure, it was the purpose of this investigation to separately estimate the different forms of soil phosphorus and to correlate them with plant-available phosphorus with a view to directly determining their contribution to phosphorus uptake by plants and thereby finding an explanation for the variation in the relative amounts of forms of phosphorus on some South Dakota soils.

MATERIALS AND METHODS

The soils collected for this investigation represent the major agricultural soils of the Chestnut soil area of South Dakota. They are essentially zonal soils, of the order Mollisols, that have developed in temperate, semi-arid climates under grass vegetation and free from ground water influence, and with a base saturation greater than 80 per cent (55, 58).

Sampling Procedure

Surface soils, approximately 0" - 6", were collected in the fall of 1965 from thirty sites belonging to three parent materials and six soil series. The soils were placed in plastic bags in order to keep them in field moist condition. See Figure 1 for geographical locations of the sample sites.

The county, site, great soil group, family and series of these soils are presented in Table 1.

About 3,000 grams of each soil-sample was transferred into another plastic bag and frozen, within 24 hours after sampling, for subsequent fractionation studies.

The field capacity of each soil was determined using the pressure membrane method (54).

The oven dry weight of each soil was then determined after subjection to a temperature of 105°C for 24 hours.

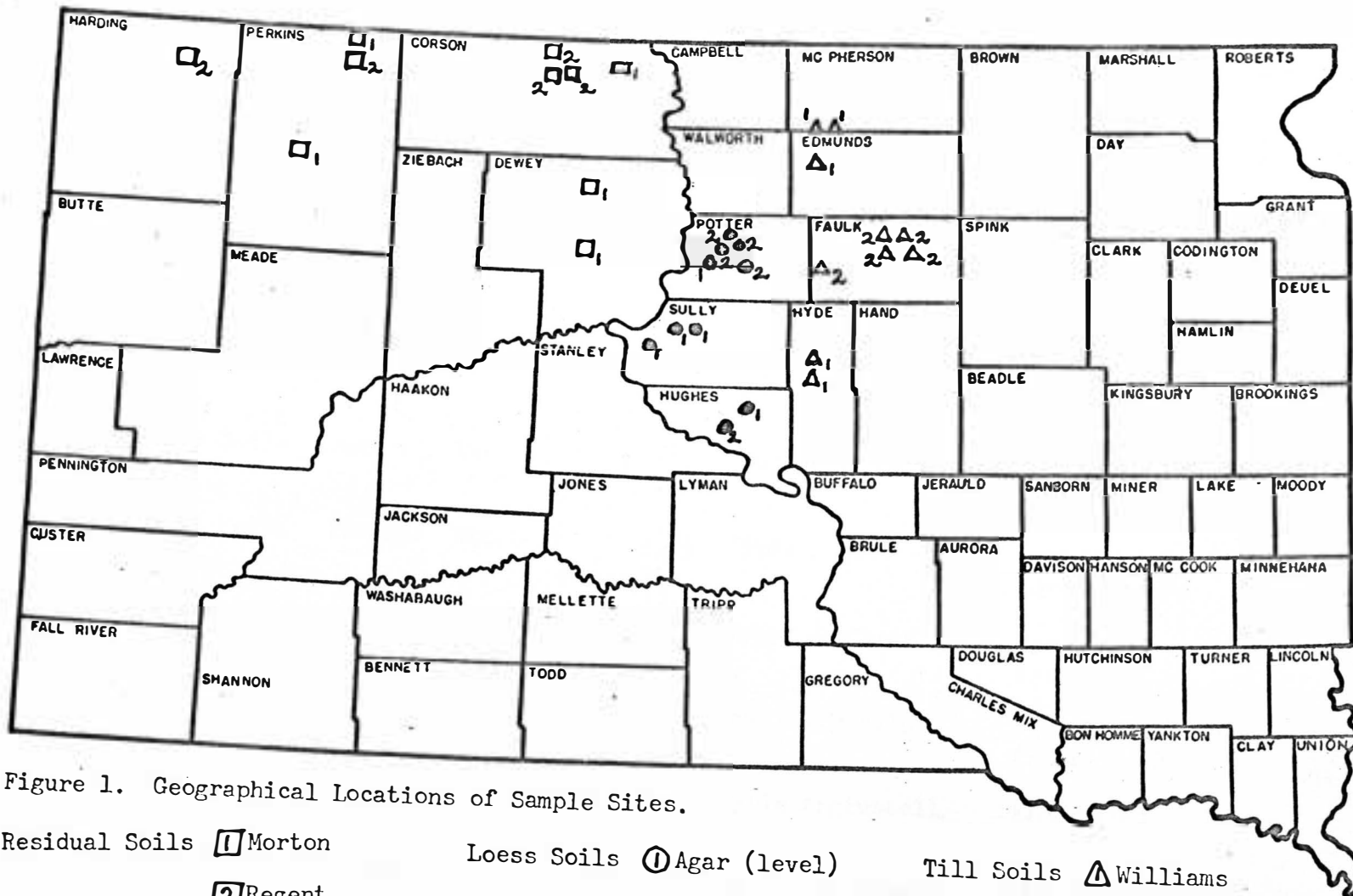


Figure 1. Geographical Locations of Sample Sites.

Residual Soils 1 Morton
2 Regent

Loess Soils 1 Agar (level)
2 Agar (sloping)

Till Soils ▲ Williams
▲ Cresbard

TABLE 1. Parent Materials, Location, and Classification of the Soils Under Study Using 7th Approximation (55).

Sample No.	Parent Material	County	Site	Great Soil Group	Family	Series
1	Residual Soils	Dewey	Dosch	Typic Argiustoll	Fine silty mixed mesic	Morton
2	Residual Soils	Dewey	Lutz	Typic Argiustoll	Fine silty mixed mesic	Morton
3	Residual Soils	Perkins	Veal	Typic Argiustoll	Fine silty mixed mesic	Morton
4	Residual Soils	Harding	Knudsen	Typic Argiustoll	Fine mixed frigid	Regent
5	Residual Soils	Perkins	Mitchell	Typic Argiustoll	Coarse loamy mixed frigid	Morton
6	Residual Soils	Perkins	Mitchell (N)	Typic Argiustoll	Fine mixed frigid	Regent
7	Residual Soils	Corson	Farstad '61	Typic Argiustoll	Fine mixed frigid	Regent
8	Residual Soils	Corson	Farstad '62	Typic Argiustoll	Fine mixed frigid	Regent
9	Residual Soils	Corson	Farstad '63	Typic Argiustoll	Fine mixed frigid	Regent

Table 1 Continued

Sample No.	Parent Material	County	Site	Great Soil Group	Family	Series
10	Residual Soils	Corson	Young G.	Typic Argiustoll	Fine silty mixed mesic	Morton
11	Loess Soils	Hughes	Stewart	Typic Argiustoll	Fine silty mixed mesic	Agar (0-2%)
12	Loess Soils	Sully	Jim Young	Typic Argiustoll	Fine silty mixed mesic	Agar (0-2%)
13	Loess Soils	Potter	Nauman	Typic Argiustoll	Fine silty mixed mesic	Agar (0-2%)
14	Loess Soils	Sully	Lyons (W)	Typic Argiustoll	Fine silty mixed mesic	Agar (0-2%)
15	Loess Soils	Sully	Lyons (E)	Typic Argiustoll	Fine silty mixed mesic	Agar (0-2%)
16	Loess Soils	Hughes	Hauschild	Typic Argiustoll	Fine silty mixed mesic	Agar (2-6%)
17	Loess Soils	Potter	N. of Gettysburg	Typic Argiustoll	Fine silty mixed mesic	Agar (2-6%)
18	Loess Soils	Potter	W. of Gettysburg	Typic Argiustoll	Fine silty mixed mesic	Agar (2-6%)

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Table 1 Continued

Sample No.	Parent Material	County	Site	Great Soil Group	Family	Series
19	Loess Soils	Potter	N.W. of Gettysburg	Typic Argiustoll	Fine silty mixed mesic	Agar (2-6%)
20	Loess Soils	Potter	N.W. of Gettysburg (eroded)	Typic Argiustoll	Fine silty mixed mesic	Agar (2-6%)
21	Till Soils	Hyde	Highmore Range* 200(0-0-0)	Typic Argiustoll	Fine loamy mixed frigid	Williams
22	Till Soils	Hyde	Highmore Range* 200(0-40-0)	Typic Argiustoll	Fine loamy mixed frigid	Williams
23	Till Soils	Edmunds	Hosmer (S)	Typic Argiustoll	Fine loamy mixed frigid	Williams
24	Till Soils	Edmunds	Hosmer (S.W.)	Typic Argiustoll	Fine loamy mixed frigid	Williams
25	Till Soils	Edmunds	Jung	Typic Argiustoll	Fine loamy mixed frigid	Williams
26	Till Soils	Faulk	Bergerson	Glossic Natriboroll	Fine mixed	Cresbard
27	Till Soils	Faulk	Norbeck (N)*	Glossic Natriboroll	Fine mixed	Cresbard

Table 1 Continued

Sample No.	Parent Material	County	Site	Great Soil Group	Family	Series
28	Till Soils	Faulk	Norbeck (N.E.)*	Glossic Natriboroll	Fine mixed	Cresbard
29	Till Soils	Faulk	Norbeck (N.W.)*	Glossic Natriboroll	Fine mixed	Cresbard
30	Till Soils	Faulk	Norbeck (W)*	Glossic Natriboroll	Fine mixed	Cresbard

*Soils from experimental station.

Greenhouse Studies

No. 10 tin cans were washed, dried and lined with polyethylene bags to prevent contamination and moisture and nutrient-element losses. An interlayer of 1000 g. of soil (oven dry basis) was placed between two 1000 g. layers of nearly inert sand. Eight cans were filled with soil from each site. All cans received 132 lbs. of N and 100 lbs. of K per two million lbs. of soil in the forms of NH_4NO_3 and KCl solutions respectively. Half the cans were then treated with 90 lbs. of P per two million lbs. of soil in the form of $(\text{NH}_4)_2\text{HPO}_4$ solution. Each can was planted to 30 barley (variety Larker) seeds which had been selected for uniformity of size. All the cans were brought to field capacity with distilled water. After germination the seedlings per can were thinned to 24.

An additional 66 lbs. of N per two million lbs. of soil was applied during the growth period so that nitrogen would not be limiting.

After eight weeks of growth the barley tops were harvested, oven dried at 65°C , and weighed. The dried tops were then ground for subsequent laboratory analysis.

Cropping of the same cans of soils was twice repeated in order to exhaust most of the available soil phosphorus.

A randomized complete block design involving two treatments (P and no P) and four replications was used for this experiment.

Laboratory Studies

The organic matter content, texture, and pH of the various soils were determined by the South Dakota State University Soil Testing Laboratory. The organic matter content was determined by the wet combustion method outlined by Jackson (33). The soil texture was determined using the method of Lunt et al. (35). The pH was determined using a glass electrode on a 1:1 soil-to-water paste (33, 54).

Determination of Total P in Plant Material

0.1 g. of plant tissue taken from each sample of the finely ground barley tops was analyzed for its total phosphorus content using the vanadomolybdophosphoric yellow color method as outlined by Jackson (33) and modified by Blanchar (10). The intensity of the color was read on a Junior Coleman Spectrophotometer Model 6A at 430 mu.

Determination of Total P in Soils

Total soil P was determined by the method outlined by Jackson (33) with the following modifications:

- (1) A 1-g. sample of soil that had been passed through a 0.5 mm. sieve was used.
- (2) After digestion on the hot plate, the filtered solution was made up to 100 ml. volume.
- (3) A 25-ml alicuot was used in making up the final 50 ml. volume.

The intensity of the color was read after ten minutes on a Junior Coleman Spectrophotometer Model 6A at 430 m μ .

Fractionation Studies

The inorganic phosphorus fractionation analysis of all the soils before cropping and of selected soils after cropping was determined by the procedure of Chang and Jackson (17) as modified by Fife (20, 21) and Hsu et al. (31). The forms determined on air-dried soils crushed to pass through a 0.5 mm. sieve were NH_4Cl -extractable P, aluminum P, iron P, calcium P and occluded P.

The soil organic P was calculated as the difference between the total soil P and the total inorganic fractions.

Estimates of the soil phosphorus fractions were reported as ppm. oven dry basis.

The multiple regression analysis, showing the relative contribution of the soil phosphorus fractions to plant-available phosphorus, was done by computer.

RESULTS

Routine laboratory analyses were conducted on the soils used with a view to characterizing some relevant chemical and physical properties of the soils. Table 2 shows these properties.

As indicated in Table 2, most of the soils have a pH less than 7 and relatively few soils have a pH above 7. The data indicate a trend toward slight acidity in the surface soils.

The per cent organic matter in the soils ranges from a low of 1.7% to a high of 3.5%.

In terms of available nitrogen based on per cent organic matter, some of the soils are low in their ability to supply adequate nitrogen for plant growth.

There are four textural classes represented, namely, loam, silt loam, silty clay loam, and silty clay. The first two constitute the coarser while the last two constitute the finer textures for purposes of comparison.

TABLE 2. Some Chemical and Physical Analyses of the Surface Six Inches of Soils Used

Sample No.	Site	Texture	Organic Matter %	pH 1:1 Soil Paste
<u>Residual Soils</u>				
1	Dosch	Loam	2.1	7.3
2	Lutz	Silt loam	1.9	6.0
3	Veal	Silty clay loam	1.8	6.5
4	Knudsen	Silty clay loam	1.7	6.7
5	Mitchell	Loam	1.8	6.6
6	Mitchell (N)	Loam	1.9	6.2
7	Farstad '61	Silt loam	1.7	7.1
8	Farstad '62	Silty clay loam	2.3	6.8
9	Farstad '63	Silty clay	2.3	6.5
10	Young G	Silty clay loam	2.3	6.4
<u>Loess Soils</u>				
11	Stewart	Loam	3.1	6.8
12	Young J	Loam	3.0	7.1
13	Nauman	Loam	2.6	7.3
14	Lyons (W)	Loam	2.7	6.5
15	Lyons (E)	Silty clay loam	1.8	6.8
16	Hauschild	Silt loam	2.4	7.2
17	N. of Gettysburg	Silt loam	1.8	7.8
18	W. of Gettysburg	Silt loam	2.1	7.7
19	N.W. of Gettysburg	Silt loam	2.2	6.5
20	N.W. of Gettysburg (eroded)	Silt loam	2.0	7.0

Table 2 Continued

Sample No.	Site	Texture	Organic Matter %	pH 1:1 Soil Paste
<u>Till Soils</u>				
21	Highmore Range 200(0-0-0)	Silty clay loam	2.6	6.7
22	Highmore Range 200(0-40-0)	Silty clay loam	2.5	6.5
23	Hosmer (S)	Silt loam	2.1	7.7
24	Hosmer (S.W.)	Silty clay loam	2.6	6.8
25	Jung	Silty clay loam	2.5	7.3
26	Bergerson	Silty clay loam	2.4	6.6
27	Norbeck (N)	Silty clay loam	2.7	6.4
28	Norbeck (N.E.)	Silty clay loam	3.1	6.3
29	Norbeck (N.W.)	Silty clay loam	3.2	6.4
30	Norbeck (W)	Silty clay loam	3.5	7.0

Fractionation Experiment

Fractionation data of the soils before cropping indicate that calcium phosphate generally was the largest fraction of soil phosphorus followed by organic, occluded, iron, aluminum, and NH_4Cl -extractable phosphates respectively. See Table 3 for the amounts of these fractions and the average total phosphorus taken up by plants on these soils.

The phosphorus variables as shown in Table 3, the per cent organic matter, and the pH were included in a multiple regression analysis. The multiple linear correlation coefficients and multiple linear coefficients of determination for selected subsets of the independent variables with plant-available phosphorus as the dependent variable are shown in Table 4.

In the analysis, aluminum phosphate alone contributed significantly to the variation in plant uptake of phosphorus.

Soil fractionation data for selected samples at the conclusion of the greenhouse experiment indicated a consistent decrease in the aluminum and organic phosphate fractions during the cropping period. On the other hand, the corresponding amounts of iron, calcium and occluded phosphates seemed to fluctuate during the growth period. See Table 5 for comparison of relative amounts of these fractions in certain selected soils before and after cropping.

TABLE 3. The Soil P Fractions and the Total Uptake of P by Barley Grown on These Surface Soils

Sample No.	Site	NH ₄ Cl-extractable P ppm.	Al-P ppm.	Fe-P ppm.	Ca-P ppm.	Occluded P ppm.	Total P ppm.	Organic P ppm.	Average Total P uptake mg./pot
<u>Residual Soils</u>									
1	Dosch	0.00	6.64	22.73	160.88	97.04	459.65	172.36	18.51
2	Lutz	0.00	23.77	52.62	145.47	86.01	459.42	152.05	38.85
3	Veal	0.00	14.22	34.52	203.09	86.31	420.39	82.25	26.80
4	Knudsen	0.00	9.18	22.94	124.91	99.42	413.99	157.54	19.84
5	Mitchell	0.00	17.17	52.53	146.48	118.70	509.14	174.26	29.67
6	Mitchell (N)	0.00	20.22	54.09	160.50	121.32	469.11	112.98	35.30
7	Farstad '61	0.00	21.42	38.25	221.83	91.79	432.43	59.14	38.35
8	Farstad '62	0.00	30.06	50.94	123.54	101.89	476.82	170.39	38.73
9	Farstad '63	0.00	22.95	46.93	142.83	86.72	422.36	122.93	36.50
10	Young G.	0.00	29.64	45.10	157.07	83.60	603.97	288.56	35.98
<u>Loess Soils</u>									
11	Stewart	0.00	39.24	29.05	264.98	89.18	576.84	154.39	37.09
12	Young J.	0.00	27.47	24.93	244.20	68.68	531.14	165.86	41.31
13	Nauman	0.00	32.59	28.51	292.77	86.56	525.46	85.03	40.56
14	Lyons (W)	0.00	28.48	30.51	264.42	81.36	616.29	211.52	37.81
15	Lyons (E)	0.00	17.05	33.09	272.32	58.54	553.80	172.80	36.26
16	Hauschild	0.00	37.61	31.00	288.42	83.86	528.56	87.67	38.79
17	N. of Gettysburg	0.00	6.61	14.25	320.51	119.56	545.38	84.45	20.50
18	W. of Gettysburg	0.00	13.23	18.83	321.85	117.04	547.53	76.58	25.14
20	N.W. of Gettysburg (eroded)	0.00	7.13	21.15	242.03	129.93	580.86	180.62	21.45

Table 3 Continued

Sample No.	Site	NH ₄ Cl extractable P ppm.	Al-P ppm.	Fe-P ppm.	Ca-P ppm.	Occluded P ppm.	Total P ppm.	Organic P ppm.	Average Total P uptake mg./pot
<u>Till Soils</u>									
21	Highmore Range 200(0-0-0)	0.00	39.36	38.60	204.42	132.05	481.46	67.03	37.10
22	Highmore Range 200(0-40-0)	1.22	53.83	47.49	190.45	124.43	501.78	106.43	57.88
23	Hosmer (S)	0.00	14.76	21.88	159.00	124.66	419.25	98.95	31.19
24	Hosmer (S.W.)	0.00	16.78	22.63	152.56	132.22	435.31	111.12	25.48
25	Jung	0.00	13.31	27.13	193.23	58.87	585.59	293.05	34.29
26	Bergerson	0.00	27.94	43.69	106.69	55.88	412.52	178.32	36.71
27	Norbeck (N)	0.00	30.53	33.08	142.48	50.89	510.89	253.91	40.42
28	Norbeck (N.E.)	0.00	39.51	43.33	99.41	58.63	568.93	328.05	42.92
29	Norbeck (N.W.)	0.20	44.77	45.53	94.12	50.88	496.54	261.04	40.10
30	Norbeck (W)	1.94	54.49	38.96	138.78	73.84	531.68	223.67	42.16

TABLE 4. The Multiple Linear Correlation Coefficients, R, and Multiple Linear Coefficients of Determination, R^2 , for Selected Subsets of the Independent Variables with Plant-Available P as the Dependent Variable.

Dependent Variable	Independent Variables	R	R^2	F
Plant-Available P	All variables	0.9014**	0.8126	
	X _{Al,Fe,Ca,Oc,pH,OM}	0.9012**	0.8123	N.S. ⁺
	X _{Al,Fe,Ca,Oc,OM}	0.9007**	0.8112	N.S. ⁺
	X _{Al,Fe,Ca,Oc}	0.8987**	0.8076	N.S. ⁺
	X _{Al,Fe,Oc}	0.8872**	0.7872	N.S. ⁺
	X _{Al,Fe}	0.8733**	0.7627	N.S. ⁺
	X _{Al}	0.8513**	0.7247	N.S. ⁺

⁺Selective elimination of independent variables not statistically significant at 5% level.

**Significantly different from zero at 1% level.

TABLE 5. The Soil P Fractions of Selected Surface Soils Before and After Cropping.

Sample No.	Site	NH ₄ Cl-extractable P ppm.	Al-P ppm.	Fe-P ppm.	Ca-P ppm.	Occluded P ppm.	Total P ppm.	Organic P ppm.
<u>Residual Soils</u>								
1	Dosch ⁺	0.00	6.64	22.73	160.88	97.04	459.65	172.36
	Dosch*	0.00	5.10	25.49	160.62	50.99	387.52	145.32
2	Lutz ⁺	0.00	23.77	52.62	145.47	86.01	459.42	152.05
	Lutz*	0.00	23.27	48.56	122.66	73.34	396.56	128.23
4	Knudsen ⁺	0.00	9.18	22.94	124.91	99.42	413.99	157.54
	Knudsen*	0.00	7.39	28.05	123.67	117.30	276.41	Negligible
9	Farstad '63 ⁺	0.00	22.95	46.93	142.83	86.72	422.36	122.93
	Farstad '63*	0.00	16.84	46.45	148.02	99.53	391.99	81.15
<u>Loess Soils</u>								
13	Nauman ⁺	0.00	32.59	28.51	292.77	86.56	525.46	85.03
	Nauman*	0.00	22.15	30.81	311.89	147.67	512.52	Negligible
18	W. of Gettysburg ⁺	0.00	13.23	18.83	321.85	117.04	547.53	76.58
	W. of Gettysburg*	0.00	6.89	22.46	319.07	137.84	465.59	Negligible

Table 5 Continued

Sample No.	Site	NH ₄ Cl-extractable P ppm.	Al-P ppm.	Fe-P ppm.	Ca-P ppm.	Occluded P ppm.	Total P ppm.	Organic P ppm.
20	N.W. of Gettysburg (eroded) [†]	0.00	7.13	21.15	242.03	129.93	580.86	180.62
	N.W. of Gettysburg (eroded)*	0.00	4.08	27.28	246.05	101.99	410.00	30.60
<u>Till Soils</u>								
22	Highmore Range 200(0-40-0) [†]	1.22	53.83	47.49	190.45	124.43	501.78	106.43
	Highmore Range 200(0-40-0)*	0.00	33.02	40.38	187.95	121.91	467.62	84.36
24	Hosmer (S.W.) [†]	0.00	16.78	22.63	152.56	132.22	435.31	111.12
	Hosmer (S.W.)*	0.00	11.19	23.40	152.63	109.38	341.88	45.28
28	Norbeck (N.E.) [†]	0.00	39.51	43.33	99.41	58.63	568.93	328.05
	Norbeck (N.E.)*	0.00	37.21	43.07	86.65	135.07	464.83	162.83

[†]Soil fractionation data before greenhouse experiment.

*Soil fractionation data at the conclusion of greenhouse experiment.

Phosphorus Recovery and Yield Experiment

Treatment of half the cans from each soil with phosphorus fertilizer resulted in increased recovery of phosphorus by the plants. The dry matter yield was correspondingly increased. Table 6 shows the percent increase in phosphorus uptake and dry matter yield upon fertilizer application to the soils.

Applied phosphorus resulted in highly significant increases in amount of phosphorus in the crop on almost all the soils. The degree of response was, however, not the same on all the soils used. Fertilizer application resulted in significant increases in yield of dry matter on almost all the soils. The degree of response was also not the same on all the soils used. The percentage increase in phosphorus uptake was roughly five times the corresponding increase in yield of dry matter.

TABLE 6. Increased P Uptake and Increased Dry-Matter Yield due to Fertilizer Phosphorus Applied to Various Surface Soils.

Sample No.	Site	Texture	Total P in Plant mg./pot		Yield of Dry Matter g./pot		Increase in P Uptake %	Increase in Yield %
			Not Fertilized	Fertilized**	Not Fertilized	Fertilized*		
<u>Residual Soils</u>								
1	Dosch	Loam	18.51	52.55	10.64	14.38	183.9	35.2
2	Lutz	Silt loam	38.85	66.93	12.49	13.88	72.3	11.1
3	Veal	Silty clay loam	26.80	52.74	11.10	14.88	96.8	34.1
4	Knudsen	Silty clay loam	19.84	62.97	10.96	15.14	217.4	38.1
5	Mitchell	Loam	29.67	58.26	11.12	13.58	96.4	22.1
6	Mitchell (N)	Loam	35.30	63.45	12.11	14.13	79.7	16.7
7	Farstad '61	Silt loam	38.35	74.59	12.45	14.13	94.5	13.5
8	Farstad '62	Silty clay loam	38.73	76.76	12.98	15.53	98.2	19.7
9	Farstad '63	Silty clay	36.50	66.27	13.23	15.33	81.6	15.9
10	Young G.	Silty clay loam	35.98	70.04	12.27	14.11	94.7	15.0
<u>Loess Soils</u>								
11	Stewart	Loam	37.09	78.26	11.93	14.58	111.0	22.2
12	Young J.	Loam	41.31	66.56	14.71	18.38	61.1	25.0
13	Nauman	Loam	40.56	76.55	13.35	14.96	88.7	12.1
14	Lyons (W)	Loam	37.81	83.34	13.96	17.04	120.4	22.1
15	Lyons (E)	Silty clay loam	36.26	64.72	12.20	14.20	78.5	16.4
16	Hauschild	Silt loam	38.79	65.46	11.42	14.62	68.8	28.0
17	N. of Gettysburg	Silt loam	20.50	59.76	8.73	11.56	191.5	32.4

Table 6 continued

Sample No.	Site	Texture	Total P in Plant mg./pot		Yield of Dry Matter g./pot		Increase in P Uptake %	Increase in Yield %
			Not Fertilized	Fertilized**	Not Fertilized	Fertilized*		
18	W. of Gettysburg	Silt loam	25.14	79.38	10.17	12.79	215.8	25.8
20	N.W. of Gettysburg (eroded)	Silt loam	21.45	67.57	8.93	12.66	215.0	41.8
21	Highmore Range							
	200(0-0-0)	Silty clay loam	37.10	74.19	11.84	13.15	100.0	11.1
22	Highmore Range							
	200(0-40-0)	Silty clay loam	57.88	76.61	15.59	16.19	32.4	3.9
23	Hosmer (S)	Silt loam	31.19	68.50	11.45	14.06	119.6	22.8
24	Hosmer (S.W.)	Silty clay loam	25.48	65.11	9.93	13.68	155.5	37.8
25	Jung	Silty clay loam	34.29	76.40	12.34	14.72	122.8	19.3
26	Bergerson	Silty clay loam	36.71	80.89	11.57	14.44	120.3	24.8
27	Norbeck (N)	Silty clay loam	40.42	73.31	13.31	15.17	81.4	14.0

Table 6 continued

Sample No.	Site	Texture	Total P in Plant mg./pot		Yield of Dry Matter g./pot		Increase in P Uptake	Increase in Yield
			Not Fertilized	Fertilized**	Not Fertilized	Fertilized*		
28	Norbeck (N.E.)	Silty clay loam	42.92	72.95	12.64	13.76	70.0	8.9
29	Norbeck (N.W.)	Silty clay loam	40.10	82.49	13.44	17.05	105.7	26.9
30	Norbeck (W)	Silty clay loam	42.16	79.52	14.52	16.89	88.6	16.3

**Statistically different from zero at 1% level.

*Statistically different from zero at 5% level.

DISCUSSION

Correlation between Soil Phosphorus Fractions
and Uptake of P by Barley Plant

The relationship between the amounts of each form of soil phosphorus and the phosphorus available to the plant was investigated by conducting a multiple regression analysis. Soil pH, organic matter content, and the soil phosphorus fractions were used as the independent variables while the phosphorus taken up by the barley plants growing on each soil was used as the dependent variable.

Soil pH and organic matter influence phosphorus availability. Organic phosphate, upon microbiological mineralization, contributes directly to plant-available phosphorus. Calcium, iron and aluminum phosphates make up a large portion of the inorganic phosphates found in the soil and are some of the forms to which soluble phosphate added to the soil is eventually converted. The occluded phosphate, however, accumulates with weathering and is unlikely to be available to the plant since the iron oxide coating would have to be removed before the phosphorus would be released.

Multiple linear regression coefficients and multiple linear coefficients of determination were computed between selected subsets of independent variables and the dependent variable. Selective elimination of the independent variables indicated that the aluminum phosphate was the most highly correlated with plant-available

phosphorus. Aluminum phosphate alone accounted for over 70 per cent of the variation in plant uptake of phosphorus. The other soil phosphorus fractions did not contribute significantly to the explained variation.

Preliminary observation of the standardized partial regression coefficients indicated, according to Snedecor (48), that the independent variables contributed to the variation in phosphorus uptake in the following decreasing order: aluminum phosphate, iron phosphate, occluded phosphate, calcium phosphate, organic matter content, pH, and organic phosphate. The inorganic soil phosphates were definitely much more related to plant-available phosphorus than was the organic phosphate.

The observation that aluminum phosphate alone contributed significantly to the explained variation differs from the reports of Al Abbas and Barber (1) and Susuki et al. (51). Al Abbas and Barber indicated that iron phosphate contributed significantly to variation in plant growth. Susuki et al., on the other hand, indicated that calcium and aluminum phosphates contributed significantly to variation in plant growth. The variation in results may be due to the interaction of the regional effect of climate with the local effect of parent material thus altering the relative amounts and distribution of soil phosphorus fractions.

The NH_4Cl -extractable phosphate is likely to be included in any extraction procedure that would evaluate the aluminum phosphate

status of the soil. The NH_4Cl -extractable phosphate represents a very small fraction of the phosphates in the soil. It is a very soluble fraction, thus being the first to be extracted in the fractionation procedure.

The Relative Amounts of Soil Phosphorus Fractions

The relative amounts of soil phosphorus fractions obtained by the fractionation procedure are in general agreement with the data of Carlson (14) and Westin and Buntley (56) regarding the relative amounts of calcium, iron, and aluminum phosphates in the surface soils of the Chestnut soil area of South Dakota.

Neither parent material nor climate seemed to considerably alter the proportional amounts of aluminum phosphate present in most of the soils used, thus indicating that the aluminum phosphate probably serves as a transitional phase for the decreasing calcium and the increasing iron phosphate fractions.

The analysis of selected soils at the conclusion of the greenhouse experiment indicated the following:

- (1) The total, organic and aluminum phosphates decrease consistently during the growth period.
- (2) The iron, calcium and occluded phosphates decreased or increased in several soils during the growth period.

This would suggest that these phosphates seem to act as

reservoirs for phosphorus which is released to the soil solution during the microbiological mineralization of organic matter and which is not taken up by the plants.

The total loss of soil phosphorus could not be accounted for by the total uptake of phosphorus by barley as determined in this experiment because only the barley tops were harvested. Phosphorus taken up by the barley roots in each cropping could not be determined without contaminating the soil interlayer with sand.

A number of investigators have concluded that there is a definite relationship between the amounts and distribution of phosphorus in soils and the degree of soil development or weathering. For the purpose of relating the weathering status of these soils to the inorganic phosphate fractions the calcium, aluminum and iron phosphates were considered. Utilizing the concept that as weathering increases there is a shift in relative abundance of inorganic phosphates from calcium toward aluminum and iron phosphates, the till soils seemed to be slightly more weathered than the residual soils whereas the soils developed from these two parent materials appeared to be considerably more weathered than the loess soils. Inclusion of the occluded fraction in another consideration showed the same trend. Table 7 presents the relative fractions of some soil inorganic phosphates as indexes of weathering. The trend of weathering observed was supported by the fact that, compared with the other parent materials, the loess soils had a larger proportion of calcium phosphate and a smaller proportion of iron phosphate fractions.

TABLE 7. Relative Fractions of Some Inorganic Phosphates as Indexes of Weathering.

Parent Materials	$\frac{\text{Fe-P} + \text{Al-P}}{\text{Fe-P} + \text{Al-P} + \text{Ca-P}}$	$\frac{\text{Fe-P} + \text{Al-P} + \text{Occluded P}}{\text{Fe-P} + \text{Al-P} + \text{Ca-P} + \text{Occluded P}}$
	Residual	0.279
Loess	0.149	0.337
Till	0.320	0.513

Phosphorus Recovery from Fertilizer Phosphate

Applied phosphate resulted in highly significant increases in phosphorus removed by the plants. The degree of response was, however, not the same on all soils. The results generally indicated that the higher the total phosphorus uptake by the plants grown without phosphate fertilizer the lower the percentage increase in phosphorus uptake due to applied phosphate. Figure 2 presents the relationship between the average total phosphorus in plants from unfertilized soils and the percentage increase in phosphorus uptake due to applied phosphate. Greenhouse fertility studies by MacClean et al. (36) also showed the same trend in uptake of phosphorus from some New Brunswick soils.

Applied phosphate resulted in varying but significant increases in yield of dry matter on almost all the soils. The results generally indicated that the higher the dry-matter yield of the plants grown without phosphate fertilizer the lower the percentage increase in dry-matter yield due to applied fertilizer. Figure 3 presents the relationship between the average dry-matter yield of plants from unfertilized soils and percentage increase in dry-matter yield due to applied phosphate.

The percentage increase in dry-matter yield due to applied phosphate was, however, much less than the corresponding percentage increase in phosphorus uptake by the plants.

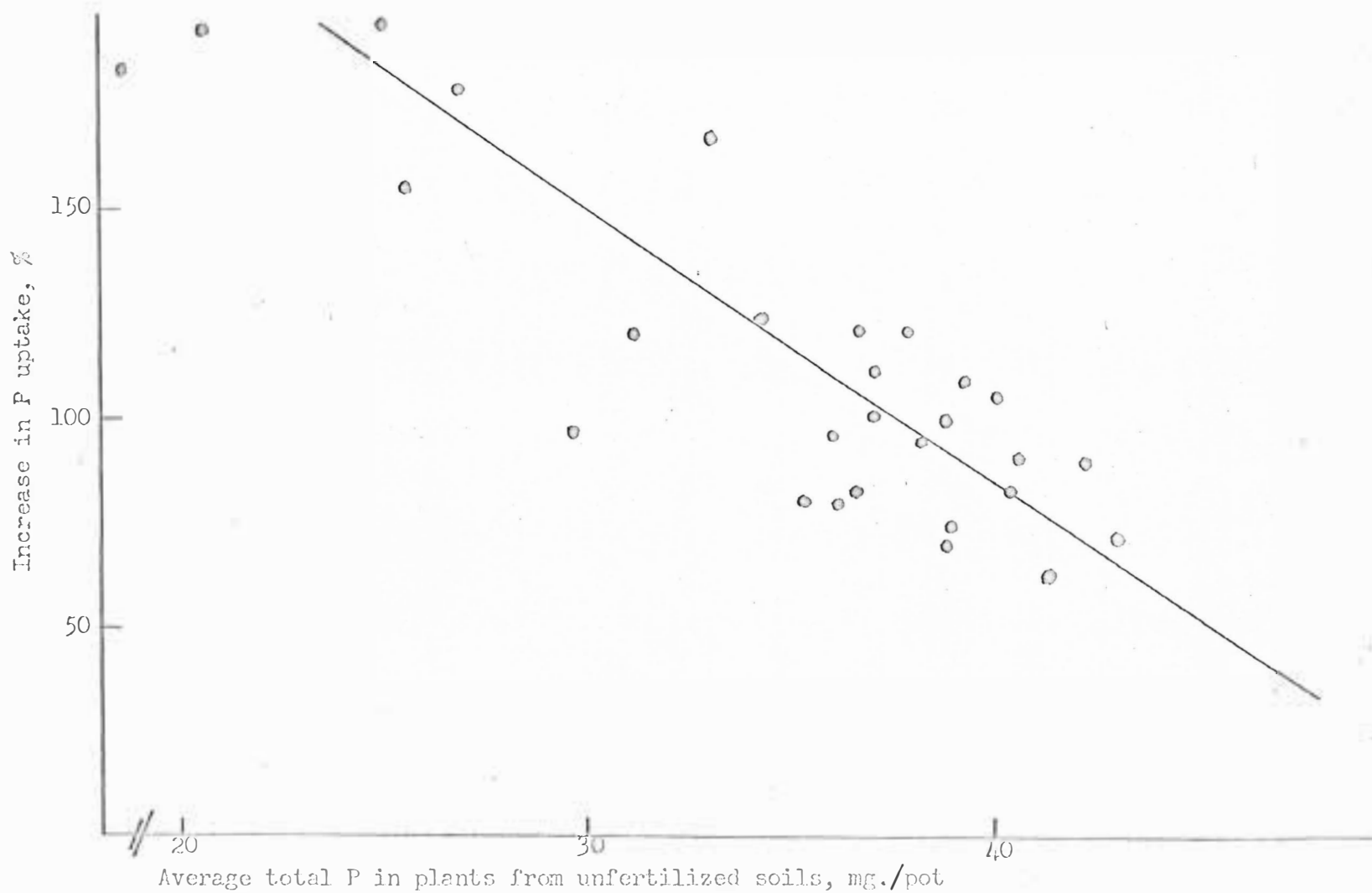


Figure 2. Relationship Between Average Total P in Plants from Unfertilized Soils and Percentage Increase in P Uptake due to Applied Phosphate.

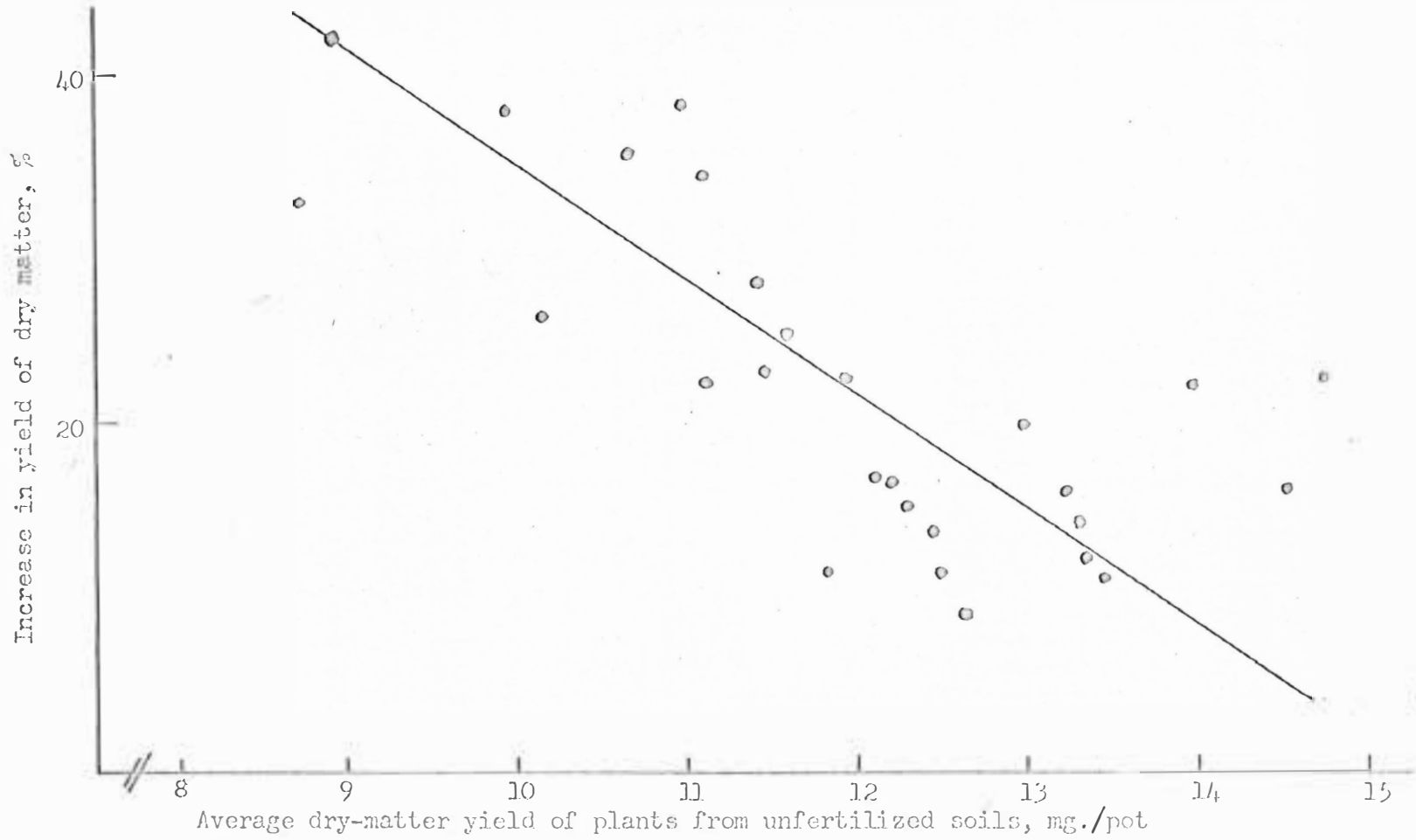


Figure 3. Relationship Between Average Dry-Matter Yield of Plants from Unfertilized Soils and Percentage Increase in Dry-Matter Yield due to Applied Phosphate.

SUMMARY AND CONCLUSIONS

The different amounts of the forms of soil phosphorus were correlated with uptake of phosphorus by barley plants grown in the greenhouse.

Regression analysis of the soil phosphorus fractions with plant-available phosphorus showed that aluminum phosphate explained most of the variation in uptake of phosphorus by the barley plants. None of the other fractions contributed significantly to the explained variation.

The fractionation data indicated that calcium phosphate generally constitutes the largest while the NH_4Cl -extractable phosphate constitutes the smallest fraction of all forms of phosphorus in the soils used. The amounts of occluded phosphate were generally higher than those of iron and aluminum phosphates respectively.

The fractionation data for selected soils at the conclusion of the greenhouse experiment indicated that (1) the aluminum and organic phosphates decrease consistently during the cropping period and that (2) the iron, calcium and occluded phosphates appear to act as reservoirs for phosphorus which is released to the soil solution during the microbiological mineralization of organic matter and which is not taken up by the plants.

Considering the sites from which the soil samples were collected and using the relative amounts of calcium, iron, aluminum and occluded

phosphates as an index of weathering, the amount of weathering in the soils increases from loess to residual to till.

The degree of plant response to applied phosphate fertilizer under greenhouse conditions was contingent upon the pre-existing levels of available phosphorus in the soils.

The choice of an extracting solution for a soil testing procedure on these soils should be one which removes aluminum phosphate to a much greater degree than any of the other forms of phosphorus present. Additional research is, however, necessary in order to fully characterize the contribution of both aluminum and iron phosphates to variation in plant uptake of phosphorus from soils of more widely separated areas.

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