A STUDY OF THE PHOSPHORUS SUPPLYING POWERS OF SOME MICHIGAN SOILS

Thesis for the Degree of Ph. D.

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Clarence C. Gray III

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This is to certify that the

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"The Phosphorus Supplying Powers of Some
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Clarence C. Gray

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of the requirements for

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L. M. Turk
Major professor

Date November 25, 1952

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ABSTRACT

A Study of the Phosphorus Supplying Powers of Some Michigan Soils

An investigation was undertaken to determine the phosphorus supplying powers of several representative Michigan soils. Forty-one different soils representing approximately eleven million acres of agricultural land in the southern half of the lower peninsula were selected for greenhouse and laboratory studies. Alfalfa was grown on each of the soils for eleven months under controlled conditions in the greenhouse. Available soil phosphorus was measured by several arbitrary chemical analyses making use of both rapid tests and more quantitative laboratory methods. Phosphorus fixation by the soils was evaluated by two different methods. One method measured the fixation of phosphorus at different rates of application and the other measured the amount of fixation with and without the free iron oxides.

Forty-one Michigan soils varied greatly in their ability to produce alfalfa without added phosphorus. No superiority of any textural group in producing alfalfa was recognized. Yields of alfalfa were increased on all soils by the addition of phosphorus.

Chemical analysis of the alfalfa revealed that the addition of phosphorus to the soils approximately doubled the percentage phosphorus composition. The recovery of phosphorus applied to the soils averaged 38.4 percent.

The amounts of chemically available phosphorus removed by the

analytical methods employed varied with the soil and with the extracting agent. No clear relationships between soil properties and soil phosphorus could be established with any of the test methods.

Definite relationships were established between soil phosphorus and alfalfa yields which showed clearly that chemically available phosphorus can be a good measure of the ability of a soil to supply phosphorus. A high degree of linear correlation was found between alfalfa yields and soil phosphorus extracted with reagents containing the fluoride ion. The Bray Adsorbed Phosphorus test, which was well correlated with alfalfa yields, percentage phosphorus composition, and total phosphorus uptake, was the best rapid test method.

Phosphorus fixation studies of twenty-two soils using several rates of applied phosphorus revealed no apparent relationship to any of the measured soil properties. The quantities of retained phosphorus varied with the soil and with the amount of applied phosphorus. The character of the fixation curves suggested that the mechanisms of fixation differed.

The removal of free iron oxides from the soils reduced phosphorus fixation from 0.6 percent to 75 percent. No relationship, however, could be established between the amount of fixation and free iron oxide content.

A classification of forty-one Michigan soils as to their phosphorus supplying powers was presented based on yield and composition of continually cropped alfalfa, soil tests for chemically available phosphorus, and phosphorus fixation studies.

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INTRODUCTION

The phosphorus supplying power of soils for agricultural plants is of considerable scientific and economic importance. Interest in the ability of a soil to furnish both native and applied phosphorus to plants has increased greatly in the last few years. The impetus for the increased interest and accompanying scientific activity has come from the introduction of improved methods of investigation, the ever increasing requirements for phosphate fertilizers, and the need for the efficient use of applied phosphates.

Workers at the New Jersey Agricultural Experiment Station have conducted extensive investigations of the phosphorus supplying powers (31) and the phosphorus-adsorbing capacities (43) of New Jersey soils. Their studies have supplied worthwhile information as to the relative need of New Jersey soils for phosphate fertilization. Additionally, their results indicate that the phosphorus-fixing capacity of a soil can be a useful guide in determining the amounts of phosphorus to apply.

In Wisconsin, experiments have been conducted to determine the relative phosphorus supplying powers of Wisconsin soils and to correlate available soil phosphorus with crop yields. Rich and Attoe (33) growing six successive crops of oats on several different Wisconsin soils recovered 32 to 62 percent of the applied phosphorus and obtained good correlation between the decrease in available soil phosphorus, as measured by 0.002 N H_2SO_4 and oat yields. Attoe and Truog (2) also found a high degree of correlation between yields of alfalfa and clover hay and levels of available phosphorus soluble in 0.002 N H_2SO_4.

The development of the fluoride methods for the extraction of soil phosphorus by Bray and his co-workers at the Illinois Agricultural Experiment Station has provided additional procedures for measuring available soil phosphorus (8,9,10). Bray has attempted to fractionate the inorganic soil phosphorus on the basis of chemical form. His methods, which purport to measure both the "adsorbed" and "acid-soluble" forms of phosphorus show promise for better correlations between soil tests and crop growth. Fluoride extractable phosphorus is well correlated with yields of general crops in Illinois when other soil nutrients are not limiting.

Michigan Agricultural Experiment Station workers Lawton, Robertson, Cook, and Rood (20) recently conducted an extensive study of the relation between crop phosphorus and potassium. The experiment was conducted over a two-year period (1946-47) on sixty-six locations in thirty-six counties of Michigan. "Available" soil phosphorus was determined by the rapid test methods of Bray, Peech, and Spurway. Linear correlation between hay yields and critical soil test levels was low. This was attributed to the wide variety of soils studies. Though they found that no individual soil test was definitely superior they concluded that in separating phosphate responsive soils from non-phosphate responsive soils, soil tests using weak acid extractants were superior to those using strong acid extractants.

In 1947, Bowers (5) working with several Michigan soils in a greenhouse study reported little correlation between soil phosphorus as measured by Bray's "Total Adsorbed, Acid-Soluble, and Organic" phosphorus extractants and alfalfa yields.

Smith (38), in 1949, had considerable success in relating Bray's rapid soil tests to wheat yields. In an extensive greenhouse experiment, using twenty Michigan soils he compared several rapid soil tests for phosphorus including Bray's "Adsorbed" and "Available" phosphorus tests. Using the principles of Mitscherlich as modified by Bray (12), Smith found that Bray's phosphorus extractions correlated well with wheat yields and were definitely superior to the Spurway Reserve test. It should be pointed out that though Bowers and Smith both made use of fluoride extraction methods for the removal of phosphorus, the methods differed considerably in the amount of fluoride used and the time of extraction, hence the amounts of phosphorus extracted varied greatly and perhaps were not comparable.

Arnold and Schmidt (1) recently reported the results of twenty-five field trials with tomatoes in the Chicago area of Illinois and southern Michigan. Their objective was to compare the tomato yields of unphosphated plots with yields from plots that had received sufficient phosphorus to supply the plants with all they could utilize. The results indicated that Bray's soil phosphorus test for acid-soluble plus adsorbed phosphorus was well correlated with the response of tomatoes to phosphate fertilizer. They concluded that

Bray's soil test for phosphorus was a valid index of the phosphorus fertility of the soils studied.

Despite the fact that phosphorus studies on Michigan soils have given varied results and in some instances have appeared conflicting and confusing, much valuable information has been obtained. However, the need for a better understanding of phosphorus levels and availability in Michigan soils still exists. The main objective of this investigation was to secure additional information relative to the phosphorus supplying powers of several Michigan soils as indicated by plant growth, chemical tests, and phosphorus fixation.

PLAN OF INVESTIGATION

This investigation was undertaken with the intention of securing data on as many representative Michigan soils as was reasonably possible.

The following general plan was adopted:

1. Study the ability of several soils to supply phosphorus for plant growth by subjecting them to the continuous root action of a phosphorus responsive plant.
2. Measure several arbitrary soil phosphorus fractions as extracted by chemical soil tests and relate them to plant growth and phosphorus uptake.
3. Study the relative phosphorus fixation by the selected soils and relate this capacity to the phosphorus supplying powers and to specific soil compounds.

EXPERIMENTAL PROCEDURE

Description of Soils Used

During the summer and fall of 1949, Doctor Kirkpatrick Lawton[1], under whose guidance this research was planned and conducted, collected representative Michigan soils and set up a phosphorus and potassium greenhouse experiment with alfalfa. This experiment, including the soils and the alfalfa grown on them, provided the basis for this investigation.

Lawton selected forty-one soils from ten counties in the southern half of the lower peninsula of Michigan. The locations by counties are shown in Figure 1 and the legal descriptions are given in Table I.

The soils represent twenty-one soil types which according to Veatch (45) comprise approximately eleven million acres of agricultural land. According to Millar (25) most of these soils were developed from material deposited by glaciers, and consequently, they are heterogenous in composition and represent a wide range in physical and chemical properties with resultant variations in fertility and productivity. Millar points out that the mineral soils, particularly the loams, silt loams and clay loams, are usually more deficient in phosphorus than in any other plant food element. The work previously cited by Lawton, et al (20) substantiates this

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[1] Associate Professor, Soil Science Department, Michigan State College.

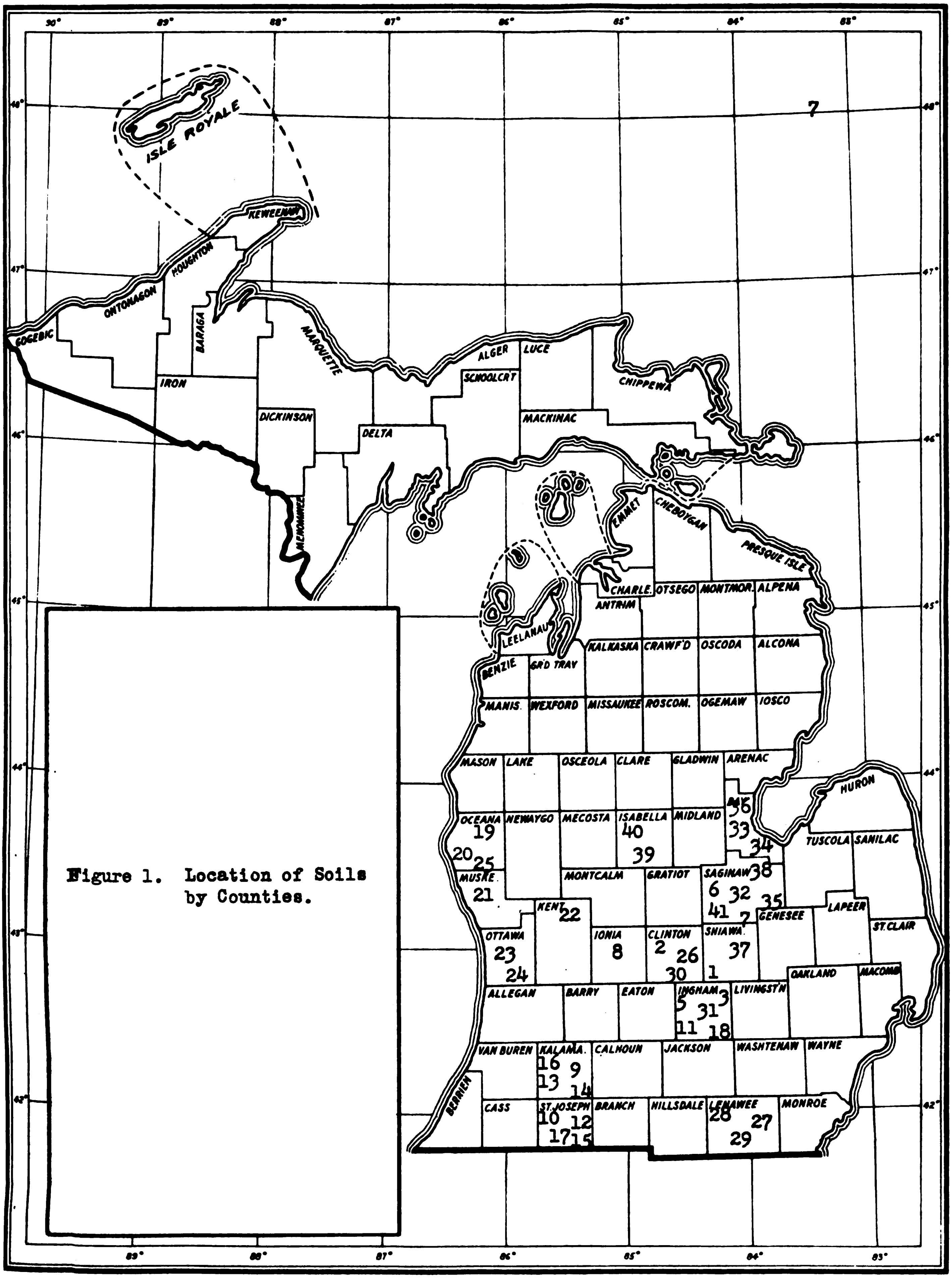

Figure 1. Location of Soils by Counties.

TABLE I

IDENTIFICATION OF SOILS

Soil no.	Soil series	County	Farm name	Legal description
1	Miami	Shiawassee	Gannsley	--
2	Miami	Clinton	Cook	--
3	Miami	Ingham	Shaw	--
4	Wisner	Tuscola	Wiergarski	--
5	Granby	Ingham	M.S.C.	SW $\frac{1}{4}$ Sec. 19 T4N R1W
6	McComb	Saginaw	Ferden	NW $\frac{1}{4}$ Sec. 33 T9N R3E
7	Brookston	Saginaw	Ferden	NW $\frac{1}{4}$ Sec. 33 T9N R3E
8	Conover	Ionia	Rudd	
9	Conover	Kalamazoo	Pancake	SW $\frac{1}{4}$ Sec. 13 T4S R10W
10	Waukesha	St. Joseph	Peters	SW $\frac{1}{4}$ Sec. 31 T7S R11W
11	Hillsdale	Ingham	Lawton	SE $\frac{1}{4}$ SW $\frac{1}{4}$ Sec. 20 T4N R1W
12	Fox	St. Joseph	Berry	SE $\frac{1}{4}$ Sec. 17 T7S R11W
13	Fox	Kalamazoo	--	SW $\frac{1}{4}$ sec. 16 T4S R9W
14	Bellefontaine	Kalamazoo	Weimer	SW $\frac{1}{4}$ Sec. 14 T4S R9W
15	Plainfield	St. Joseph	Babcock	SE $\frac{1}{4}$ Sec. 10 T7S R11W
16	Warsaw	Kalamazoo	--	NE $\frac{1}{4}$ Sec. 29 T4S R11W
17	Bellefontaine	St. Joseph	Lahrkey	SW $\frac{1}{4}$ Sec. 20 T7S R10W
18	Fox	Ingham	--	NE $\frac{1}{4}$ NW $\frac{1}{4}$ Sec. 35 T2N R1W
19	Kalkaska	Oceana	Postema	NW $\frac{1}{4}$ Sec. 23 T15N R17W
20	Kalkaska	Oceana	Tibbits	SE $\frac{1}{4}$ Sec. 27 T15N R16W
21	Kent	Muskegon	Schneider	SE $\frac{1}{4}$ Sec. 7 T12N R17W
22	Kent	Kent	--	Center Sec. 12 T6N R11W
23	Isabella	Ottawa	Fritz	SW $\frac{1}{4}$ Sec. 24 T8N R13W
24	Isabella	Ottawa	Schoenborn	NE $\frac{1}{4}$ Sec. 9 T8N R13W
25	Emmet	Oceana	Haight	SE $\frac{1}{4}$ Sec. 2 T15N R16W
26	Miami	Clinton	--	NW $\frac{1}{4}$ SW $\frac{1}{4}$ Sec. 2 T6N R2W
27	Brookston	Lenawee	--	SE $\frac{1}{4}$ Sec. 10 Ogden Twp.
28	Napanee	Lenawee	German	NW $\frac{1}{4}$ Sec. 26 Raisin Twp.
29	Toledo	Lenawee	Campbell Soup Co.	NW $\frac{1}{4}$ Sec. 9 Riga Twp.
30	Plainfield	Clinton	--	NE $\frac{1}{4}$ SW $\frac{1}{4}$ Sec. 30 T5N R1W

TABLE I (continued)

IDENTIFICATION OF SOILS

Soil no.	Soil series	County	Farm name	Legal description
31	Hillsdale	Ingham	—	SW ¼ Sec. 20 T1N R1E
32	Brookston	Saginaw	Prairie Farms	SE ¼ SW ¼ Sec. 15 T10N R4E
33	Kawkawlin	Bay	Walter	SE ¼ SW ¼ Sec. 32 T14N R4E
34	Wisner	Bay	Colberg	NE ¼ Sec. 27 T13N R6E
35	Clyde	Saginaw	Prairie Farms	SW ¼ Sec. 6 T10N R4E
36	Wisner	Bay	Munsch	SW ¼ SE ¼ Sec. 29 T13N R6E
37	Conover	Shiawassee	Survoy	
38	Conover	Saginaw	Bitterman	SW ¼ NW ¼ Sec. 23 T9N R4E
39	Selkirk	Isabella	Stilgenbauer	SE ¼ Sec. 31 T14N R3W
40	Selkirk	Isabella	Campbell	SW ¼ SE ¼ Sec. 24 T15N R4W
41	Brookston	Saginaw	Indlehofer	NW ¼ NE ¼ Sec. 17 T9N R4E

for they found that phosphorus was the element most needed on the soils studied. Veatch (45) has recently presented a comprehensive description of each of the soil types utilized in this experiment. A brief summary of each series follows:

Bellefontaine Series. This soil series usually occurs as sandy loams occupying ridges and plateau-like uplands. Widely distributed in both large and small bodies these soils are generally of medium fertility. Soil number 17, a Bellefontaine sandy loam, was secured from the farm of E. Lahrkey in St. Joseph County. Previous history shows that it was of low fertility and had been in small grain in 1948.

Brookston Series. This soil series occurs as loams and clay loams on level plains and in valleys. More than two million acres are found in extensive areas on lake bed plains. The plow soil is dark colored and underlain with wet, mottled, gritty clay. Generally, Brookston soils are high in organic matter and are very productive. Four representatives of this type were selected, soils number 7, 27, 32, and 41. Soil number 7 was secured from the experimental plots on the Lee Ferden farm in Saginaw County. Soil number 27 was obtained from the Prairie Farm in Saginaw County. Soil number 41 was secured from the farm of Frank Indlehofer in Saginaw County.

Clyde Series. This series occurs as loams and clay loams in swampy and marshy land and comprises not more than 50,000 acres. Clyde soils are generally high in organic matter and when drained are very productive. Soil number 35 was secured from the Prairie Farm

in Saginaw County.

Conover Series. This series occurs as dark-colored loams and silt loams on smooth plains. Widely distributed in the southern and eastern parts of the state, Conover soils are high in fertility and produce good yields of alfalfa, grains, and hay. Soils number 8, 9, 37, and 38 represent the Conover series in this investigation. Soil number 8 was obtained from the Rudd farm in Ionia County. Soil number 9 was obtained from the farm of M. Pancake in Kalamazoo County. Soil number 37 was obtained from the S. Survoy farm in Shiawassee County. Soil number 38 was obtained from the farm of L. Bitterman in Saginaw County.

Emmet Series. This series occurs as deep, penetrable sands and sandy loams on the ridges and plateau highlands. They are characterized by a light gray leached sand at the surface and brown sand or sandy loam at six to twelve inches. Emmet soils are widely distributed and the sandy loams where not too hilly are of fair fertility. Soil number 25 was secured from the farm of E. Haight in Oceana County. Past history shows that it was heavily fertilized with 0-20-20 fertilizer in 1948 and cropped with beans.

Fox Series. This series occurs as light brown and brown sandy loams and loams over reddish sandy and gravelly clay on level plains, terraces, and old beach ridges. Fox soils are widely distributed and when limed and fertilized produce good yields of general crops, truck crops, and small fruits. Three soils of the Fox series, numbers 12, 13, and 18 were selected. Soil number 12, a Fox sandy loam, was obtained from the F. Berry farm in St. Joseph County and had been in sod for the past five years. Soil number 13 was obtained from Kalamazoo County while number 18 was from Ingham County.

Granby Series. This series occurs as dark colored loams and sandy loams in flat areas such as low plains or borders of lakes and muck swamps. The series is found as small areas in association with the more calcareous sandy soils. Generally, the areas are too wet or in too small bodies to be of high agricultural value. Soil number 5 was secured from the Michigan State College farm in Ingham County and past records show low to average yields were produced from this area.

Hillsdale Series. This series occurs as light brownish and yellowish loams and light loams on hilly to smooth rolling uplands. Hillsdale soils are widely distributed and are of medium to high value for general agriculture when managed properly. Soil number 11, secured from the K. Lawton farm in Ingham County, was strongly acid and in a state of low chemical fertility. Soil number 31 was taken from a site in the southern part of Ingham County and had a high content of native phosphorus in "available" forms.

Isabella Series. This series occurs as light brownish loam and clay loam soils on gently rolling to moderately hilly upland clay plains. These soils are widely distributed and have a relatively high value for general farming. Soil number 23 was obtained from the farm of C. Fritz in Ottawa County and the evidence available indicated medium fertility. Soil number 24, obtained from the W. Schoenborn farm in Ottawa County, was taken from an old peach orchard where severe erosion had taken place.

Kalkaska Series. This series occurs as dark brown sands and light sandy loams on level and pitted plains, and dry, bench land. Kalkaska soils comprise extensive areas and produce low to fair yields because of their low water holding capacity. Soil number 19 was obtained from the D. Postema farm in Oceana County and had a past history of low fertility. It had been marled in 1948. Soil number 20 was obtained from the farm of O. Tibbits in Oceana County. It had received no lime or fertilizer in the past five years but had been manured in 1948.

Kawkawlin Series. This series occurs as dark colored loamy soils over compact, granular and gritty clays on level clay plains of old lake beds. Kawkawlin soils are of relatively high fertility and are of medium to high agricultural value. Soil number 33 was obtained from the farm of L. Walter in Bay County and had received no fertilizer or manure in the past three years.

Kent Series. This series occurs as light brown and gray heavy silt loams and clay over plastic compact, and relatively impervious clays. Kent soils are distributed mostly in small areas on level, upland clay plains and are used mostly for hay and small grains. Soil number 21 was obtained from the F. Schneider farm in Muskegon County and past cropping data indicated it was in a state of medium fertility. Soil number 22 was taken from a roadside site in an eroded area in Kent County and was probably mixed with some subsoil.

Macomb Series. This series occurs as dark brown and dark gray coarse friable loams. Generally found in small bodies on flattish swampy land, Macomb soils are similar to Brookston soils but coarser in texture. High in the element of chemical fertility, these soils when properly drained are productive. Soil number 6 was obtained from the L. Ferden farm in Saginaw County and was considered to be in a medium condition of fertility.

Miami Series. This series occurs as light brown loams and silt loams over brownish, compact, retentive but granular clays on gently rolling upland clay plains. Miami soils comprise one of the more important series in aggregate acreage under agricultural production. They are widely distributed soils and rank high in fertility. They are extensively used for general farming purposes. Four Miami soils were selected for this investigation. Soil number 1 was obtained from the Gannsley farm in Shiawassee County. Soil number 2 was obtained from the R. Cook farm in Clinton County and was of moderate fertility. Soil number 3 was obtained from the farm of E. Shaw in Ingham County and was taken from an eroded area. Soil number 26 was taken from a farm site in Clinton County and was known to be of low fertility at least with respect to phosphorus.

Napanee Series. This series occurs as gray and light brown silts and clay loams over very compact yellowish clays. Generally found on level and rolling uplands, the Napanee soils are not widely distributed. Soil number 28 was secured from the farm of W. German in Lenawee County and was in a medium state of fertility.

Plainfield Series. This series occurs as light brown sands and light sandy loams on level sand plains and dry sandy valleys. Plainfield soils are low in organic matter and the mineral elements of fertility. They are widely distributed and total a large aggregate acreage in crop production. They are low in value for general agriculture but when fertilized and irrigated can be used successfully for truck and small fruit farming. Soil number 30 was obtained from an abandoned area in Clinton County. Soil number 15 was obtained from the Babcock farm in St. Joseph County.

Selkirk Series. This series occurs as grayish clay soils underlain with plastic limy clays. Fairly widely distributed in the northern part of the lower peninsula, Selkirk soils are usually found on flat clay plains containing numerous wet depressions. Though these soils are difficult to drain and till they are suitable for hay, small grains, and pasture and can be moderately productive. Soil number 39 was obtained from the R. Stilgenbauer farm in Isabella County and from farm records was considered to have a moderate fertility status. Soil number 40 was obtained from the farm of R. Campbell in Isabella County and was moderately productive.

Toledo Series. This series occurs as dark colored wet soils on flat clay plains and is distinguished from the Brookston series by the more plastic nature of the underlying clay which is lacustrine in origin and free from imbedded pebbles and boulders. The relatively small areas of Toledo soil are unimportant agriculturally, although they can be made highly productive when properly drained. Soil number

29 was secured from the Campbell Soup Company Experimental Plots in Lenawee County.

Warsaw Series. This series occurs as dark sandy loams, loams and silt loams on level dry plains. The total acreage is rather small but is mostly under cultivation. In most cases the soil is rather productive. Soil number 16 taken from an uncultivated roadside site in Kalamazoo County.

Waukesha Series. Waukesha soils include well drained, dark colored prairie soils and are equivalent to the Warsaw. Soil number 10 was obtained from a field on the C. Peters farm in St. Joseph County, which had been in sod since 1948.

Wisner Series. This series occurs as light gray loams and clay loams over plastic wet clays and silt loams. The total acreage of Wisner soils is small. Generally they are found in low lying wet areas. They are limy at the surface and are relatively fertile when properly drained. Such soils are moderately productive for alfalfa, small grains, beans, and beets. Soil number 4 was obtained from the Wiergorski farm in Tuscola County. Soil number 36 was obtained from the farm of H. Munsch in Bay County. No fertilizer or manure had been applied on the latter soil for two years. Beans had been grown in 1949.

Physical and Chemical Determinations of Soils Used

In order to evaluate the difference between the soils under investigation, several physical and chemical determinations were carried out.

The particle size distribution by the method of Bouyoucous is presented in Table II. The soils varied in texture from coarse sandy soils to heavy clay loams.

The cation exchange capacity, total exchangeable bases, pH, and the organic matter content of the soils are shown in Table III. Cation exchange capacity and pH were determined by the methods of Peech (28) and total exchangeable bases were measured as outlined by Bray and Wilhite (7). Organic matter was determined by a dry combustion method essentially as described by Piper (30). In reaction, the soils ranged from strongly acid to alkaline with the hydrogen concentration varying inversely with the degree of base saturation. The cation exchange capacities ranged from 4.3 milliequivalents per 100 grams of soil in the case of the acid Plainfield loamy sand to 30.0 milliequivalents in the case of the alkaline Granby sandy loam high in organic matter. The percentage of organic matter varied from a high of 12.67 percent to a low of 1.42 percent. It can be observed that the values for exchange capacity vary directly with the percent of clay and organic matter since high exchange capacities were associated with high percentages of clay and organic matter.

Greenhouse Experiment with Alfalfa

The greenhouse experiment as designed by Lawton was set up to measure the phosphorus and potassium supplying powers of the soils. The treatments on each soil were:

TABLE II

THE PARTICLE SIZE DISTRIBUTION OF SOILS USED*

	Percent composition		
	Size of particles in millimeters		
Soil type and number	2.00-0.05	0.05-0.002	0.002
1 Miami sandy loam	55.0	26.0	19.0
2 Miami clay loam	52.0	28.0	20.0
3 Miami clay loam	57.0	23.0	27.0
4 Wisner sandy clay loam	64.0	15.6	20.4
5 Granby sandy loam	69.2	16.2	14.6
6 Macomb sandy loam	62.0	23.6	14.4
7 Brookston sandy clay loam	54.0	16.0	34.0
8 Conover loam	44.0	35.0	21.0
9 Conover loam	45.0	30.0	25.0
10 Waukesha sandy loam	64.8	17.2	18.0
11 Hillsdale sandy loam	65.0	22.0	13.0
12 Fox loamy sand	82.0	9.0	9.0
13 Fox loam	50.0	33.0	17.0
14 Bellefontaine sandy loam	54.0	30.0	16.0
15 Plainfield sandy loam	74.0	12.0	14.0
16 Warsaw loam	52.0	30.0	18.0
17 Bellefontaine sand	87.5	7.0	5.5
18 Fox sandy loam	74.4	13.2	12.4
19 Kalkaska sand	88.0	6.0	6.0
20 Kalkaska sand	92.0	3.5	4.5
21 Kent sandy clay loam	55.4	18.6	26.0
22 Kent clay loam	44.0	18.0	36.0
23 Isabella sandy clay loam	50.8	28.2	21.0
24 Isabella sandy clay loam	58.0	22.0	20.0
25 Emmet sandy loam	78.0	14.0	8.0
26 Miami loam	52.4	28.0	19.6
27 Brookston sandy clay	56.4	8.0	35.6
28 Napanee sandy clay loam	48.4	26.0	25.6
29 Toledo clay loam	42.0	25.6	32.4
30 Plainfield loamy sand	83.6	10.2	6.2
32 Brookston loam	44.0	30.0	26.0
33 Kawkawlin sandy clay loam	61.0	18.0	21.0
34 Wisner sandy clay loam	49.0	21.4	29.6
35 Clyde clay loam	35.0	28.6	36.4
36 Wisner sandy clay loam	50.0	20.0	30.0
37 Conover sandy clay loam	58.0	22.0	20.0
38 Conover sandy clay loam	48.0	26.4	25.6
39 Selkirk loam	48.0	36.6	16.0
40 Selkirk sandy clay loam	62.0	8.0	30.0
41 Brookston sandy loam	64.0	21.0	15.0

* Determined according to Bouyoucos (4)

TABLE III

THE pH, BASE EXCHANGE CAPACITY, TOTAL EXCHANGEABLE BASES, AND ORGANIC MATTER CONTENT OF THE SOILS

Soil type	pH[1]	Base exchange capacity[1] me./100 grams	Total exchangeable bases[2] me./100 grams	O.M.[3] percent
1 Miami sandy loam	7.80	10.82	8.13	2.98
2 Miami clay loam	6.25	12.84	8.97	2.13
3 Miami clay loam	7.50	11.26	8.46	3.13
4 Wisner sandy clay loam	7.70	12.80	9.33	6.91
5 Granby sandy loam	7.60	30.00	14.24	12.67
6 Macomb sandy loam	8.00	14.00	12.64	5.55
7 Brookston sandy clay loam	6.35	18.20	10.20	4.30
8 Conover loam	6.60	21.64	11.92	4.66
9 Conover loam	6.20	20.00	11.24	3.65
10 Waukesha sandy loam	5.05	15.20	5.76	4.00
11 Hillsdale sandy loam	4.85	8.86	3.10	2.38
12 Fox loamy sand	5.55	4.42	1.90	1.14
13 Fox loam	6.10	10.90	5.10	3.78
14 Bellefontaine sandy loam	4.70	10.82	1.62	1.79
15 Plainfield sandy loam	5.20	7.60	1.50	2.08
16 Warsaw loam	5.50	24.88	7.86	4.31
17 Bellefontaine sand	6.75	6.00	3.50	1.34
18 Fox sandy loam	6.20	11.66	5.28	2.39
19 Kalkaska sand	7.40	9.20	4.30	1.54
20 Kalkaska sand	6.20	10.48	5.00	1.36
21 Kent sandy clay loam	5.50	13.80	5.24	2.09
22 Kent clay loam	7.60	12.80	10.50	1.76
23 Isabella sandy clay loam	7.20	8.26	6.20	3.10
24 Isabella sandy clay loam	5.90	8.60	5.52	1.93
25 Emmet sandy loam	6.55	10.40	3.60	1.65
26 Miami loam	5.30	18.42	8.20	2.17
27 Brookston sandy clay	6.98	22.90	11.80	4.71
28 Napanee sandy clay loam	6.20	20.80	10.40	4.51
29 Toledo clay loam	5.85	23.62	11.12	4.75
30 Plainfield loamy sand	5.50	4.30	1.40	1.54

TABLE III (continued)

THE pH, BASE EXCHANGE CAPACITY, TOTAL EXCHANGEABLE BASES, AND ORGANIC MATTER CONTENT OF THE SOILS

Soil type	pH[1]	Base exchange capacity[1] me./100 grams	Total exchangeable bases[2] me./100 grams	O.M.[3] percent
32 Brookston loam	7.40	16.80	13.82	5.01
33 Kawkawlin sandy clay loam	6.60	17.22	10.88	3.72
34 Wisner sandy clay loam	7.80	14.40	14.80	4.75
35 Clyde clay loam	6.65	27.30	14.22	6.90
36 Wisner sandy clay loam	7.40	14.00	10.42	3.60
37 Conover sandy clay loam	6.15	13.22	6.80	3.39
38 Conover sandy clay loam	5.90	8.00	4.64	2.70
39 Selkirk loam	6.75	16.02	7.40	2.78
40 Selkirk sandy clay loam	7.20	22.80	8.50	3.94
41 Brookston sandy loam	6.40	12.80	4.96	3.93

1 Determined according to Peech (28).
2 Determined by the method of Bray and Wilhite (7).
3 Dry combustion method.

Treatment	Elements Applied
Check	Nitrogen
1	Nitrogen and Potassium
2	Nitrogen and Phosphorus
3	Nitrogen, Potassium, and Phosphorus

This investigation was concerned only with treatments 1 and 3. It was assumed that a comparison of the results of these two treatments would give the most reliable information concerning phosphorus. Each treatment was replicated three times.

According to Lawton, the soils were limed, fertilized, and planted to alfalfa in one-gallon glazed pots on August 25, 1949. In Table IV information is presented relative to the amounts of the individual soils used and a summary of the initial fertilizer treatment. Potassium and nitrogen were applied at the approximate rates of 525 pounds potassium and 110 pounds nitrogen per acre respectively as potassium chloride and ammonium sulfate. The phosphorus treated soils received phosphorus at the approximate rate of 246 pounds of phosphorus per acre as mono-calcium phosphate. Lime requirement was determined by the method of Bradfield and Allison (6).

After emergence, the alfalfa seedlings were thinned to twelve per jar. By periodic weighings the soils were kept approximately at the moisture equivalent. The alfalfa was grown on the soils for approximately eleven months. Seven harvests were taken on the following dates;

TABLE IV

INITIAL FERTILIZER TREATMENT OF GREENHOUSE SOILS

Soil Number	Weight of soil per pot grams	Grams of chemicals per pot		
		$CaCO_3$	$(NH_4)SO_4$	KCl & $Ca(H_2PO_4)_2 \cdot H_2O$
1	4000	None	1.0	2.0
2	4000	6.4	1.0	2.0
3	4300	None	1.1	2.2
4	4000	None	1.0	2.0
5	4000	None	1.0	2.0
6	4300	None	1.1	2.2
7	4000	6.4	1.0	2.0
8	4000	None	1.0	2.0
9	4000	10.6	1.0	2.0
10	4000	18.2	1.0	2.0
11	4000	13.0	1.0	2.0
12	4500	5.2	1.1	2.2
13	4000	8.6	1.0	2.0
14	4200	18.0	1.1	2.2
15	4500	10.6	1.1	2.2
16	4000	15.0	1.0	2.0
17	4500	7.7	1.1	2.2
18	4400	7.2	1.1	2.2
19	4500	3.0	1.1	2.2
20	4500	7.7	1.1	2.2
21	4000	16.1	1.0	2.0
22	4000	None	1.0	2.0
23	4000	4.3	1.0	2.0
24	4000	10.7	1.0	2.0
25	4500	7.2	1.1	2.2
26	4000	15.0	1.0	2.0
27	4000	None	1.0	2.0
28	4000	8.6	1.0	2.0
29	4000	10.6	1.0	2.0
30	4500	10.2	1.1	2.2
31	4000	3.0	1.0	2.0
32	4000	3.0	1.0	2.0
33	4200	4.0	1.1	2.2
34	4000	None	1.0	2.0
35	4000	10.7	1.0	2.0
36	4000	None	1.0	2.0
37	4100	15.0	1.1	2.2
38	4100	6.4	1.1	2.2
39	4500	4.3	1.1	2.2
40	4000	4.3	1.0	2.0
41	4100	8.6	1.0	2.0

First Harvest	-- October 23-26, 1949
Second Harvest	-- December 3-6, 1949
Third Harvest	-- January 17-20, 1950
Fourth Harvest	-- March 20-27, 1950
Fifth Harvest	-- May 15, 1950
Sixth Harvest	-- June 14-16, and 23-24, 1950
Seventh Harvest	-- July 15-20, 1950

As indicated by the number of harvests growth was rapid especially in the spring of 1950. Additional fertilizer treatments were made at four times during the course of the experiment. On October 30, 1949, the equivalent per acre of 110 pounds of N as NH_4NO_3, 10 pounds of $CuSO_4 \cdot 5H_2O$, 10 pounds of $Co(NO_3)_2$, 10 pounds of $Na_2B_4O_7 \cdot 10H_2O$, 5 pounds of $ZnSO_4$, and 1 pound of $(NH_4)_2\ MoO_4$ were added to each jar in solution. On December 10, 1949, 0.5 grams of $(NH_4)_2SO_4$ (approximately 50 pounds per acre of nitrogen) and 1.0 grams of KCl (approximately 263 pounds per acre of potassium) were added in solution to each pot. At the same time there was applied an additional 1.0 gram of $Ca(H_2PO_4)_2 \cdot H_2O$ per pot (approximately 123 pounds of phosphorus). On February 12, 1950 the nitrogen and minor element application of October 30, 1949 was repeated. On April 10, 1950 an additional equivalent of 333 pounds per acre of NH_4NO_3 was applied in solution. The total amounts of the nutrients applied during the course of the experiment were:

<u>Nutrient</u>	<u>Pounds per Acre</u>
Nitrogen	499.55 to 514.23

Nutrient	Pounds per Acre
Phosphorus	349.56 to 383.66
Potassium	746.66 to 819.50
Copper	2.55
Cobalt	2.03
Zinc	1.14
Molybdenum	0.45
Boron	2.15

Phosphorus Determinations

Soils. The soils for phosphorus analysis were air-dried and screened through a 20-mesh sieve. They were stored in paper cartons until ready for use. Soil phosphorus was extracted by the methods of Spurway and Lawton (39) and Bray (11,12). The soil test extraction procedures are summarized as follows:

Spurway's Reserve Phosphorus. Five grams of soil were shaken for exactly one minute in 0.135 N HCl.

Bray's Adsorbed Phosphorus. One gram of soil was shaken exactly 40 seconds in a solution of 0.03 N NH_4F in 0.025 N HCl.

Bray's Available Phosphorus. One gram of soil was shaken exactly 40 seconds in a solution of 0.03 N NH_4F in 0.1 N HCl.

Bray's Total Acid-Soluble and Adsorbed Phosphorus. One gram of soil was shaken in 0.1 N HCl for 30 minutes after which time one gram of solid N H_4F was added and the mixture shaken for an additional hour.

Bray's Total Acid-Soluble, Adsorbed, and Organic Phosphorus. One gram of soil was digested on a steam bath for 30 minutes with 15 milliliters of 30 percent H_2O_2 and 10 milliliters of water. Then, 10 milliliters of 0.5 N HCl and sufficient water were added to make the total volume 50 milliliters. This soil solution suspension, 0.1 N with respect to HCl, was shaken for 30 minutes after which one gram of solid NH_4F was added and the suspension shaken for an additional hour.

Bray's Organic Phosphorus. According to Bray (11), organic phosphorus is calculated by subtracting the total acid-soluble and adsorbed phosphorus from the total acid-soluble, adsorbed, and organic phosphorus.

For the extractions longer than one minute, a reciprocating type shaking machine was used. Phosphorus in the soil extracts was determined colormetrically using Bray's procedure (12) and a Coleman Spectrophotometer utilizing a 6500 Angstrom wavelength band.

Alfalfa. The seven harvests of alfalfa tops were oven dried at 60°C, weighed, and ground in a Wiley semi-micromill to pass through a 20-mesh screen. Ten percent of the weight of each of the harvests was taken and composited into one sample for phosphorus analysis. These composited samples were stored in sealed thirty millimeter glass bottles for future use. The roots and crowns were removed from the soils by screening through a one-quarter inch galvanized wire screen. They were washed free of soil particles and dried, weighed, ground, and stored in the same manner as the tops.

For total phosphorus analysis, one gram samples of plant material were dried over night at 65°C and wet digested using the perchloric, sulphuric, and nitric method as described by Piper (30). Digested samples were made up to 100 milliliter volume and phosphorus determined on an aliquot using the same procedure as used with the soil extracts.

Fixation Studies

Rate of Applied Phosphorus. Twenty-four soils representing each soil type under investigation were selected to measure the fixation of phosphorus applied at increasing rates. The method employed was as follows:

A 20 gram sample of 20-mesh soil and 10 milliliters of distilled water were placed in a one-half pint mason jar. While being mechanically stirred, 10 milliliters of a K_2HPO_4 solution containing a calculated amount of phosphorus was added. After thorough mixing was effected, the sample was placed on a rack and allowed to evaporate to dryness. One week was required to completely air-dry all samples. The rates of phosphorus applied to duplicate samples were 0, 25, 100, and 150 parts per million on a soil basis. The amount of phosphorus fixed was measured by the amount not removed from the air-dry soil by a 40 second extraction with Bray's 0.025 N HCl and 0.03 N NH_4F solution. The soils were treated with phosphorus on June 30, 1952 and the phosphorus determinations were made July 10-11, 1952.

Removal of Free Iron Oxides. In an effort to evaluate the influence of free iron oxides on phosphorus fixation in the soils being studied, they were removed from all of the soils by the sodium hydrosulphite method as described by Deb (16). Phosphorus fixation was measured on the untreated (original soil) and treated (iron oxides removed) soils in the following manner:

50 milliliters of 10 parts per million phosphorus solution made from K_2HPO_4 was added from a burette to a one gram sample in a one-half pint mason jar. Using normal HCl and NaOH and a Beckman glass electrode pH meter, the pH was adjusted to that of the original untreated soil. All of the treated soils had to be adjusted because the acid wash in the iron oxide removal had left them strongly acid. Some of the untreated soils which were strongly buffered did not require adjustment. In no instance was more than two drops of NaOH or HCl needed to reach the desired pH. Investigation indicated that the pH as adjusted did not drift appreciably in a 48 hour period. After treatment the jars were sealed and placed on a rack and left at room temperature. Each day the jars were shaken to insure thorough mixing of the soils and the phosphorus solutions. Thoroughly sealed to prevent evaporation loss, the jars were allowed to stand for a period of fifteen days. On the last day, a five milliliter aliquot of the supernatant liquid was removed and analyzed for phosphorus. The amount of phosphorus fixed was calculated from the difference in the phosphorus concentration of the solution at the beginning and at the end of the incubation period.

RESULTS AND DISCUSSION

Greenhouse Experiment

Alfalfa yields. A summary of the observations of alfalfa growth during the course of the experiment is given in Table V. Legume growth on the phosphorus treated soils was good in all instances. With the exception of the appearance of slight potassium deficiency symptoms after the sixth harvest on several soils, there were no apparent limitations to growth. The symptoms were only slight and perhaps had no appreciable effect on dry weight yields. Growth on the non-phosphated soils varied from good to poor depending on the soil type. In a few cases the differences in growth which resulted from the phosphorus treatments were not easily distinguished, especially in the early stages of the experiment. However, on most soils the response to the phosphate fertilizer was plainly evident from the beginning. After the sixth harvest, the phosphorus supply had become so limited in most of the unphosphated soils that growth was severely checked. As a consequence, it was decided to end the experiment after the seventh harvest.

The yields of tops and roots for seven harvests are given in Table VI. The soils are arranged in order of hay yields without phosphorus fertilizer. The yields show that the soils varied greatly in their ability to produce alfalfa without added phosphorus. The yields for seven harvests range from a low of 33.1 grams per pot on the Kalkaska sand to 103.7 grams on the Hillsdale loam with the

TABLE V

OBSERVATIONS OF ALFALFA GROWTH ON FORTY-ONE MICHIGAN SOILS[a]

Soil number and type	Treatment: No phosphorus	Treatment: Phosphorus
1 Miami sandy loam	F to P[b]	G[b]
2 Miami clay loam	F	G*
3 Miami clay loam	F	G*
4 Wisner sandy clay loam	F	G
5 Granby sandy loam	M- F	G*
6 Macomb sandy loam	G to P	G*
7 Brookston sandy clay loam	G	G*
8 Conover loam	M to F	G
9 Conover loam	M	G*
10 Waukesha sandy loam	G to P	G*
11 Hillsdale sandy loam	F to P	G
12 Fox loamy sand	P to VP	G
13 Fox loam	G	G
14 Bellefontaine sandy loam	F to VP	G
15 Plainfield sandy loam	G to F	G*
16 Warsaw loam	F to P	G
17 Bellefontaine sand	G to F	G
18 Fox sandy loam	G	G
19 Kalkaska sand	P to VP	G
20 Kalkaska sand	F to P	G*
21 Kent sandy clay loam	G to M	G
22 Kent clay loam	F	G
23 Isabella sandy clay loam	G- F	G
24 Isabella sandy clay loam	F to VP	G
25 Emmet sandy loam	G	G
26 Miami loam	P to VP	G
27 Brookston sandy clay	G to M	G
28 Napanee sandy day loam	P	G
29 Toledo clay loam	P	G
30 Plainfield loamy sand	G to F	G
31 Hillsdale	G	G
32 Brookston loam	M to F	G
33 Kawkawlin sandy clay loam	F	G
34 Wisner sandy clay loam	P	G
35 Clyde clay loam	F	G
36 Wisner sandy clay loam	P	G
37 Conover sandy clay loam	F	G
38 Conover sandy clay loam	F to P	G
39 Selkirk loam	P	G*
40 Selkirk sandy clay loam	G to M	G
41 Brookston sandy loam	M- F	G

[a] Average relative appearance of the seven harvests.

[b] P = poor, f = fair, M = medium, G = good.

* Slight potassium deficiency symptoms apparent on seventh harvest.

TABLE VI

THE EFFECT OF APPLIED PHOSPHORUS ON ALFALFA YIELDS — SEVEN HARVESTS

Rank according to yield without P	Soil series		Dry Weight in Grams** Seven Harvests No P	Dry Weight in Grams** Seven Harvests P	Dry Weight in Grams** Roots No P	Dry Weight in Grams** Roots P	Total Dry Weight grams No P	Total Dry Weight grams P	Increase in Yield of Tops P grams	Increase in Yield of Tops No P percent
1	Hillsdale	(31)*	103.7	113.3	43.2	41.1	146.9	154.4	9.6	9.2
2	Fox	(18)	102.5	105.6	40.3	29.8	142.8	135.4	3.1	3.0
3	Fox	(13)	95.9	107.2	40.9	40.8	136.8	148.0	11.3	11.8
4	Brookston	(27)	94.8	108.2	34.6	39.2	129.4	147.4	13.4	14.1
5	Emmet	(25)	93.4	112.9	40.8	44.3	134.2	157.2	19.5	20.9
6	Clyde	(35)	91.5	103.1	32.5	38.3	124.0	141.4	11.6	12.7
7	Selkirk	(40)	83.4	103.5	***	***			20.1	24.1
8	Bellefontaine	(17)	81.8	93.2	35.9	38.6	117.7	131.8	11.4	13.9
9	Plainfield	(15)	77.9	98.4	41.1	42.7	119.0	141.1	20.5	26.3
10	Hillsdale	(11)	77.8	89.5	41.6	43.6	119.4	133.1	11.7	15.0
11	Brookston	(7)	77.6	99.7	28.1	39.7	105.7	139.4	22.1	28.5
12	Kent	(21)	77.2	93.6	35.5	38.7	112.7	132.3	16.4	21.2
13	Plainfield	(30)	74.2	92.4	38.5	49.3	112.7	141.7	18.2	24.5
14	Conover	(8)	70.9	101.6	38.2	39.4	109.1	141.0	30.7	43.3
15	Waukesha	(10)	69.7	88.4	40.7	40.4	110.4	128.8	18.7	26.8
16	Miami	(3)	68.8	98.7	36.0	46.0	104.8	144.7	29.9	43.5
17	Kent	(22)	64.5	101.9	25.6	33.9	90.1	135.8	37.4	58.0
18	Brookston	(32)	59.2	97.5	31.2	42.1	90.4	139.6	38.3	64.7
19	Miami	(2)	56.9	94.6	27.4	33.3	84.3	127.9	37.7	66.3
20	Kalkaska	(20)	56.2	91.8	34.6	30.7	90.8	122.5	35.6	63.3
21	Brookston	(41)	55.9	100.2	***	***			44.3	79.2
22	Conover	(38)	51.5	104.2	23.1	30.6	74.6	134.8	52.7	102.3
23	Macomb	(6)	51.1	123.1	27.3	46.2	78.4	169.3	72.0	140.9
24	Napanee	(28)	50.8	101.1	30.5	41.8	81.3	142.9	50.3	99.0
25	Conover	(37)	50.0	106.4	20.7	35.0	70.7	141.4	56.4	112.8
26	Toledo	(29)	49.1	103.0	26.4	38.1	75.5	141.1	53.9	109.8
27	Wisner	(34)	48.1	92.2	18.1	32.1	66.2	124.3	44.1	91.6
28	Isabella	(23)	47.9	97.7	32.0	45.2	79.9	142.9	49.8	103.9
29	Granby	(5)	45.9	94.6	26.6	49.9	72.5	144.5	48.7	106.1
30	Bellefontaine	(14)	44.0	94.6	30.2	41.8	74.2	136.4	50.6	115.0

TABLE VI (continued)

THE EFFECT OF APPLIED PHOSPHORUS ON ALFALFA YIELDS -- SEVEN HARVESTS

Rank according to yield without P	Soil series		Dry Weight in Grams** Seven Harvests No P	Seven Harvests P	Roots No P	Roots P	Total Dry Weight grams No P	Total Dry Weight grams P	Increase in Yield of Tops P grams	Increase in Yield of Tops No P percent
31	Kawkawlin	(33)	43.5	100.3	27.6	34.4	71.1	134.7	56.8	130.6
32	Warsaw	(16)	41.7	93.0	23.6	45.1	65.3	138.1	51.3	123.0
33	Wisner	(4)	41.3	108.3	26.1	48.1	67.4	157.4	67.0	162.2
34	Fox	(12)	40.5	87.0	32.8	41.2	73.3	128.2	46.5	114.8
35	Wisner	(36)	39.7	106.4	19.3	37.6	59.0	144.0	66.7	168.1
36	Miami	(1)	38.6	97.5	23.6	38.3	62.2	135.8	58.9	152.6
37	Miami	(26)	37.8	93.5	22.1	41.5	59.9	135.0	55.7	147.4
38	Conover	(9)	36.9	105.9	20.7	40.6	57.6	146.5	69.0	187.0
39	Isabella	(24)	36.8	104.8	24.1	42.0	60.9	146.8	68.0	184.8
40	Selkirk	(39)	36.5	106.2	21.2	42.5	57.7	148.7	69.7	191.0
41	Kalkaska	(19)	33.1	105.1	23.1	37.4	56.2	142.5	72.0	217.5
Average			60.9	100.5	30.4	40.0	90.9	140.5	39.6	65.0

* Original soil number.
** Average of three replications.
*** Data lost.

average yield on the forty-one soils at 60.9 grams. This wide difference in total dry weight was reduced where phosphorus was added. The yields on the phosphorus treated soils ranged from 88.4 grams per pot on the Waukesha sandy loam to a high of 123.1 grams on the Macomb sandy loam with the average yield at 100.5 grams. Yield increases due to added phosphorus varied from 3.1 grams in the case of the Fox sandy loam to 72.0 grams in the case of the Macomb sandy loam with an average increase of 39.6 grams per pot.. From a percentage standpoint, the increases were more impressive. The greatest percent increase was 216.8 percent on the Kalkaska sand and the lowest was 3.0 percent on the Fox sandy loam. The average percent increase in yield caused by the phosphorus fertilizer was 65.0 percent. These yield data indicate that an almost perfect inverse relationship existed between the response to added phosphorus and the yields without phosphorus. For example, soils 31, 18, 13, and 27, which ranked one, two, three, and four respectively in total yield (without phosphorus), ranked forty, forty-one, thirty-nine, and thirty-six in percentage increase caused by the addition of phosphorus. Conversely, soils 19, 39, 24, and 9 which ranked forty-one, forty, thirty-nine and thirty-eight in the total yields, ranked one, two, four and three respectively in percent increase in yield caused by added phosphorus. A similar yield relationship holds for the remainder of the soils.

An examination of the data on dry weights of the roots shows that on the unphosphated soils the root yields were approximately one-half the total top yields for the seven cuttings or about one-third of the total weight of plant material produced. The average dry weight of the roots was 30.4 grams. Considering all the soils added phosphate increased the root yields by approximately one-third to 40.0 grams per pot. However, the ratios of root weight to top weight and of root weight to total weight were decreased by the phosphate applications.

A comparison of the total dry weights of tops and roots shows that the phosphorus treated soils yielded an average of 54.6 per-cent more dry plant material than did the unphosphated soils.

The yield data in Table VI show that the heavier soils did not produce larger yields of alfalfa than did the sandy or sandy loam soils. The data show that relatively high and low yields were obtained from both the coarse and fine textured groups. It is interesting to note that though one-fourth of the soils were originally above pH 7, the fifteen highest yielding soils without added phosphorus were, with one exception, acid soils. It should be remembered however, that most of these soils had been limed. In every instance, added phosphorus produced an increase in yield indicating that none of the soils contained sufficient phosphorus for maximum production of alfalfa under greenhouse conditions. In several instances the yield increases were small.

On the basis of response to added phosphorus under greenhouse conditions and when properly limed, the soils were arranged in order of their relative need for phosphate. In Table VII this grouping is

TABLE VII

GROUPING OF FORTY-ONE MICHIGAN SOILS IN RELATION TO THEIR RELATIVE PHOSPHORUS REQUIREMENTS FOR THE PRODUCTION OF ALFALFA UNDER GREENHOUSE CONDITIONS*

Greatest	Marked	Moderate	Least
1. Kalkaska sand (19)	11. Warsaw loam (16)	21. Brookston sandy clay (41)	31. Selkirk sandy clay loam (40)
2. Conover loam (9)	12. Bellefontaine sandy loam (14)	22. Miami clay loam(2)	32. Plainfield loamy sand (30)
3. Selkirk sandy clay loam (39)	13. Fox loamy sand (12)	23. Brookston loam (32)	33. Kent clay loam(21)
4. Isabella sandy clay loam (24)	14. Conover sandy clay loam (37)	24. Kalkaska sand (20)	34. Emmet sandy loam (25)
5. Wisner sandy clay loam (36)	15. Toledo clay loam(29)	25. Kent clay loam (22)	35. Hillsdale sandy loam (11)
6. Wisner sandy clay loam (4)	16. Granby sandy loam (5)	26. Miami clay loam(3)	36. Brookston sandy clay (27)
7. Miami sandy loam (1)	17. Isabella sandy clay loam (23)	27. Conover loam (8)	37. Bellefontaine sand (17)
8. Miami loam (26)	18. Conover sandy clay loam (38)	28. Brookston sandy clay loam (7)	38. Clyde clay loam (35)
9. Macomb sandy loam(6)	19. Napanee sandy clay loam (28)	29. Waukesha sandy loam (10)	39. Fox loam (13)
10. Kawkawlin sandy clay loam (33)	20. Wisner sandy clay loam (34)	30. Plainfield sandy loam (15)	40. Hillsdale (31)
			41. Fox sandy loam(18)

* Arrangement based on yield response to added phosphorus.

presented in decreasing order of response to added phosphorus. It should be remembered that the soils differed in their past cropping and fertilization histories and as a result tended to reflect their level of fertility. However, if response to added phosphorus can be considered a valid measure of the relative need for phosphorus fertilization the arrangement has merit. For an example, it shows that under the conditions of this experiment the Hillsdale, Brookston, Plainfield, and Kent soil types have relatively low requirements for phosphorus as compared with the Wisner and Isabella types. In contrast, alfalfa grown on the Conover, Kalkaska, Miami and Bellefontaine soils showed considerable variation in its response to phosphate fertilizer.

Phosphorus Content of Alfalfa. The data recorded in Table VIII show the effect of soil type and phosphorus fertilization on the total phosphorus content of alfalfa tops and roots. The percentage of phosphorus in the tops from the unphosphated soils ranged from 0.277 percent, in the case of soil number 31, which ranked first in total weight of tops produced, to 0.114 percent in the case of soil number 36. The average phosphorus content of alfalfa tops on the unphosphated soils was 0.167 percent. An examination of these data show no exact relationship between total yield of tops and the percentage composition of phosphorus, but generally higher than average percentage phosphorus compositions were associated with high yields. Added phosphate almost doubled the percentage composition of alfalfa in the tops. The average for the phosphorus treated plants was 0.323

TABLE VIII

PERCENTAGE OF TOTAL PHOSPHORUS IN SEVEN HARVESTS

OF ALFALFA AND ROOTS

Soil series and number		Seven Harvests* No P percent	Seven Harvests* P percent	Roots* No P* percent	Roots* P percent
1	Miami	.165	.392	.090	.208
2	Miami	.142	.408	.079	.267
3	Miami	.180	.330	.110	.256
4	Wisner	.165	.341	.078	.280
5	Granby	.155	.311	.078	.235
6	Macomb	.115	.359	.074	.246
7	Brookston	.185	.338	.090	.305
8	Conover	.162	.319	.125	.272
9	Conover	.152	.290	.061	.202
10	Waukesha	.190	.317	.129	.229
11	Hillsdale	.201	.345	.120	.244
12	Fox	.171	.432	.089	.248
13	Fox	.216	.446	.116	.283
14	Bellefontaine	.171	.339	.091	.224
15	Plainfield	.228	.370	.069	.198
16	Warsaw	.169	.338	.089	.172
17	Bellefontaine	.194	.405	.160	.338
18	Fox	.222	.352	.172	.285
19	Kalkaska	.153	.352	.088	.243
20	Kalkaska	.184	.394	.126	.287
21	Kent	.224	.370	.129	.294
22	Kent	.162	.307	.069	.231
23	Isabella	.165	.344	.072	.251
24	Isabella	.127	.268	.070	.191
25	Emmet	.241	.358	.213	.345
26	Miami	.129	.262	.081	.230
27	Brookston	.152	.308	.071	.275
28	Napanee	.128	.248	.070	.213
29	Toledo	.146	.242	.074	.227
30	Plainfield	.199	.289	.145	.296
31	Hillsdale	.277	.375	.195	.332
32	Brookston	.153	.278	.071	.227
33	Kawkawlin	.156	.271	.069	.251
34	Wisner	.140	.217	.075	.227
35	Clyde	.159	.268	.100	.264
36	Wisner	.114	.255	.067	.249
37	Conover	.127	.253	.096	.260
38	Conover	.145	.263	.097	.231
39	Selkirk	.120	.315	.071	.300
40	Selkirk	.159	.262	.079	.183
41	Brookston	.123	.315	.090	.250
Average		.167	.323	.098	.252

* Average of three replications.

percent. As for the roots, the percentage of phosphorus in the unphosphated and phosphated alfalfa was 0.098 percent and 0.252 percent respectively, a greater percentage increase than occured in the tops.

The data presented in Table IX show the effect of soil type and phosphorus fertilizer on the total amount of phosphorus removed by the alfalfa from each pot. On the unphosphated soils, the amounts of phosphorus in the tops varied widely, from a low of 43.8 milligrams to a high of 227.6 milligrams per pot. The average for all soils was 104.7 milligrams. The corresponding average for the roots was 33.0. More than three times these amounts of phosphorus were found in the tops and roots of alfalfa grown on the phosphated soils. The average in the tops was 324.2 milligrams and in the roots 101.7 milligrams. In terms of total amounts of phosphorus removed by the tops and roots, the plants on the phosphorus treated soils removed an average of 427.6 milligrams per pot whereas those on unphosphated soils removed an average of 138.0 milligrams. The percentage increase in total phosphorus removed was 209.8.

An account of the recovery of applied phosphorus in milligrams and percent is given in Table X. The recovery of applied phosphorus was obtained by subtracting the uptake values on the unphosphated soils from the respective values on the soils which received phosphorus. This method of calculating the recovery of applied phosphorus has been used by other investigators. Prince, et al (31) used it in their phosphorus studies and more recently Rich and Attoe (23)

TABLE IX

THE TOTAL CONTENT OF PHOSPHORUS IN SEVEN HARVESTS OF ALFALFA AND ROOTS

Soil series and number		No Phosphorus* Seven Harvests mgms.	Roots mgms.	Total mgms.	Phosphorus Added* Seven Harvests mgms.	Roots mgms.	Total mgms.
1	Miami	63.7	21.2	84.9	382.2	79.7	461.9
2	Miami	80.8	21.7	102.5	386.0	88.9	474.9
3	Miami	123.8	39.6	163.4	325.7	117.8	443.5
4	Wisner	63.2	20.4	83.6	369.3	134.7	504.0
5	Granby	71.2	20.8	92.0	294.2	117.3	411.5
6	Macomb	58.8	20.2	79.0	441.9	113.7	555.6
7	Brookston	143.6	25.3	168.9	337.0	121.1	458.1
8	Conover	114.9	47.8	162.7	324.1	107.2	431.3
9	Conover	56.1	12.6	68.7	307.1	82.0	389.1
10	Waukesha	132.4	52.5	184.9	280.2	92.5	372.7
11	Hillsdale	156.4	49.9	206.3	308.8	106.4	415.2
12	Fox	69.3	29.2	98.5	375.8	102.2	478.0
13	Fox	207.1	47.4	254.5	478.1	115.5	593.6
14	Bellefontaine	75.2	27.5	102.7	320.7	93.6	414.3
15	Plainfield	177.6	69.5	247.1	364.1	84.6	448.7
16	Warsaw	70.5	21.0	91.5	314.3	77.6	391.9
17	Bellefontaine	158.7	57.4	216.1	377.5	130.5	508.0
18	Fox	227.6	69.3	296.9	371.7	84.9	456.6
19	Kalkaska	50.6	20.3	70.9	370.0	90.9	460.9
20	Kalkaska	103.4	43.6	147.0	361.7	88.1	449.8
21	Kent	172.9	45.8	218.7	346.3	113.8	460.1
22	Kent	104.5	17.7	122.2	312.8	78.3	391.1
23	Isabella	79.0	23.0	102.0	336.6	113.5	450.1
24	Isabella	46.7	16.9	63.6	280.9	80.2	361.1
25	Emmet	225.1	86.9	312.0	404.2	152.8	557.0
26	Miami	48.8	17.9	66.7	245.0	95.5	340.5
27	Brookston	144.1	24.6	168.7	333.3	107.8	441.1
28	Napanee	65.0	21.4	86.4	248.3	89.0	337.3
29	Toledo	71.7	19.5	91.2	249.3	86.5	335.8
30	Plainfield	147.7	55.8	203.5	267.0	145.9	412.9
31	Hillsdale	183.6	84.2	267.8	424.9	136.5	561.4
32	Brookston	90.6	22.2	112.8	271.1	95.6	366.7
33	Kawkawlin	67.9	19.0	86.9	271.8	86.3	358.1
34	Wisner	67.3	13.6	80.9	200.1	72.9	273.0
35	Clyde	145.5	32.5	178.0	276.3	101.1	377.4
36	Wisner	45.3	12.9	58.2	271.3	93.6	364.9

TABLE IX (continued)

THE TOTAL CONTENT OF PHOSPHORUS IN SEVEN HARVESTS OF ALFALFA AND ROOTS

	No Phosphorus*			Phosphorus Added*		
Soil series and number	Seven Harvests mgms.	Roots mgms.	Total mgms.	Seven Harvests mgms.	Roots mgms.	Total mgms.
37 Conover	63.5	19.9	83.4	269.2	91.0	360.2
38 Conover	74.7	22.4	97.1	274.1	70.7	344.8
39 Selkirk	43.8	15.1	58.9	334.5	127.5	462.0
40 Selkirk	132.6			271.2		
41 Brookston	68.7			315.6		
Average	104.7	33.0	138.0	324.2	101.7	427.6
Average Increase (percent)						209.8

* Average of three replications.

TABLE X

RECOVERY* OF APPLIED PHOSPHORUS

Soil series and number		Phosphorus Content** Seven Harvests of Tops mgms.	Roots mgms.	Total mgms.	Recovery of Applied P percent
1	Miami	318.5	58.5	377.0	51.2
2	Miami	305.2	67.2	372.4	50.5
3	Miami	201.9	78.2	280.1	35.6
4	Wisner	306.1	114.3	420.4	57.1
5	Granby	223.0	96.5	319.5	43.4
6	Macomb	383.1	93.5	476.6	60.6
7	Brookston	193.4	95.8	289.2	39.3
8	Conover	209.2	59.4	268.6	36.5
9	Conover	251.0	69.4	320.4	43.5
10	Waukesha	147.4	40.0	187.4	25.4
11	Hillsdale	152.4	56.5	208.9	28.4
12	Fox	306.5	73.0	379.5	48.3
13	Fox	271.0	68.1	339.1	46.0
14	Bellefontaine	245.5	66.1	311.6	39.6
15	Plainfield	186.5	15.1	201.6	25.6
16	Warsaw	243.8	56.6	300.4	40.8
17	Bellefontaine	218.8	73.1	291.9	37.1
18	Fox	144.1	15.6	159.7	20.3
19	Kalkaska	319.4	70.6	390.0	49.6
20	Kalkaska	258.3	44.5	302.8	38.5
21	Kent	173.4	68.0	241.4	32.8
22	Kent	208.3	60.6	268.9	36.5
23	Isabella	257.6	90.5	348.1	47.2
24	Isabella	234.2	63.3	297.5	40.4
25	Emmet	179.1	65.9	245.0	31.2
26	Miami	196.2	77.6	273.8	37.2
27	Brookston	189.2	83.2	272.4	37.0
28	Napanee	183.3	67.6	250.9	34.1
29	Toledo	177.6	67.0	244.6	33.2
30	Plainfield	119.3	90.1	209.4	26.6
31	Hillsdale	241.3	52.3	293.6	39.8
32	Brookston	180.5	73.4	253.9	34.5
33	Kawkawlin	203.9	67.3	271.2	34.5
34	Wisner	132.8	59.3	192.1	26.1
35	Clyde	130.8	68.6	199.4	27.1
36	Wisner	226.0	80.7	306.7	41.6
37	Conover	205.7	71.1	276.8	35.2
38	Selkirk	199.4	48.3	247.7	33.6
39	Selkirk	290.7	112.4	403.1	51.3
Average		220.9	68.7	289.6	38.4

* Obtained by subtracting phosphorus content of alfalfa grown on soil to which no phosphorus was applied from that of alfalfa grown on phosphorus treated soils.

** Average of three replications.

used it in their investigation of the phosphorus supplying powers of Wisconsin soils. Certainly this method is questionable since it cannot be proved that the difference in uptake came from the applied phosphorus. However, since the soil and plant roots were confined to the relatively small area of the pots and the roots had no access to any unfertilized soil, it is quite likely that the difference does represent the portion obtained from the applied phosphorus. Of the total quantity of phosphorus applied, the portion recovered ranged from 20.3 percent on Fox sandy loam to 60 percent on the Wisner sandy loam. The average recovery was 38.4 percent. Low and high recoveries do not necessarily indicate high and low fixation by the soils. Perhaps the recoveries were influenced by original levels of available native phosphorus more than any other factor. Considering the magnitude of phosphorus fixation in most soils, the amounts recovered indicate a greater utilization of applied phosphorus than is normally expected in field soils. The results are similar to those obtained by Rich and Attoe (31). They recovered 36 to 62 percent of the applied phosphorus in six successive crops of oats on Wisconsin soils. Prince, et al (31), recovered from 4.2 to 41.9 percent of the phosphorus applied in either harvests and the roots of alfalfa grown on twenty New Jersey soils.

Soil Phosphorus

The work of Smith (38) showed that the method of analysis may affect the results obtained from correlations between soil phosphorus determinations and crop yields on Michigan soils. Specifically, the type of extractant and the soil extracting solution ratios were shown to be important. Consideration of these factors prompted a preliminary comparison between the alfalfa yields obtained in this experiment and the results obtained from several phosphorus extracting and testing methods. The results are summarized in Table XI. The best correlation was obtained with 0.03 N NH_4F in 0.025 N HCl. With this extractant, the soil-extracting solution ratio did not appreciably affect the correlation. This conclusion agrees with reports by Bray (12) that both ratios extract a proportional amount of the adsorbed phosphorus. The Spurway test for phosphorus is usually made at a 1 to 4 soil-extracting solution ratio, but for comparison purposes the ratios of 1 to 10 and 1 to 50 were used; consequently, the results obtained may have been somewhat different from those which would be obtained at the ratio for which the test has been calibrated.

On the basis of the preliminary measurements of soil phosphorus, three rapid test methods were chosen for the rapid soil phosphorus determinations. They were: (1) Spurway reserve test (0.135 N HCl) at a 1-4 ratio, (2) Bray adsorbed test (0.03 N NH_4F in 0.025 N HCl) at a 1 to 10 ratio, and (3) Bray available phosphorus (0.03 N NH_4F in 0.1 N HCl). In addition to these rapid test methods, more quantitative laboratory methods by Bray for phosphorus, as previously described, were used. The results are summarized in Table XII.

Rapid Tests for Phosphorus. The smallest amount of phosphorus

TABLE XI

PRELIMINARY COMPARISON OF SEVERAL RAPID SOIL TESTS FOR SOIL PHOSPHORUS AND ALFALFA YIELDS ON FORTY MICHIGAN SOILS

Soil Test (X)*	Ratio of Soil to Extracting Solution	Alfalfa Yield (Y)**	Coefficient of Correlation (r)
Bray's Adsorbed Phosphorus 0.03 N NH_4F in 0.025 N HCl	1 - 10	Seven Harvests	0.734
"	1 - 10	Seven Harvests and Roots	0.807
"	1 - 50	Seven Harvests	0.752
"	1 - 50	Seven Harvests and Roots	0.767
Bray's Available Phosphorus 0.03 N NH_4F in 0.1 N HCl	1 - 10	Seven Harvests	0.664
"	1 - 10	Seven Harvests and Roots	0.667
"	1 - 50	Seven Harvests	0.499
"	1 - 50	Seven Harvests and Roots	0.454
Spurway's Reserve Phosphorus 0.135 N HCl	1 - 50	Seven Harvests	0.170
"	1 - 50	Seven Harvests and Roots	0.105

* Soil phosphorus in parts per million of original soils.
** Yields from no phosphorus treatment.

TABLE XII

PHOSPHORUS CONTENT OF SOILS BEFORE CROPPING AS MEASURED BY SEVERAL CHEMICAL TESTS

Soil type and number	Rapid Tests			Bray Laboratory Methods		
	Spurway Reserve Phosphorus ppm	Bray Adsorbed Phosphorus ppm	Bray Available Phosphorus ppm	Acid Soluble and Adsorbed Phosphorus ppm	Organic Phosphorus ppm	Total Organic, Acid Soluble, and Adsorbed Phosphorus ppm
1 Miami sandy loam	7	5	12	142	358	500
2 Miami clay loam	7	7	13	210	403	613
3 Miami clay loam	33	16	56	240	494	734
4 Wisner sandy clay loam	30	10	44	236	264	500
5 Granby sandy loam	30	24	80	420	570	990
6 Macomb sandy loam	21	23	29	274	482	756
7 Brookston sandy clay loam	41	16	62	300	524	824
8 Conover loam	17	14	29	254	546	800
9 Conover loam	10	6	15	300	315	615
10 Waukesha sandy loam	16	46	59	286	652	938
11 Hillsdale sandy loam	13	30	40	312	363	675
12 Fox loamy sand	4	12	22	264	324	588
13 Fox loam	20	28	50	342	533	875
14 Bellefontaine sandy loam	4	14	20	302	233	535
15 Plainfield sandy loam	12	45	60	350	420	770
16 Warsaw loam	5	14	20	258	430	688
17 Bellefontaine sand	16	44	65	324	436	760
18 Fox sandy loam	27	39	67	360	343	703
19 Kalkaska sand	4	7	14	240	73	313
20 Kalkaska sand	6	18	29	312	241	553
21 Kent clay loam	13	23	37	294	581	875
22 Kent clay loam	14	9	27	228	235	463
23 Isabella sandy clay loam	12	8	21	252	368	620
24 Isabella sandy clay loam	3	5	10	200	333	533
25 Emmet sandy loam	66	68	93	300	588	888
26 Miami loam	3	5	11	212	213	425
27 Brookston sandy clay	67	35	80	400	524	924
28 Napanee sandy clay loam	8	5	14	252	278	530
29 Toledo clay loam	77	11	54	404	85	485
30 Plainfield loamy sand	10	33	55	354	131	485

TABLE XII (continued)

PHOSPHORUS CONTENT OF SOILS BEFORE CROPPING AS MEASURED BY SEVERAL CHEMICAL TESTS

Soil type and number	Rapid Tests		Bray Laboratory Methods			
	Spurway Reserve Phosphorus ppm	Bray Adsorbed Phosphorus ppm	Bray Available Phosphorus ppm	Acid Soluble and Adsorbed Phosphorus ppm	Organic Phosphorus ppm	Total Organic, Acid Soluble, and Adsorbed Phosphorus ppm
*						
32 Brookston loam	77	14	68	302	286	588
33 Kawkawlin sandy clay loam	33	9	40	254	319	573
34 Wisner sandy clay loam	65	15	88	274	439	713
35 Clyde clay loam	81	23	75	398	542	940
36 Wisner sandy clay loam	40	10	49	286	389	675
37 Conover sandy clay loam	9	9	19	294	344	638
38 Conover sandy clay loam	5	6	12	284	224	508
39 Selkirk sandy clay loam	7	5	14	294	191	485
40 Selkirk sandy clay loam	32	17	44	284	369	653
41 Brookston sandy clay	29	11	34	340	460	800
Average	24.4	18.5	40.8	290.8	372.6	663.8

* Original sample of soil 31 lost.

removed by the Spurway reserve extractant was 3 parts per million of phosphorus on a soil basis from soil number 24, while a maximum of 88 parts per million of phosphorus was extracted from soils numbers 29 and 32. The average amount of phosphorus removed by Spurway's extractant was 24.4 parts per million on a soil basis, which was higher than the average removed by the Bray adsorbed phosphorus extractant. The latter value of 18.5 parts per million was lower than the average amount removed by the Bray available phosphorus extractant which was 40.8 parts per million. The variation in amounts removed by the Bray adsorbed phosphorus and available phosphorus tests ranged from 5 parts per million to 68 parts per million and 10 parts per million to 93 parts per million respectively.

The effect of cropping on the phosphorus content of soils is presented in Table XIII. Bray's adsorbed phosphorus extracting agent was used to determine changes in phosphorus level. It must be kept in mind that some of the cropped soils were limed, consequently, exact comparisons are probably not in order; however, some idea of the effect of cropping on the levels of available phosphorus can be gained.

It is generally recognized that the supply of available phosphorus for plant use throughout a given growing period may exist in the soil in different forms of variable availability. In order to correlate soil phosphorus with plant growth a good test should measure either the total amount available or a proportionate amount of that total. According to Spurway (39) his reserve test measured the amounts of the

TABLE XIII

PHOSPHORUS CONTENT OF SOILS BEFORE AND AFTER CROPPING*

		Soil Phosphorus		
			After Cropping**	
Soil type and number		Original Soil ppm	No Phosphorus ppm	Phosphorus Added ppm
1	Miami sandy loam	5	4	18
2	Miami clay loam	7	5	22
3	Miami clay loam	16	6	24
4	Wisner sandy clay loam	10	5	20
5	Granby sandy loam	24	18	33
6	Macomb sandy loam	23	4	36
7	Brookston sandy clay loam	16	7	25
8	Conover loam	14	7	23
9	Conover loam	6	5	17
10	Waukesha sandy loam	46	22	62
11	Hillsdale sandy loam	30	15	56
12	Fox loamy sand	12	7	37
13	Fox loam	28	14	42
14	Bellefontaine sandy loam	14	9	42
15	Plainfield sandy loam	45	22	69
16	Warsaw loam	14	8	37
17	Bellefontaine sand	44	25	74
18	Fox sandy loam	39	14	55
19	Kalkaska sand	7	5	24
20	Kalkaska sand	18	11	55
21	Kent sandy clay loam	23	11	42
22	Kent clay loam	9	7	22
23	Isabella sandy clay loam	8	5	22
24	Isabella sandy clay loam	5	4	25
25	Emmet sandy loam	68	33	74
26	Miami loam	6	5	23
27	Brookston sandy clay	35	8	24
28	Napanee sandy clay loam	5	5	16
29	Toledo clay loam	11	6	23
30	Plainfield loamy sand	33	18	51
32	Brookston loam	14	8	28
33	Kawkawlin sandy clay loam	9	5	37
34	Wisner sandy clay loam	15	10	59
35	Clyde clay loam	23	12	32
36	Wisner sandy clay loam	10	7	21
37	Conover sandy clay loam	9	5	20
38	Conover sandy clay loam	6	5	22
39	Selkirk loam	5	4	49
40	Selkirk sandy clay loam	17	9	24
41	Brookston sandy clay	11	5	22

* As measured by Bray's Adsorbed Phosphorus Solution.

** Some soils were limed.

less soluble soil nutrients. If this concept is applied to the element phosphorus, a strong acid extractant such as 0.135 N HCl may dissolve rock phosphate and other acid-soluble forms which may or may not be available. Such an extractant would be expected to give positive tests on soils containing large amounts of acid-soluble phosphorus, but in most instances would probably give unsatisfactory tests when adsorbed forms of phosphorus were present in appreciable quantities. Bray (10) has presented evidence that acid extractants do not effectively remove adsorbed phosphates. Bray and Dickman (8) have shown that adsorbed forms, when present in relatively large amounts, are much more available than acid-soluble forms. Hence, poor correlations of crop yields with phosphorus removed by strong acids may result. When soil phosphorus is comprised largely of acid-soluble forms the Spurway extractant would more than likely give a clear picture of the total amount of inorganic phosphorus present, which may or may not be available for plant use. Examination of the amounts of phosphorus removed from the different soils by this extractant indicates a wide range in levels of acid-soluble phosphorus.

Despite the fact that Bray's adsorbed phosphorus extractant was much weaker with respect to acidity and that the extraction time was one-third shorter, it removed more phosphorus from quite a few soils than did the stronger Spurway reagent. Bray's available phosphorus extractant which was slightly weaker with respect to acidity and which also employed a shorter extraction period removed more phosphorus in all but two soils than did the Spurway reagent. These results indicate clearly that the fluoride ion was effective in removing phosphorus which was not removed by the acid.

An attempt to explain the role of the fluoride ion in the release of adsorbed phosphorus has been made by several investigators. Swenson, Cole, and Sieling (40) expressed the view that the fluoride ion formed stable complexes with iron and aluminum compounds thereby liberating phosphorus. Turner and Rice (44) substantiated this opinion by presenting evidence that neutral NH_4F reacted with $Al(OH)_3$ gels to form $(NH_4)_3\ AlF_6$ and that phosphorus adsorbed by the gels was more or less completely released by the action of the fluoride. On the other hand, their results showed that $Fe(OH)_3$ gels are not attacked by the fluoride and the adsorbed phosphate was not released to any appreciable extent.

Close examination of the soils in this experiment and the amounts of phosphorus removed by Bray's adsorbed extractant shows a somewhat general relationship between the amount of adsorbed phosphorus and the percent of sand. The soils having large proportionate amounts of sand, in most instances, gave high tests for adsorbed phosphorus.

Additionally it should be mentioned that the soils above pH 7.0 generally gave low to medium values for adsorbed phosphorus.

Bray's Laboratory Methods. The more quantitative methods of Bray for the extraction of soil phosphorus which make use of a greater amount of fluoride and a longer extraction period removed considerably larger quantities of phosphorus than the rapid test methods. The amounts of total acid-soluble and adsorbed phosphorus ranged from 142 parts per million to 420 parts per million with the average at 290.8. The total organic, acid-soluble, and adsorbed phosphorus in the soils varied from 313 parts per million to 990 parts per million with the average amount at 663.8 parts per million. The organic phosphorus ranged from 73 parts per million to 652 parts per million with an average of 372.6 parts per million.

In most instances, the amounts of the total acid-soluble and adsorbed fractions were proportionate to the amounts removed by the rapid test methods. The test values obtained are somewhat higher than those obtained by Bowers (5) in a similar study. The differences can probably be attributed to the type of shaking machines used. Bowers used a slowly revolving end-over-end machine that did very little shaking, whereas in this study a reciprocating type shaker which effected a vigorous shaking was used. Consideration of the extracting solution with respect to concentration of acid and fluoride and the length of extraction leaves little doubt that the total amounts of acid-soluble and sdsorbed phosphorus were not removed. Certainly this extraction removes a greater quantity of the more resistant and insoluble phosphorus than the rapid soil tests.

By the use of hydrogen peroxide and a steam bath, the organic phosphates were brought into solution and measured along with the inorganic forms. The difference without the peroxide and heat treatments represents the organic phosphorus. The full reliability of this procedure is open to question, especially since the hydrogen peroxide and the increased temperature may bring additional inorganic phosphates into solution. However, the method does give a measure of the phosphorus in organic combination. Bray's method is less tedious than some of the other methods for the measurement of the organic phosphorus and may be just as reliable. The values obtained compare favorably with measures of organic phosphorus obtained by other investigators on similar soil types. The levels of organic phosphorus in the soils of this investigation varied considerably ranging from 73 parts per million to 570 parts per million on a soil basis. In general, the values for organic phosphorus were directly related to the organic matter content of the soils. In several cases, the results indicated that perhaps phosphorus other than just the organic was included in the values obtained.

The preliminary correlations of soil phosphorus tests with alfalfa yields indicated that perhaps Bray's adsorbed phosphorus test was the best measure of the phosphorus supplying powers of a soil. For this reason, Bray's adsorbed phosphorus tests results were used to arrange the soils in order of their supplying power for phosphorus. In Table XIV the soils were arranged in descending order of their phosphorus soil tests and were arbitrarily grouped into high, medium, and low categories. Comparison of this arrangement with that of Table VII in which the soils are listed according to their need for phosphorus as indicated by growth response to added phosphorus, shows a rather striking agreement. Soils in the

TABLE XIV

THE PHOSPHORUS SUPPLYING POWERS OF FORTY MICHIGAN SOILS

AS INDICATED BY BRAY'S ADSORBED PHOSPHORUS TEST

High[3]			Medium[2]			Low[1]		
1.	Emmet sandy loam	(25)*	14.	Kalkaska sand	(20)	28.	Conover sandy clay loam	(37)
2.	Waukesha sandy loam	(10)	15.	Selkirk sandy clay loam	(40)	29.	Kawkawlin sandy clay loam	(33)
3.	Plainfield sandy loam	(15)	16.	Brookston sandy clay loam	(7)	30.	Kent clay loam	(22)
4.	Bellefontaine sand	(17)	17.	Miami clay loam	(3)	31.	Isabella sandy clay loam	(23)
5.	Fox sandy loam	(18)	18.	Wisner sandy clay loam	(34)	32.	Kalkaska sand	(19)
6.	Brookston sandy clay	(27)	19.	Brookston loam	(32)	33.	Miami clay loam	(2)
7.	Plainfield loamy sand	(30)	20.	Warsaw loam	(16)	34.	Conover loam	(9)
8.	Hillsdale sandy loam	(11)	21.	Conover loam	(8)	35.	Miami loam	(26)
9.	Fox loam	(13)	22.	Bellefontaine sandy loam	(14)	36.	Conover sandy clay loam	(38)
10.	Granby sandy loam	(5)	23.	Fox loamy sand	(12)	37.	Selkirk sandy clay loam	(39)
11.	Macomb sandy loam	(6)	24.	Brookston sandy clay	(41)	38.	Napanee sandy clay loam	(28)
12.	Kent clay loam	(21)	25.	Toledo clay loam	(29)	39.	Isabella sandy clay loam	(24)
13.	Clyde clay loam	(35)	26.	Wisner sandy clay loam	(4)	40.	Miami sandy loam	(1)
			27.	Wisner sandy clay loam	(36)			

* Numbers in parenthesis refer to the original soil numbers.
1 Low - 0 to 10 parts per million phosphorus.
2 Medium - 11 to 19 parts per million phosphorus.
3 High - 20 and above parts per million phosphorus.

"High" category of Table XIV fall in the "Least" and "Moderate" categories of Table VII. On the other hand, soils which have "Greatest" and "Marked" requirements for phosphorus on the basis of response to phosphorus are found in the "Low" supplying group as indicated by the soil test. This agreement between these two entirely different methods of measuring a soil's ability to supply phosphorus was close enough to substantiate the soil test as a valid method.

Fixation Studies

Rate of Applied Phosphorus. The amounts of phosphorus fixed by several soils when applied at the rates of 25 parts per million, 50 parts per million and 100 parts per million per 20 grams of soil are presented in Table XV. The results indicate a wide difference in the capacity of the soils to fix phosphate against extraction with 0.03 N NH_4F in 0.025 N HCl. The average amount of phosphorus fixed at the four rates of application ranged from 17 to 79 percent. In addition, the data show that the amount of fixation by an individual soil varies with the amount of phosphorus applied. In Figures 2 through 7, graphical presentation is given to indicate the character of the fixation by the individual soils.

The soils included in this fixation study vary widely in chemical and physical properties. It has been generally accepted that most of the retaining power of a soil for phosphorus lies in the finer mechanical fractions, especially the clay. Hibbard (17) determined

TABLE XV

PHOSPHORUS FIXATION BY SELECTED SOILS AT SEVERAL RATES

Soil number	Amount of Phosphorus Applied to 20 grams of Soil* — 25 ppm: Phosphorus Fixed ppm	25 ppm: Percent Fixed	50 ppm: Phosphorus Fixed ppm	50 ppm: Percent Fixed	100 ppm: Phosphorus Fixed ppm	100 ppm: Percent Fixed	150 ppm: Phosphorus Fixed ppm	150 ppm: Percent Fixed	Average Percent Fixed
2	8.8	35	18.0	36	32.8	33	39.6	26	33
4	3.0	12	16.0	32	34.3	34	54.0	36	29
5	25.0	100	49.2	98	76.4	76	92.4	61	84
6	22.0	88	32.0	64	39.6	40	42.8	29	55
9	25.0	100	48.4	97	62.8	63	85.2	57	79
10	4.6	18	5.6	11	23.2	23	63.0	42	24
12	25.0	100	40.2	80	55.4	55	60.0	40	69
13	25.0	100	30.0	60	51.0	51	87.6	58	67
14	11.4	45	12.3	25	15.6	16	20.0	13	25
16	6.0	24	11.6	23	22.0	22	40.0	27	24
19	12.2	49	16.4	33	24.0	24	47.0	31	34
21	3.6	14	7.6	15	13.2	13	54.0	36	20
24	13.6	54	16.4	33	22.0	22	34.0	23	33
25	25.0	100	33.2	66	46.8	47	90.0	60	68
26	8.0	32	19.6	39	26.4	26	39.2	26	31
28	9.2	37	24.4	49	53.2	53	88.4	59	50
29	20.0	80	26.0	52	42.8	43	79.6	53	57
30	5.6	22	17.2	34	21.6	22	44.4	30	27
35	23.0	92	26.6	53	50.0	50	79.2	53	62
38	6.2	25	11.8	24	20.4	20	67.2	45	29
40	6.6	26	12.8	26	16.8	17	29.6	20	22
41	2.2	9	6.8	14	12.8	13	47.6	32	17

* Results of duplicate samples.

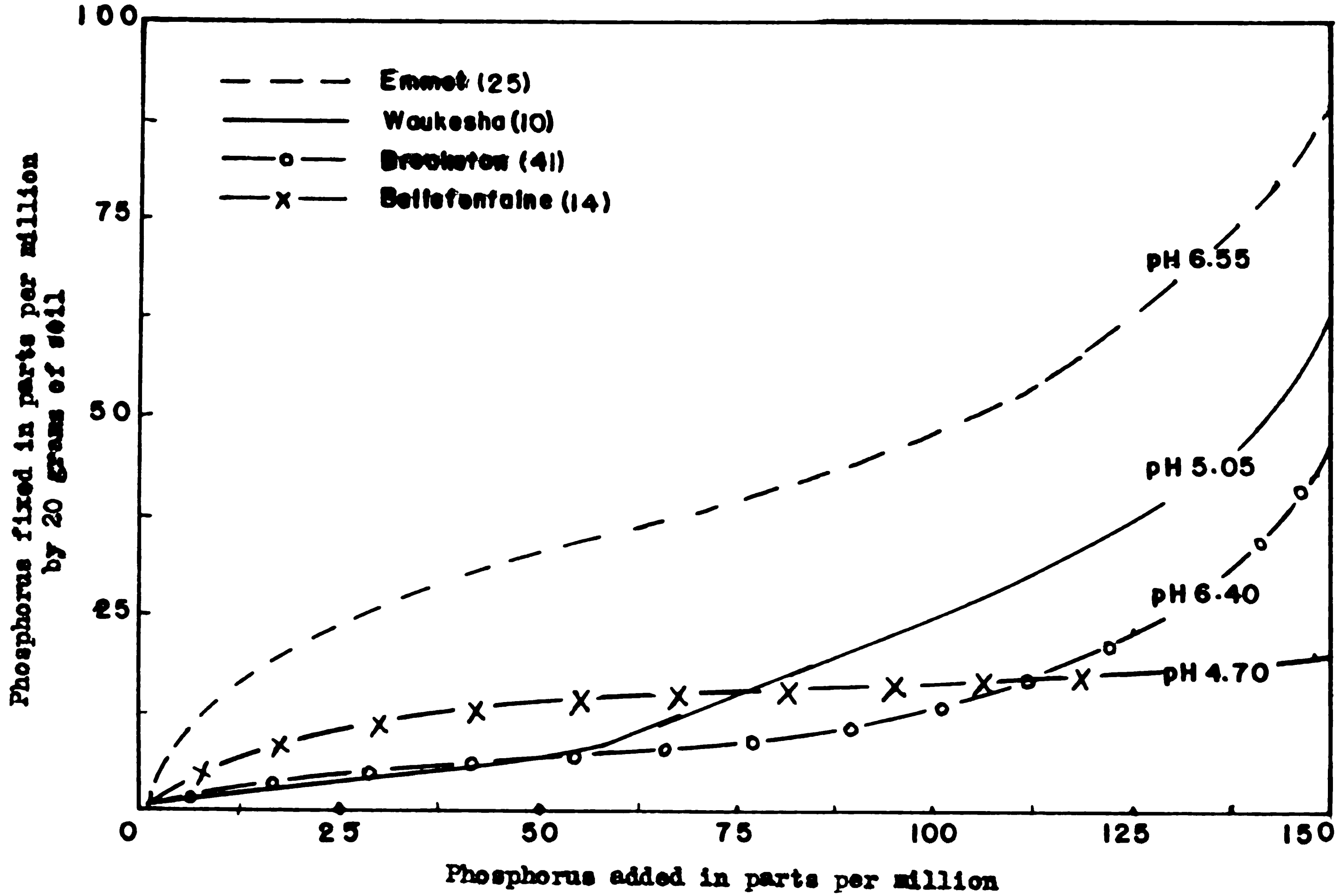

Figure 2. Fixation of phosphorus by several acid sandy loam soils.

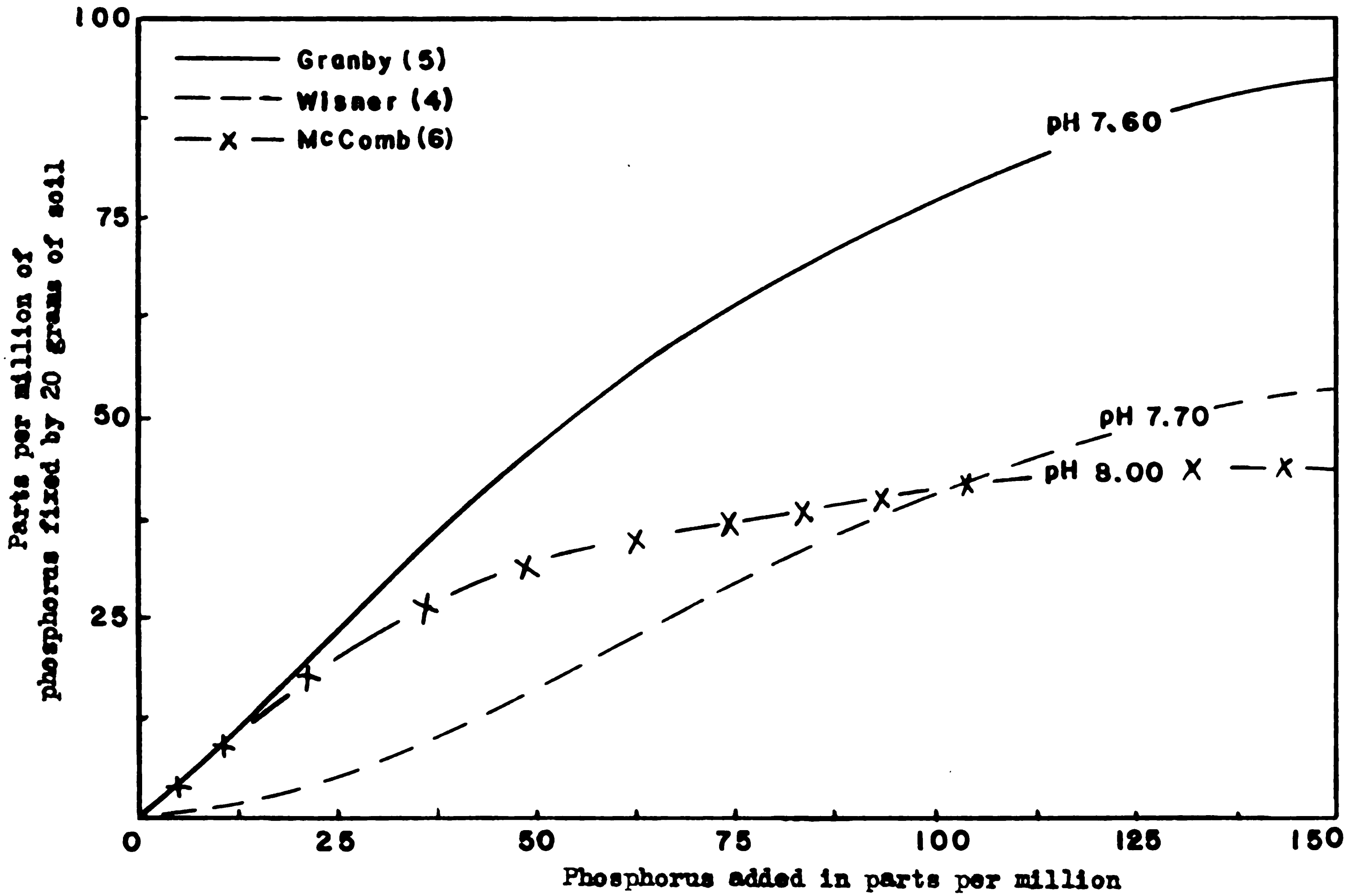

Figure 3. Fixation of phosphorus by several alkaline sandy loam soils.

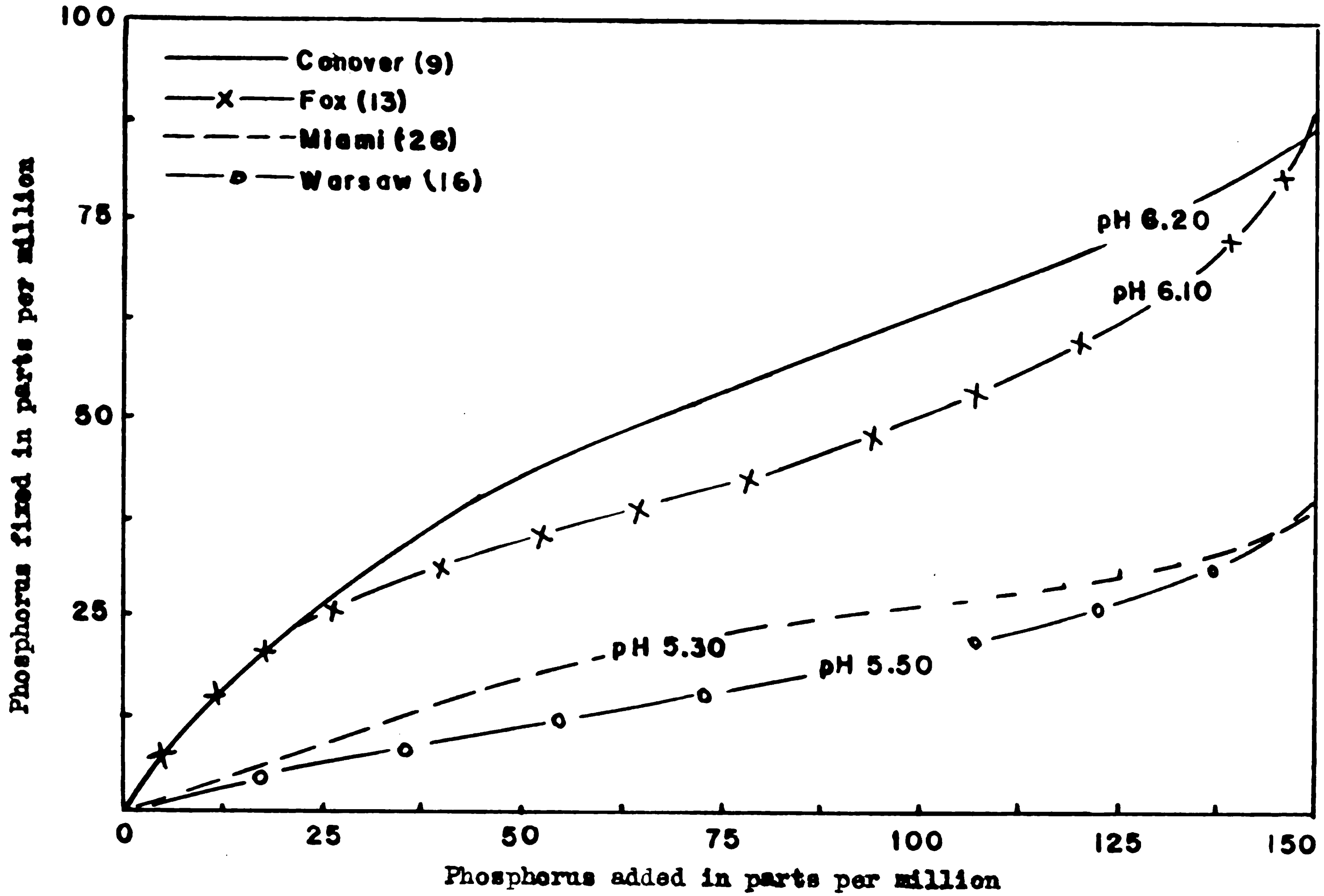

Figure 4. Phosphorus fixation by several acid loam soils.

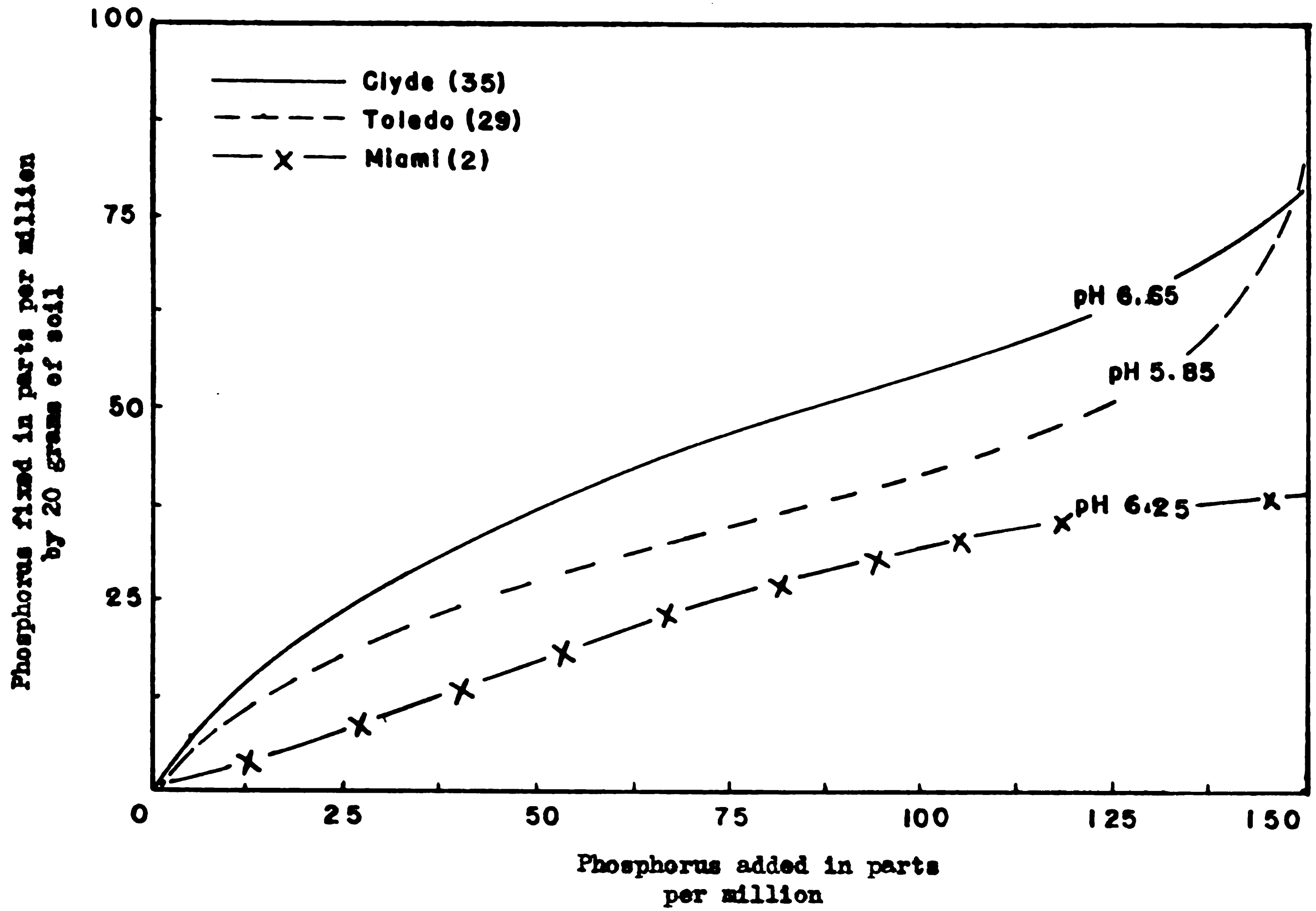

Figure 5. Fixation of phosphorus by several acid clay loam soils.

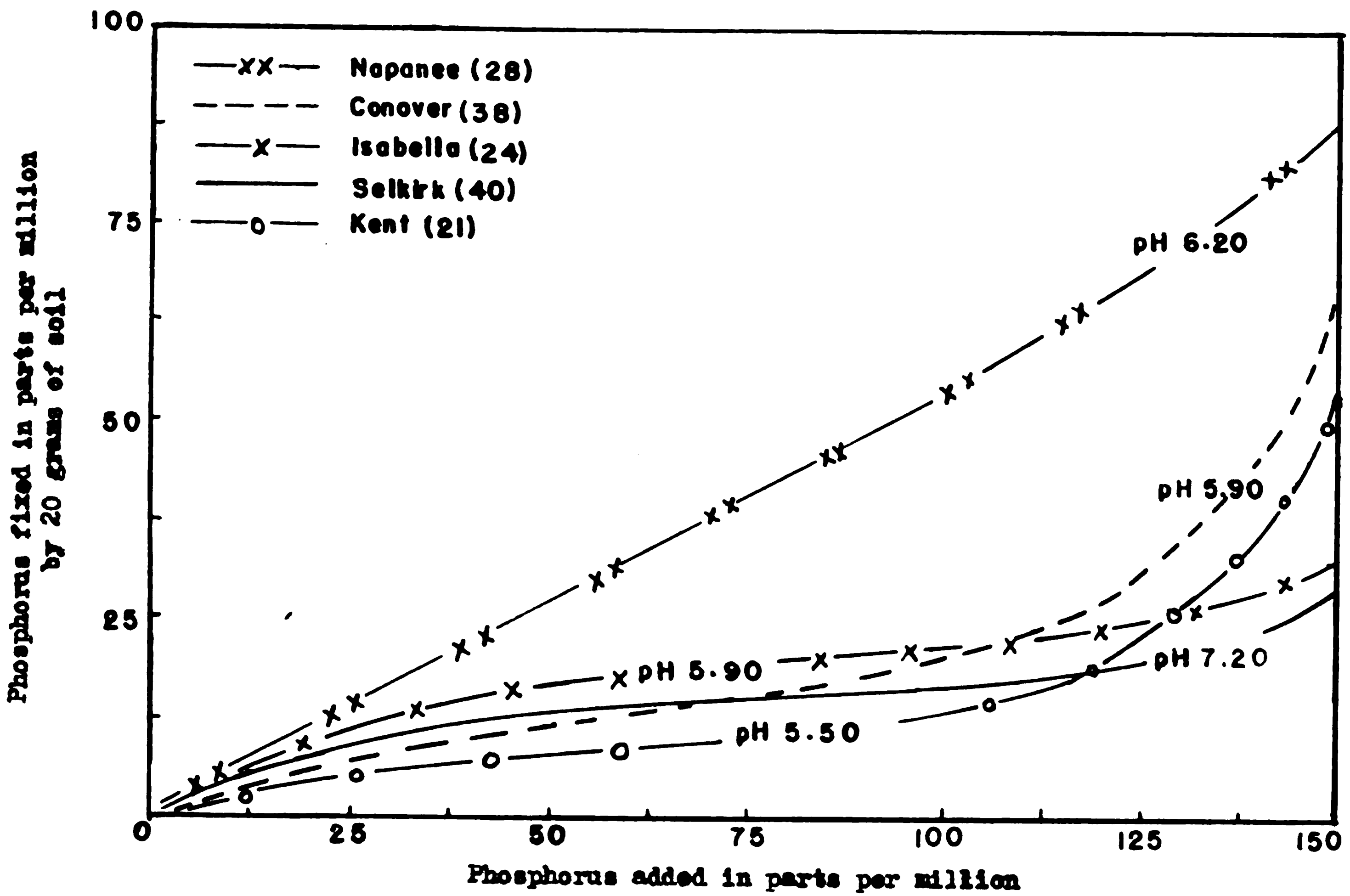

Figure 6. Phosphorus fixation by several sandy clay loam soils.

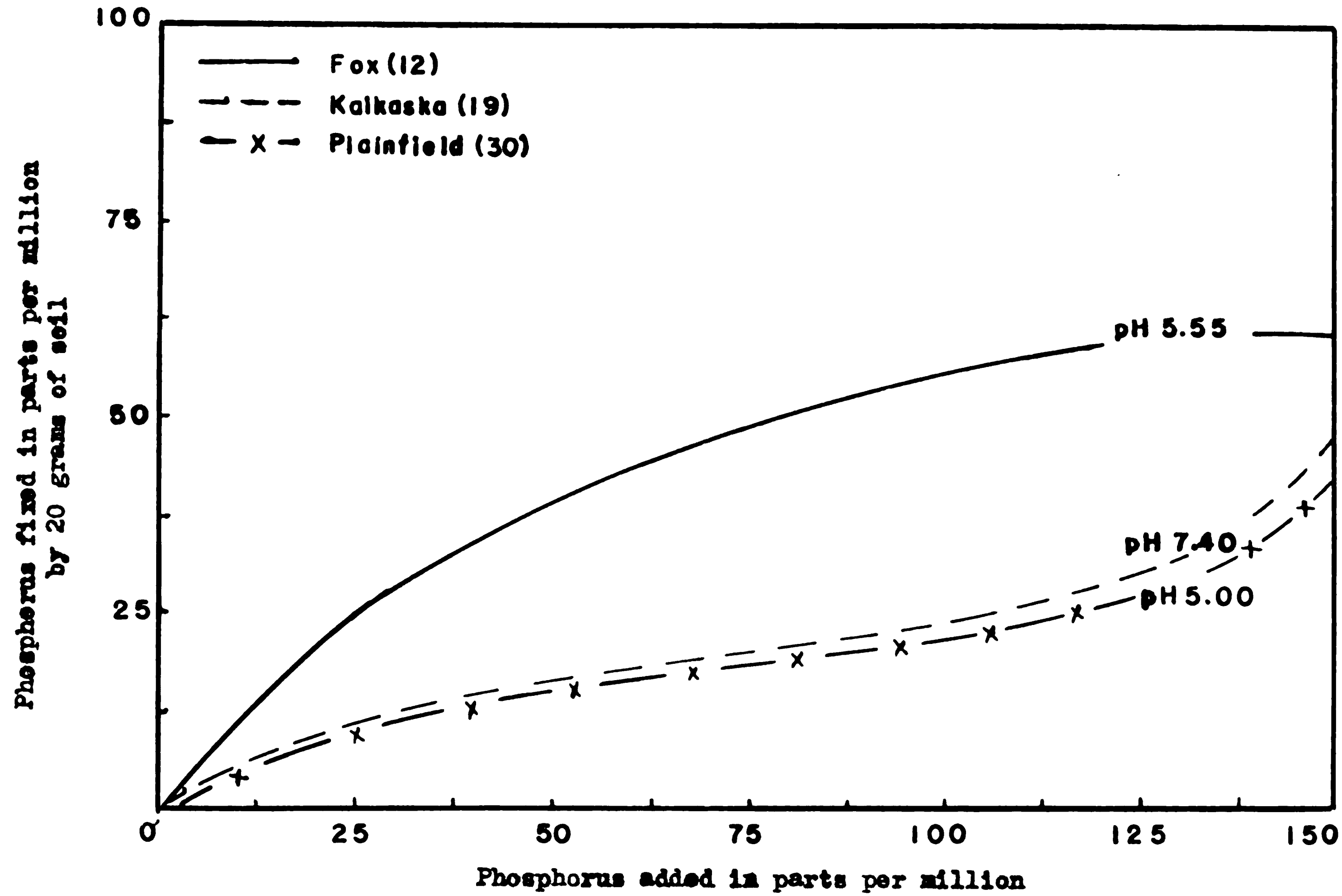

Figure 7. Phosphorus fixation by several sandy soils.

the retention of phosphate by three soil fractions that were retained on 1-millimeter, 40-mesh, and 100-mesh sieves. The soil that passed through a 100-mesh sieve fixed the greatest amount of phosphate while the least fixation occurred in the 1-millimeter fraction. Perkins, Wagoner, and King (29) divided a soil sample into six mechanical fractions and found that on a weight basis, phosphate retention increased with decreasing particle size. On a surface-area basis a direct relationship was noted. A study of the data in Tables II and XV revealed no particular relationship between the percentage of clay in the soils and the amount of phosphorus fixed by the soils.

Russell and Prescott (35), Hibbard (17), Davis (15), Kurtz, DeTurk, and Bray (19) have shown that fixation of phosphorus increases as the ratio of phosphorus to soil increases. Examination of the amounts of phosphorus fixed by the soils in this investigation show a similar increase as the amount of applied phosphorus increased. The relationship between phosphate fixation and phosphate concentration generally follows the familiar Freundlich adsorption isotherm. Chemical precipitation processes also give results which fit the Freundlich adsorption isotherm, thus it cannot be implied that the fixation was an adsorption process.

With respect to hydrogen ion concentration, it is generally accepted that in the acid range the greatest fixation of phosphorus occurs below pH 6.5 and in the alkaline range between pH 8.0 and 9.0. Roszman (34) found that the greatest fixation with the electrodialized clay fraction of Putman silt loam was at pH 3.0 to 4.0 with little retention above pH 10. Coleman (14), working with montmorillonitic and kaolinitic clays, showed that most phosphorus fixation took place at pH 3.0. Black (3) obtained similar results with Cecil clay, in which the greatest retention of phosphorus occurred at pH 3.0 to 4.0. On the other hand, Scarseth (37) found that the greatest fixation by an electrodialized bentonite was at pH 6.0 to 7.0. An inspection of the data obtained in this study shows that hydrogen ion concentration had no effect on the amount of phosphorus fixed.

Since the cation exchange capacity of a soil can be taken as a measure of its chemical reactivity, it was thought that perhaps some relationship might exist between this characteristic and the amount of phosphorus fixed. An examination of the data, however, showed that such a relationship did not exist.

It has been established that phosphorus fixation by soils is influenced by the type of clay mineral present, with 2:1 types, such as montmorillonite, generally fixing less phosphorus than the 1:1 types, such as kaolinite. The variation in fixation could not be explained in this way, however, because this investigation did not include a mineralogical examination of the clay fraction.

As indicated in the preceding paragraphs, no clear relationship exists between any one of several physical and chemical properties and the amounts or percentage of phosphorus fixed by the soils at the four rates of application. It should be remembered, of course, that the method of measuring the fixation was purely an arbitrary one, and its suitability is conjectural. The diverse properties of the soils present an impasse when an attempt is made to explain the differences in fixation. Perhaps the only reasonable explanation would be that the amount of phosphorus fixed by any of these soils is the resultant of the interaction of several physical and chemical phenomena that prevail in each.

Removal of Free Iron Oxides. In Table XVI are presented the results of the effect of the removal of free iron oxides on the amount of phosphorus fixated by the individual soils. As with the previous experiment, soils varied greatly in this respect. The amounts of phosphorus fixed by the untreated soils ranged from 0.044 to 0.224 milligrams per gram of soil. The soils from which the free iron oxides had been removed fixed from 0.015 to 0.155 milligrams per gram of soil. The data show that with some soils the removal of the iron oxides greatly decreased the amount of fixating but with other soils the removal of the oxides had little effect on phosphorus fixation.

Since Voelcker (46), in 1863, first showed that hydrogen, iron, and aluminum were active in phosphate retention in soils, many investigations have been concerned with this role of iron and aluminum. In most soils, iron and aluminum are concentrated in the clay fraction. In clay minerals such as the montmorillonitic types, these elements occur mainly in the octahedral structure, though aluminum may proxy for silicon in the telrahedral portion. In the kaolinitic types, aluminum is found only in the octahedral coordination. They also exist in soils as hydrated oxides and oxides; aluminum as

TABLE XVI

THE EFFECT OF THE REMOVAL OF FREE IRON OXIDES ON PHOSPHORUS FIXATION

Rank according to amount phosphorus fixed	Soil type and number		Phosphorus per gram Fixed soil Untreated mgms.	Phosphorus per gram Fixed soil Treated** mgms.	Decrease in Phosphorus Fixed mgms.	Percent Decrease	Fe_2O_3** Removed per gram soil mgms.
1	Granby sandy loam	(5)*	.224	.052	.172	77	4.0
2	Wisner sandy clay loam	(34)	.200	.126	.074	37	5.0
3	Warsaw loam	(16)	.186	.142	.044	24	21.6
4	Conover loam	(9)	.176	.155	.021	12	10.3
5	Bellefontaine sandy loam	(14)	.167	.092	.075	45	8.8
6	Isabella sandy clay loam	(24)	.165	.153	.012	7	14.6
7	Napanee sandy clay loam	(28)	.162	.136	.026	16	12.4
8	Waukesha sandy loam	(10)	.162	.084	.078	48	8.5
9	Kent clay loam	(22)	.156	.092	.064	41	22.4
10	Plainfield sandy loam	(15)	.155	.100	.055	35	11.0
11	Clyde clay loam	(35)	.154	.126	.028	18	6.1
12	Macomb sandy loam	(6)	.142	.048	.094	66	9.1
13	Miami loam	(26)	.138	.117	.021	15	18.9
14	Brookston loam	(32)	.138	.117	.021	15	5.9
15	Selkirk sandy clay loam	(40)	.135	.115	.020	15	9.6
16	Wisner sandy clay loam	(36)	.133	.104	.029	22	5.9
17	Kawkawlin sandy clay loam	(33)	.133	.092	.041	31	6.1
18	Isabella sandy clay loam	(23)	.130	.092	.038	29	14.6
19	Hillsdale sandy loam	(11)	.130	.044	.086	66	8.2
20	Miami clay loam	(3)	.127	.058	.069	34	8.7
21	Conover loam	(8)	.122	.090	.032	26	18.9
22	Toledo clay loam	(29)	.117	.103	.014	12	13.2
23	Conover sandy clay loam	(38)	.115	.084	.031	27	10.3
24	Conover sandy clay loam	(37)	.109	.104	.005	5	12.1
25	Kalkaska sand	(19)	.104	.044	.060	58	8.7

TABLE XVI (continued)

THE EFFECT OF THE REMOVAL OF FREE IRON OXIDES ON PHOSPHORUS FIXATION

Rank according to amount phosphorus fixed	Soil type and number		Phosphorus per gram soil Untreated mgms.	Phosphorus per gram soil Treated** mgms.	Decrease in Phosphorus Fixed mgms.	Percent Decrease	Fe_2O_3** Removed per gram soil mgms.
26	Kent sandy clay loam	(21)	.103	.092	.011	11	15.3
27	Wisner sandy loam	(4)	.096	.075	.021	22	3.7
28	Brookston sandy clay	(27)	.096	.075	.021	22	19.7
29	Brookston sandy loam	(41)	.092	.070	.022	24	6.0
30	Miami clay loam	(2)	.090	.075	.015	17	10.1
31	Brookston sandy clay loam	(7)	.090	.066	.024	27	11.4
32	Miami sandy loam	(1)	.090	.049	.041	45	10.1
33	Fox loamy sand	(12)	.088	.044	.044	50	4.9
34	Selkirk loam	(39)	.082	.046	.036	44	6.4
35	Fox loam	(13)	.082	.040	.042	51	8.6
36	Emmet sandy loam	(25)	.068	.035	.033	48	7.6
37	Plainfield loamy sand	(30)	.068	.029	.039	57	6.0
33	Fox sandy loam	(18)	.064	.040	.024	37	15.4
39	Kalkaska sand	(20)	.052	.040	.008	2	5.7
40	Bellefontaine sand	(17)	.044	.015	.029	66	7.4

* Original soil numbers.
** Free iron oxides removed by the sodium hydrosulfite method.

gibbsite, and iron as hematite, goethite, limonite and magnotite. In addition, some aluminum and iron may be present as exchangeable cations. Waksman (47) has pointed out that iron is present in soil organic matter and it is likely that aluminum occurs similarly. With the exception of acid soils, it is generally thought that the active amounts of iron and aluminum in the soil solution are small.

It has been definitely established that iron and aluminum compounds can retain phosphorus under the conditions that normally exist in soils. Experiments with hydrogels (26), ferric hydroxide (18), and with soluble iron and alumnnum (21, 27, 32, 40, 41) have produced an overwhelming weight of evidence to support that conclusion. Mattson (22,23), Scarseth and Tidmore (36), and Toth (42) have demonstrated that phosphorus fixation varies inversely with the silica-sesquioxide ratio of the soil colloids.

As in this investigation, several workers have studied the effect of the removal of iron and aluminum from soils and soil colloids on phosphorus fixation. Toth (42,43), Chandler (13), Black (3), Coleman (14), Metzger (24), and Kelly and Midgely (18) have shown that the removal of iron and aluminum oxides from soils reduced the amount of phosphorus fixation. The results, of course, varied with the colloid or soil under investigation, but tended to emphasize that in acid soils, iron and aluminum are actively involved in phosphorus fixation.

Removal of the iron oxides from the soils in this study generally had a marked effect on the amount of phosphorus fixed. The results are comparable to those obtained by other workers. The quantities of iron oxides removed from soils were more closely related to the clay content than to any other soil property. There was no apparent relation between the amounts of iron oxides removed and the degree of acidity of the soils. This is contrary to what had been expected since it is generally assumed that iron activity increases with acidity and consequently more iron should be removed from the more acid soils. It is possible that the fraction of iron removed was not related to the chemically active amount in the soils. However, a test for free iron oxides should give a measure of the "active" iron in a soil. The method used for free iron oxide removal was compared by Deb (16) at Rothamstead with several other recognized methods and he concluded that the method was superior to the others because it efficiently removed free iron oxides and had less destructive effect on clay minerals.

In making an evaluation of the effect of the removal of the iron oxides on fixation it must be remembered that the method used in this investigation, as with methods used by other investigators, was not specific for iron and may have removed other compounds which are effective in phosphate fixation. This point is probably of particular importance in the case of the alkaline soils known to contain large amounts of calcium and organic matter. As in the hydrosulfite method, all chemical methods for the removal of free iron oxides involve a destruction of the organic matter, reduction of the iron compounds with a reducing agent, and removal of the reduced iron by suitable solvents. Though little change occurs in the structure of the clay minerals, radical changes in the overall chemical system results, and therein may be the explanation for some of the variations in results. An excellent example, is the case of soil number 5, an alkaline soil which in both experiments fixed the largest quantities of phosphorus. The amount of free iron oxides in this soil as shown by the data in Table XVI was only 4.0 milligrams per gram of soil. Fixation of phosphorus in this soil was reduced 77 percent by the removal of these iron oxides. It was quite probable that the reduced fixation was due more to the removal of calcium than of iron compounds. This would probably be true of any alkaline soil high in organic matter. However, with highly acid soils which are low in organic matter, there is a more valid relationship between phosphorus fixing capacity and the free iron oxides. Though it cannot be denied that iron oxides were removed from the soils in this investigation, the question of what other substances effective in phosphorus fixation were removed, and just how much of the reduction in fixation in the case of each soil can be attributed to iron oxides, remains unanswered.

Relation Between Alfalfa Yields and Soil Phosphorus

The successful use of chemical soil tests in helping to formulate soil management recommendations is dependent upon calibration of the test with crop yields. Critical nutrient levels, above which substantial crop response to added nutrients will not occur, must be established before the fertilizer needs of soils can be properly appraised. In the succeeding paragraphs the relationships between the yield data secured in this study and the soil phosphorus as measured by the various methods are presented.

Spurway's Reserve Test. In Figures 8 and 9 scatter diagrams are presented of the relation of the yields of alfalfa to soil phosphorus as measured by Spurway's reserve test. The coefficient of correlation between the yield of tops and soil phosphorus was 0.312, a rather low degree of linear correlation. When the root yields were combined with the top yields the correlation coefficient was 0.302. These results indicate that Spurway's reserve test is of doubtful value in measuring the phosphorus supplying power of the soils for alfalfa under the conditions of greenhouse cropping in this experiment. Obviously from the data given, the strong acid extractant (0.135 N HCl) did not measure a proportionate amount of the phosphorus which was available to the growing plant. This is further substantiated by an examination of the percentage phosphorus composition and total phosphorus content of the alfalfa. A negative correlation of 0.142 was obtained between the levels of soil phosphorus and the total phosphorus uptake. The correlation coefficient between soil phosphorus and percentage phosphorus content of the alfalfa was 0.046. Further evidence of the failure of Spurway's test to measure forms of soil phosphorus which are available for plant use was seen in the amount of soil phosphorus extracted from certain soils. For an example, with certain heavier textured soils,

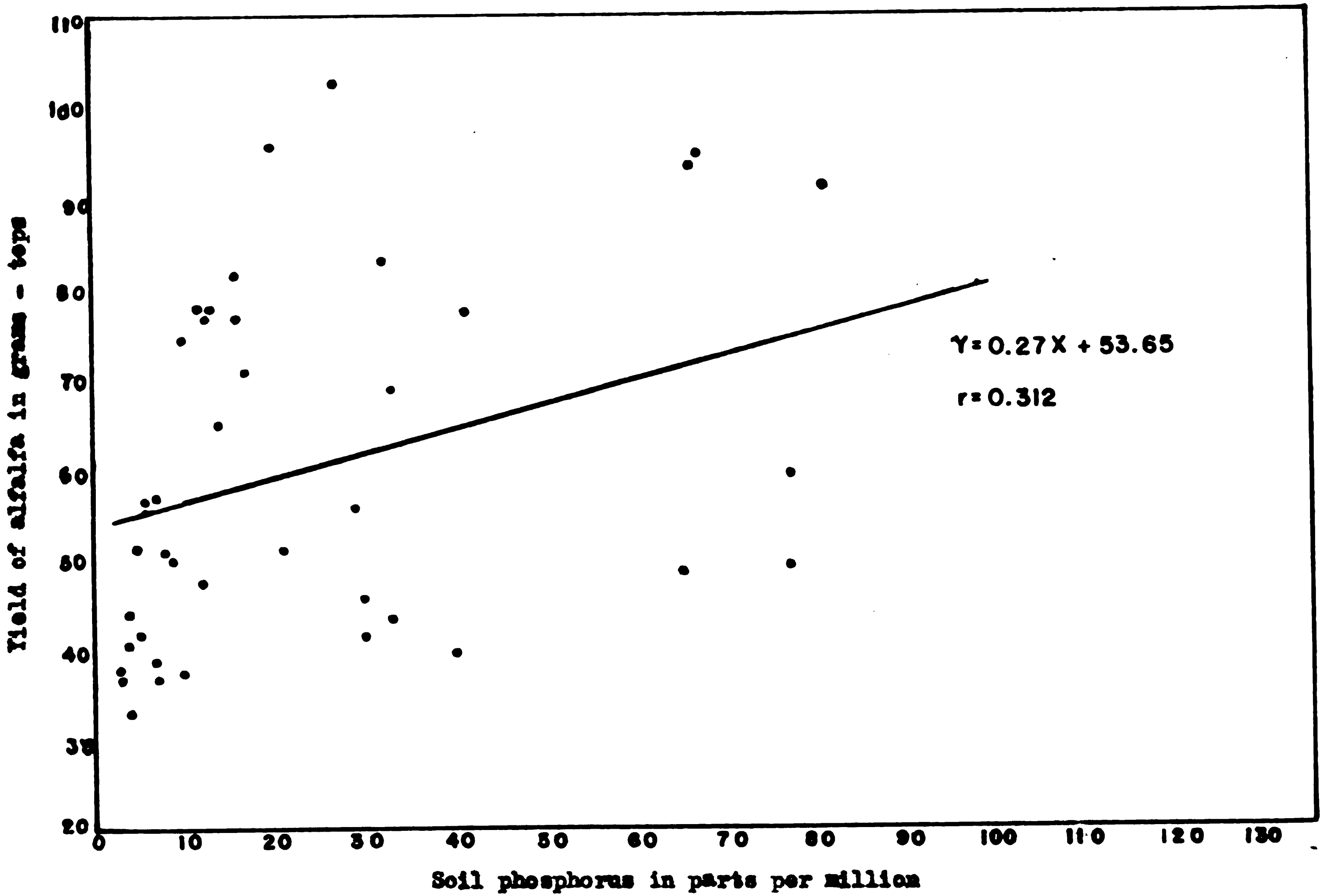

Figure 8. Relation Between Alfalfa Yield and Soil Phosphorus as Measured by the Spurway Reserve Method.

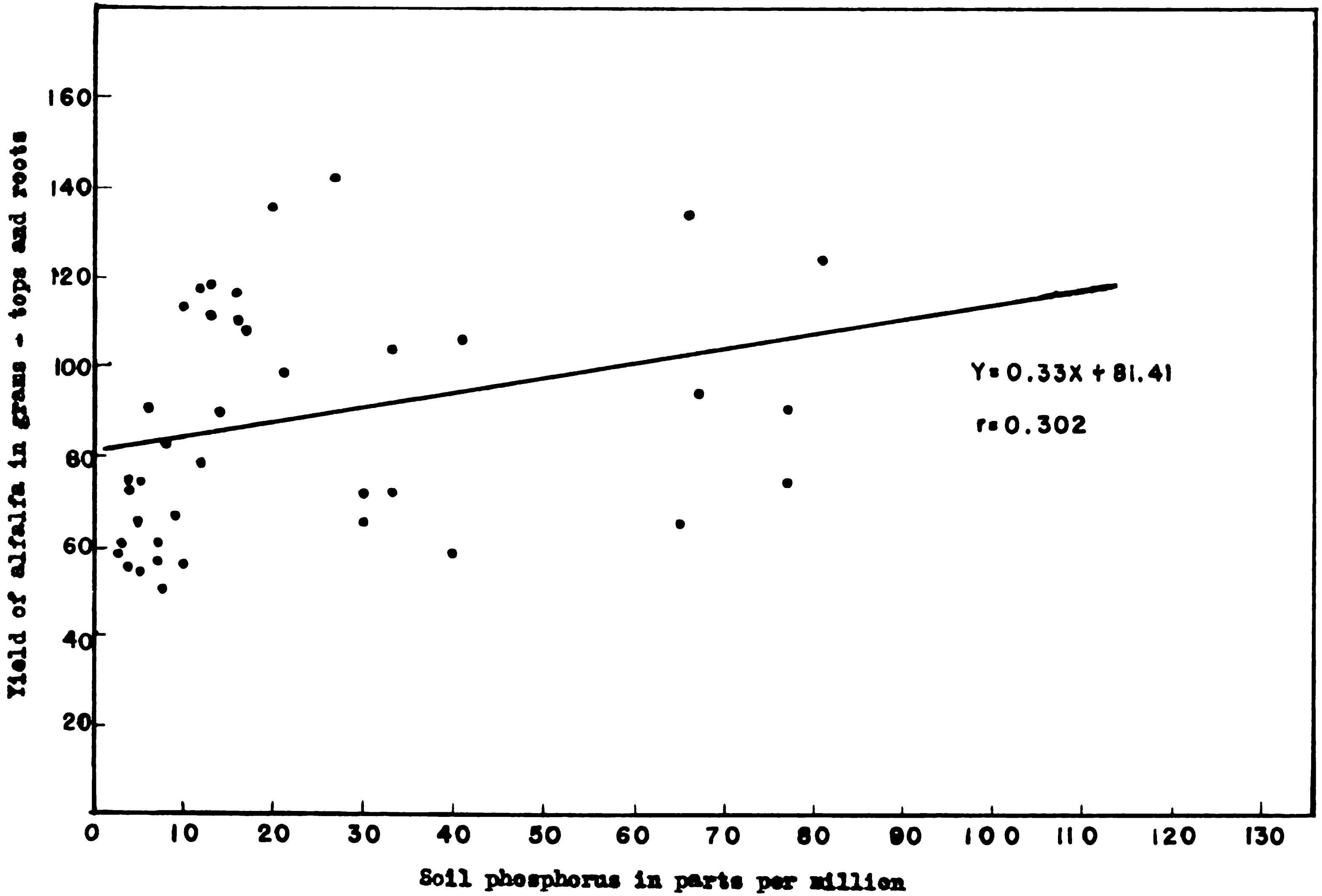

Figure 9. Relation between alfalfa and soil phosphorus as measured by the Spurway Reserve Method.

numbers 36, 34, 29, and 32, the acid extractant removed large amounts of phosphorus which were not reflected in the yields. On the other hand, with several of the lighter textured soils, numbers 30, 18, and 17, the levels of phosphorus were low and not commensurate with the high yields obtained without added phosphorus.

Bray's Available Phosphorus Test. The acid concentration used in this test approximates that used in the Spurway reserve test. However, included in the extractant was sufficient ammonium fluoride to make it 0.03 normal with respect to that reagent. The evidence that the results from Bray's available test for phosphorus were more closely related to alfalfa yields than the Spurway test values is shown in Figures 10 and 11. As previously presented in Table XII the average amount of phosphorus removed was 40.8 parts per million which almost doubled the average amount removed by the Spurway test. The coefficients of correlation between soil phosphorus and yield of tops and between soil phosphorus and total yields were 0.635 and 0.599 respectively. The decided improvement in the correlations over those obtained with the Spurway test was attributed to the increased amounts of phosphorus removed by the fluoride ion especially from the lighter textured soils. From these data it was apparent that Bray's available phosphorus test was a good measure of the power of the soils to supply the phosphorus needed by alfalfa.

Bray's Adsorbed Phosphorus Test. The scatter diagrams for the relation of alfalfa yields to adsorbed soil phosphorus are given in Figures 12 and 13. The respective correlation coefficients were 0.754

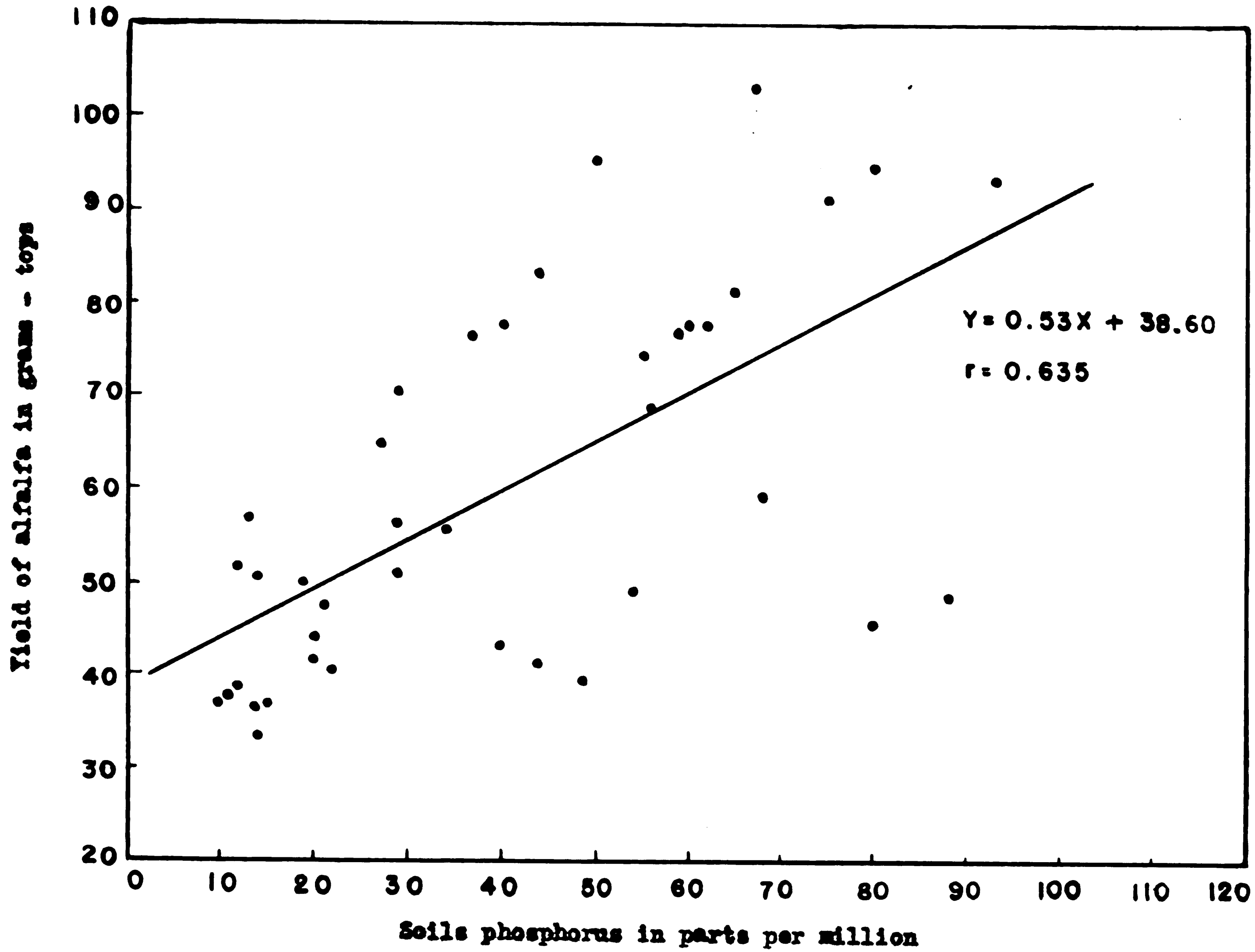

Figure 10. Relation between alfalfa yield and soil phosphorus as measured by the Bray Available Phosphorus Method.

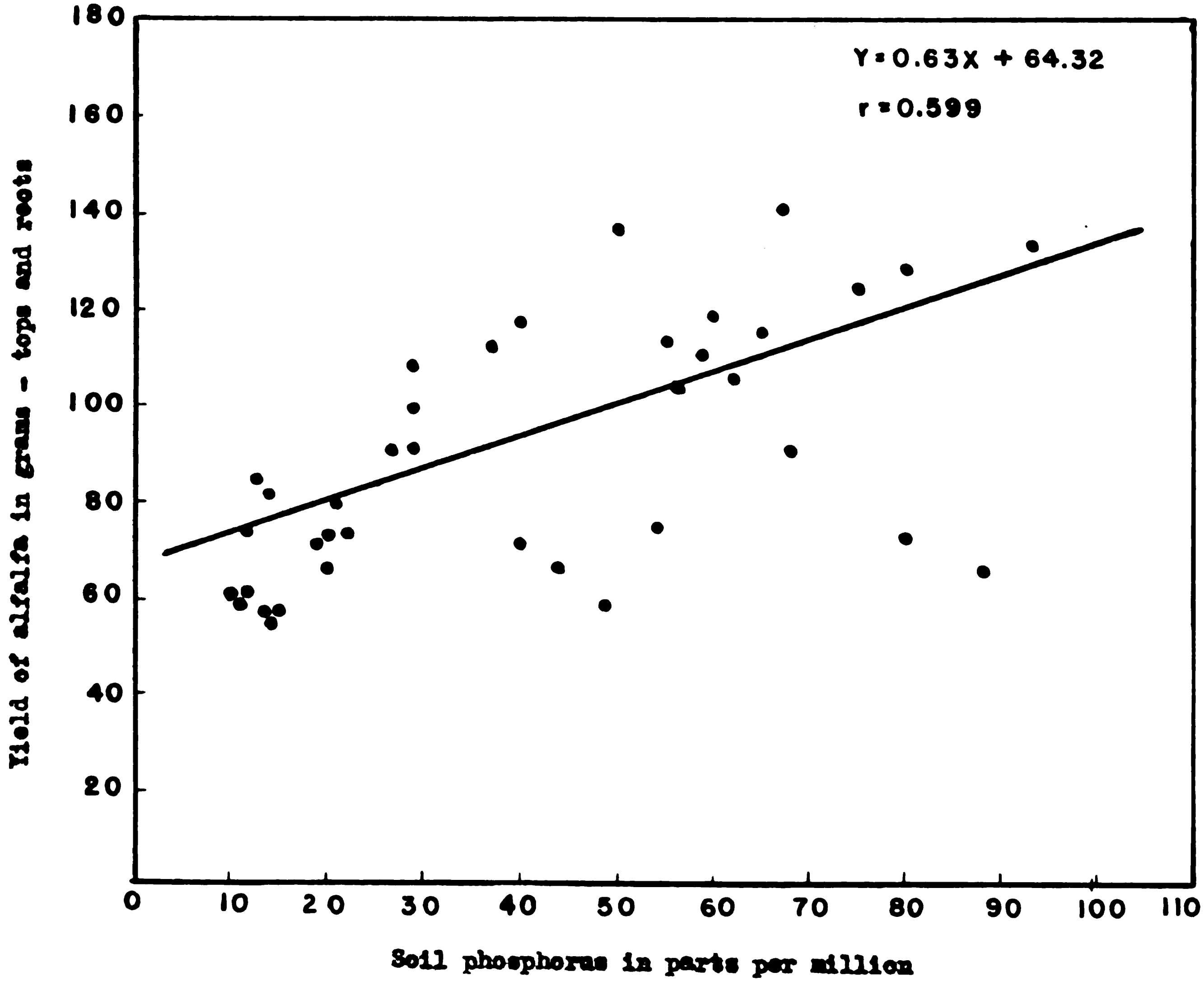

Figure 11. Relation between alfalfa yield and soil phosphorus as measured by the Bray Available Phosphorus Method.

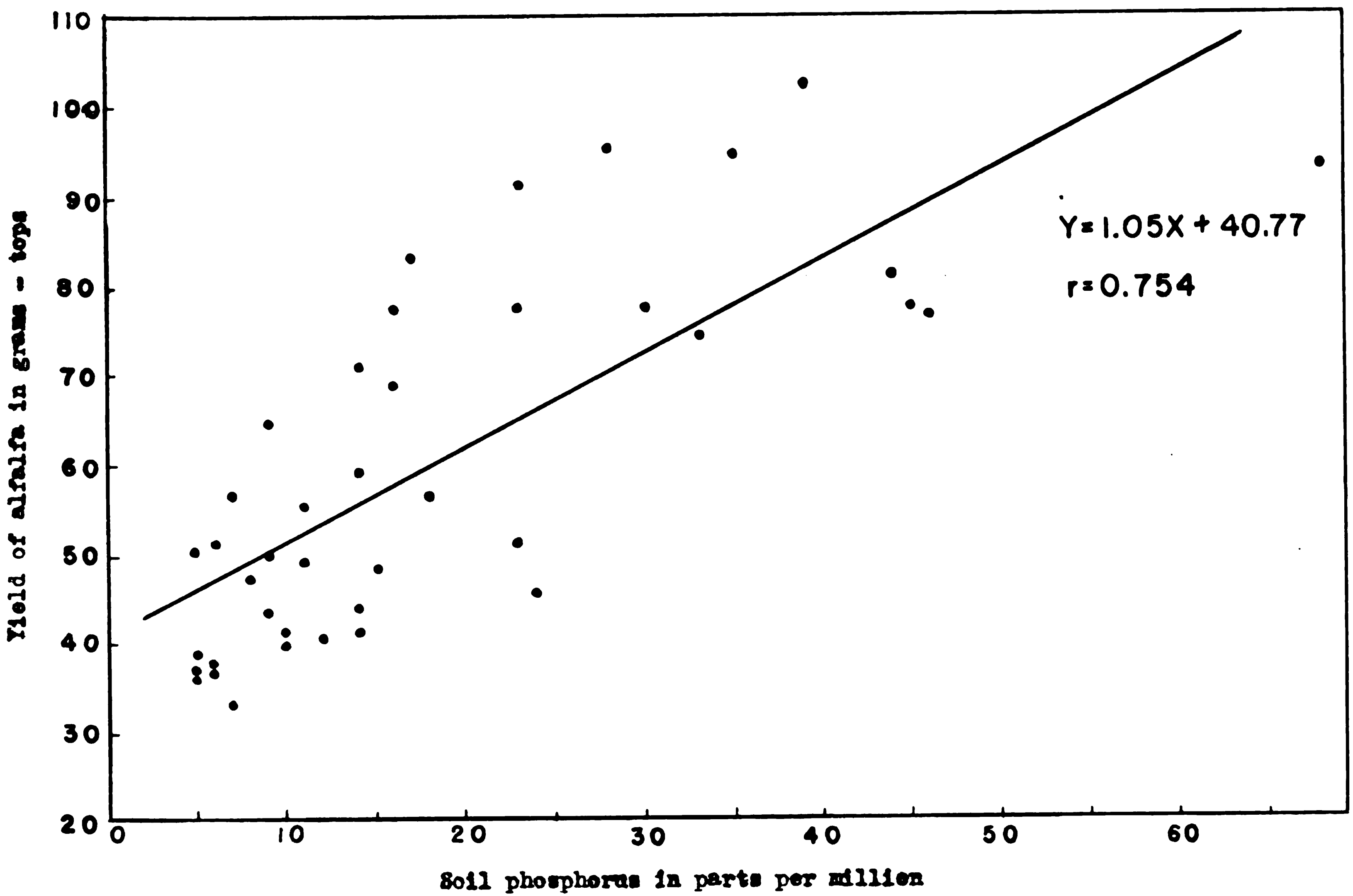

Figure 12. Relation between alfalfa yield and soil phosphorus as measured by the Bray Adsorbed Phosphorus Method.

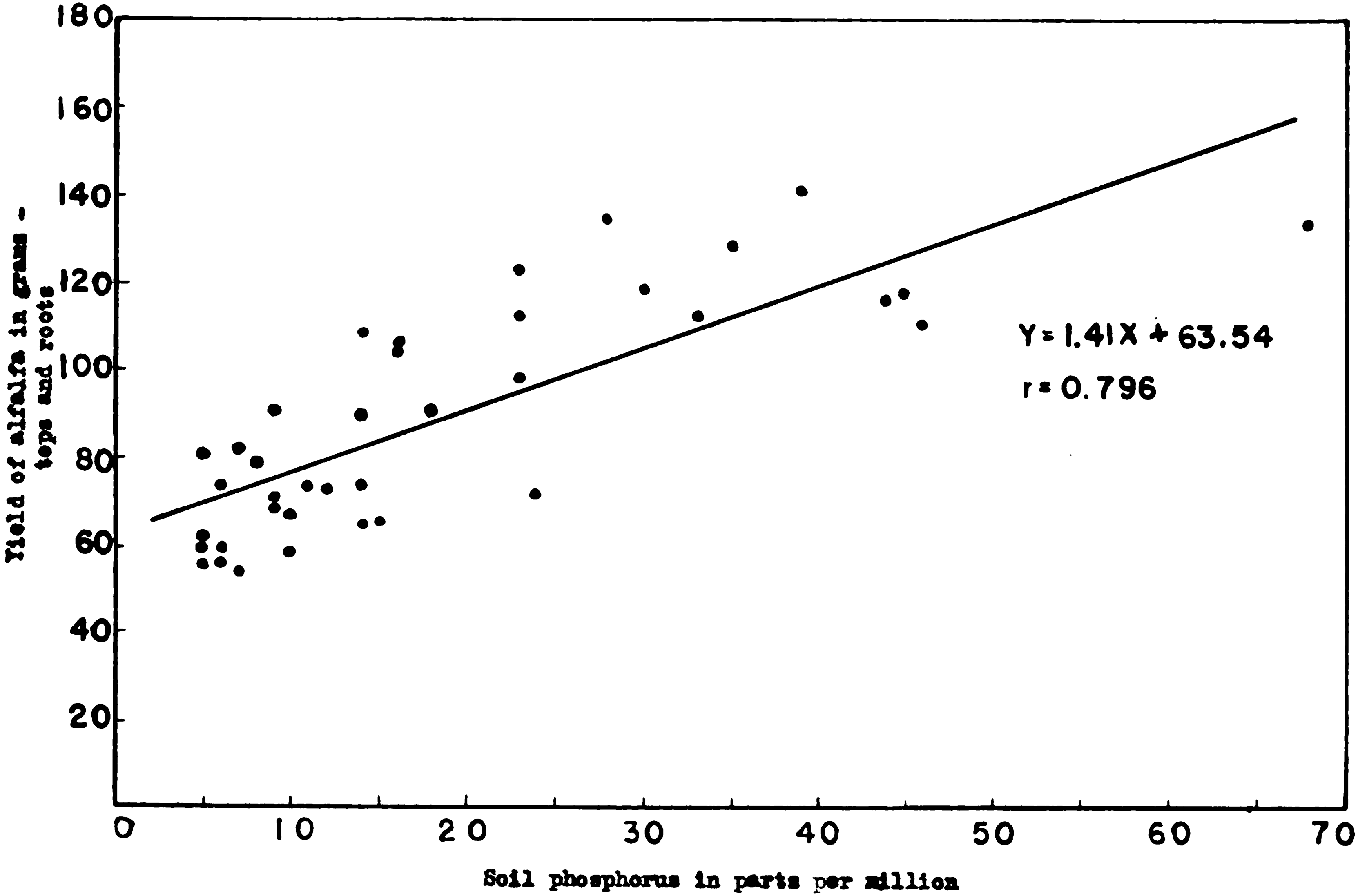

Figure 13. Relation between alfalfa yield and soil phosphorus as measured by the Bray Adsorbed Phosphorus Method.

and 0.796 indicating very high correlation in each case. The diagrams show that differences in amounts of phosphorus removed between soils are of a smaller magnitude than those obtained with the Bray available phosphorus extractant thus increasing the difficulty of making a cursory separation of the yielding powers on the basis of their phosphorus contents. However, the differences between the levels of adsorbed phosphorus were greater than those obtained by the Spurway reagent even though the acid concentration was only 0.025 normal. This further emphasizes the effectiveness of the fluoride ion in the removal of soil phosphorus, especially those forms well correlated with plant growth.

The amounts of adsorbed soil phosphorus were reflected in the total phosphorus uptake by the alfalfa and also in the percentage phosphorus composition. With total uptake the coefficient of correlation was 0.416 and with the percentage phosphorus content it was a high 0.749.

From the correlations presented, it is apparent that of the three rapid tests, Bray's adsorbed phosphorus test was the most reliable as a measure of the soils' phosphorus supplying powers.

Bray's Total Acid-Soluble and Adsorbed Phosphorus. In Figures 14 and 15 data are presented to show the relation of alfalfa yields to soil phosphorus as measured by Bray's method of determining total acid soluble and adsorbed phosphorus. The scatter diagrams reveal a fair degree of linear correlation between these more resistant and less soluble forms of phosphorus and the yield data. The correlation coefficients are 0.499 and 0.501 respectively. The phosphorus

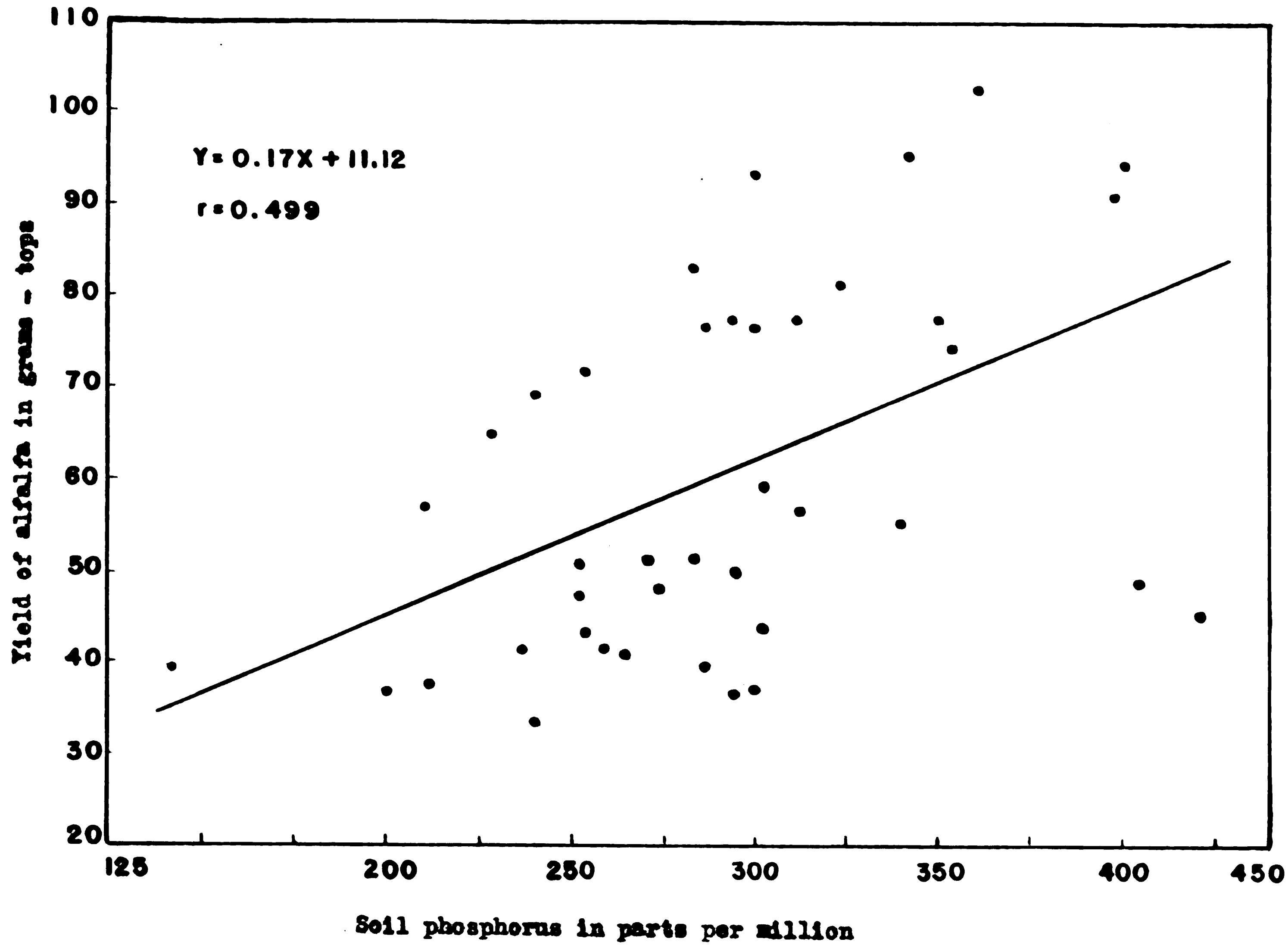

Figure 14. Relation between soil phosphorus and alfalfa yield as measured by the Bray Method for total adsorbed and acid-soluble phosphorus.

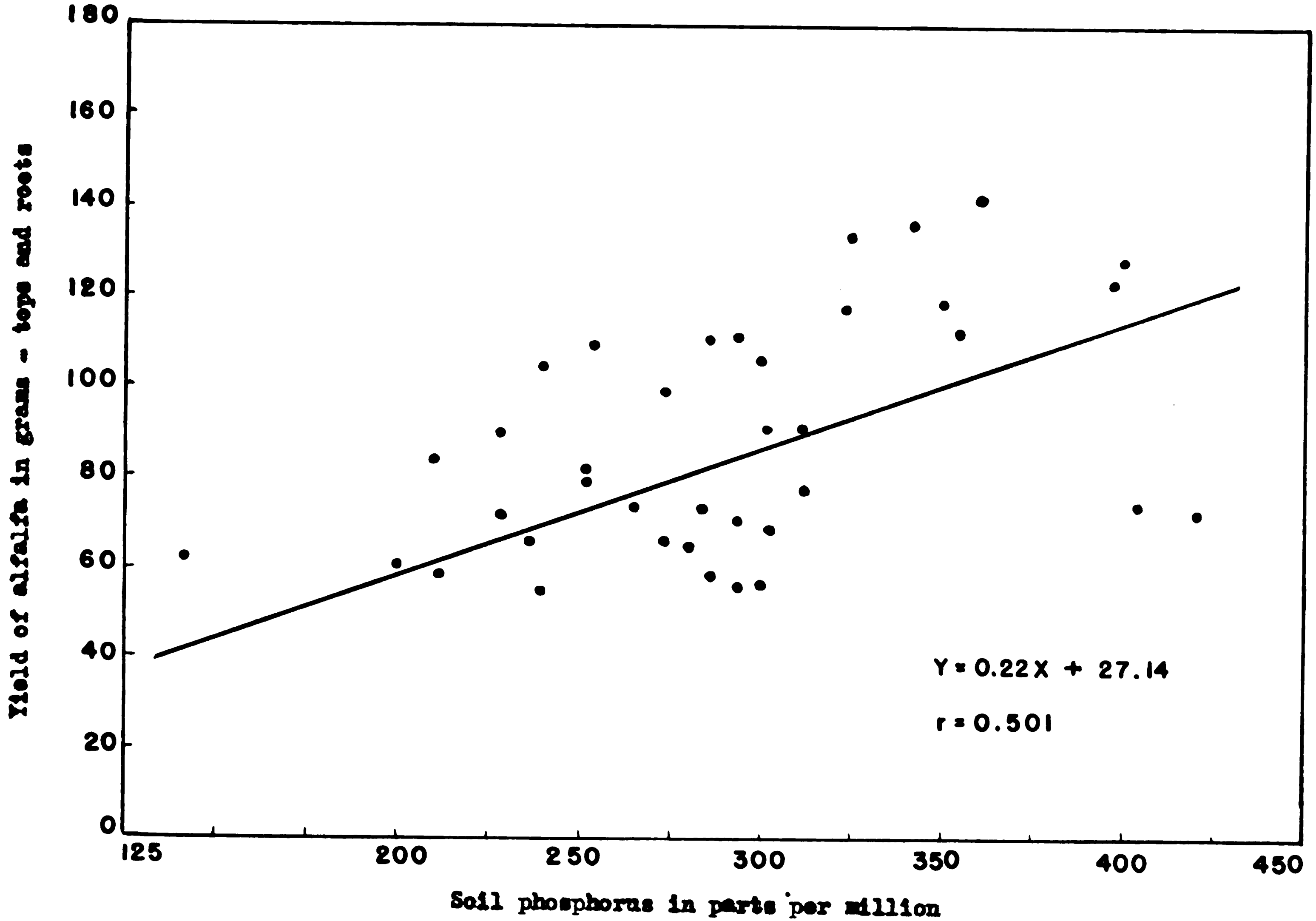

Figure 15. Relation between soil phosphorus and alfalfa yield as measured by the Bray Total Adsorbed and Acid-Soluble Phosphorus Method.

values are large as compared with those obtained in the rapid tests, and the variations between the results from different soils are sufficiently great to make possible separations into low, medium, and high yielding groups.

Organic Phosphorus. In Figures 16 and 17 scatter diagrams of the relation between yields and organic phosphorus are presented. The correlation coefficients are 0.487 and 0.532. These results are not surprising when consideration is given to the duration of the experiment and the intensive root action to which the soils were subjected. The length of the experiment permitted sufficient time for the mineralization of organic phosphorus for plant use. An examination of the levels of inorganic phosphorus before and after cropping showed that the phosphorus content did not decrease to any great extent. Since appreciable quantities of phosphorus were removed by cropping, it can be concluded that organic phosphorus was mineralized. The degree of correlation obtained emphasized the point that over a long growing period organic phosphates play an important role in maintaining the available supply of phosphorus and that under such conditions organic phosphorus can be an adequate measure of the phosphorus supplying power of soils.

Bray's Total Acid-Soluble, Adsorbed, and Organic Phosphorus. As would be expected from the other results, a high degree of linear correlation was obtained between yields and the quantities of phosphorus measured by Bray's methods for total acid-soluble, adsorbed, and organic phosphorus. Figures 18 and 19 present the scatter diagrams.

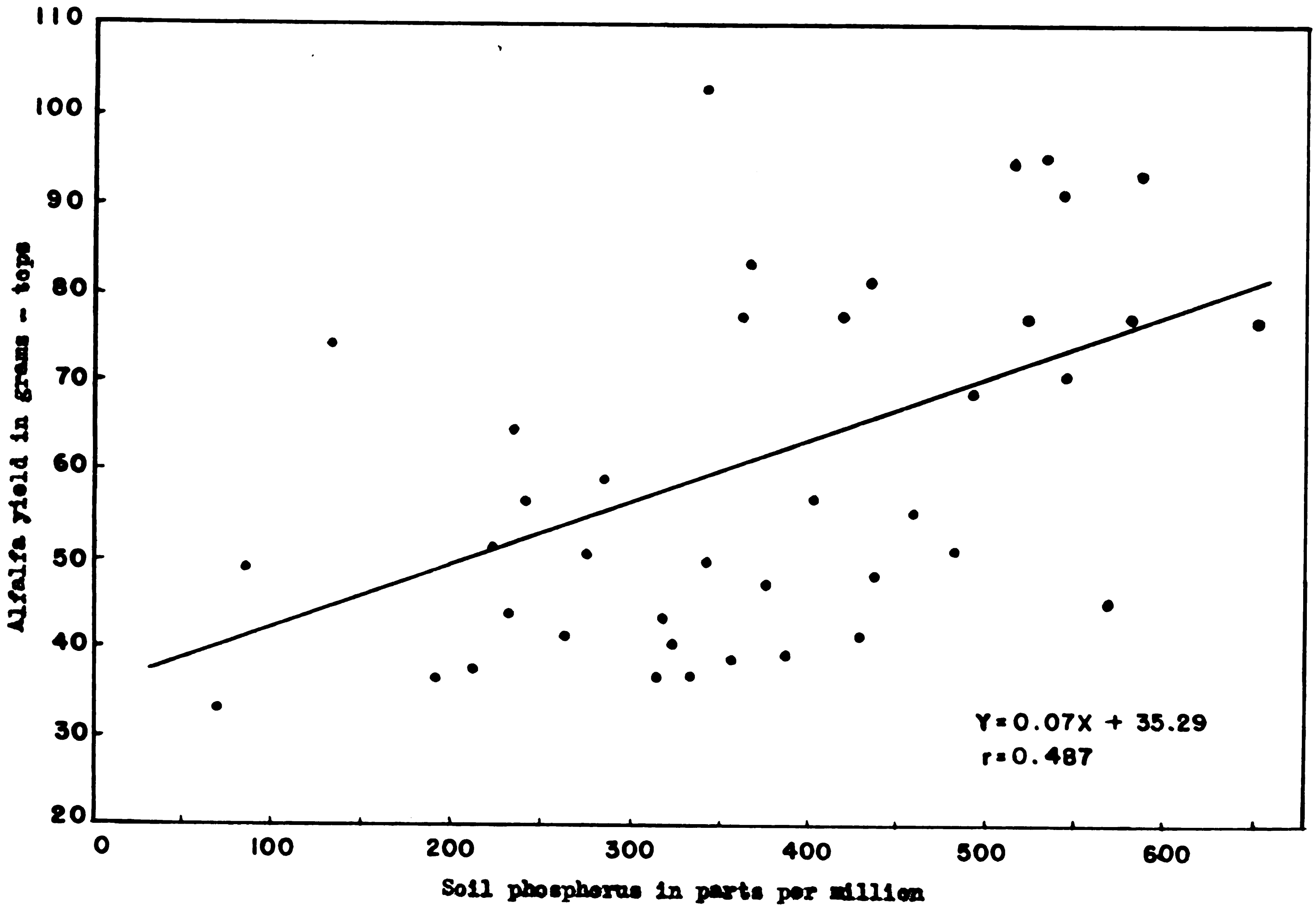

Figure 16. Relation between soil phosphorus and alfalfa yield as measured by the Bray Organic Phosphorus Method.

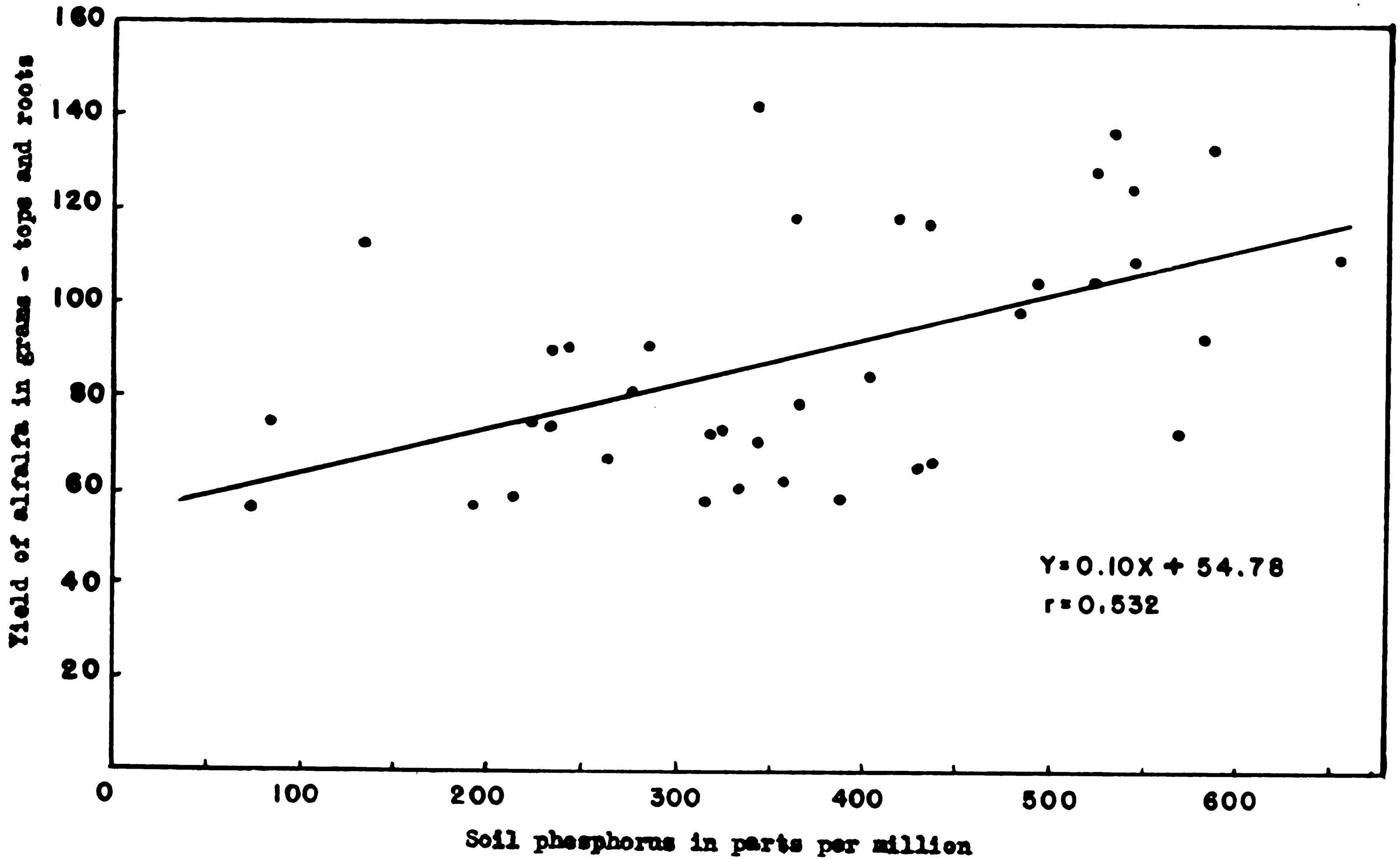

Figure 17. Relation between soil phosphorus and alfalfa yield as measured by the Bray Organic Phosphorus Method.

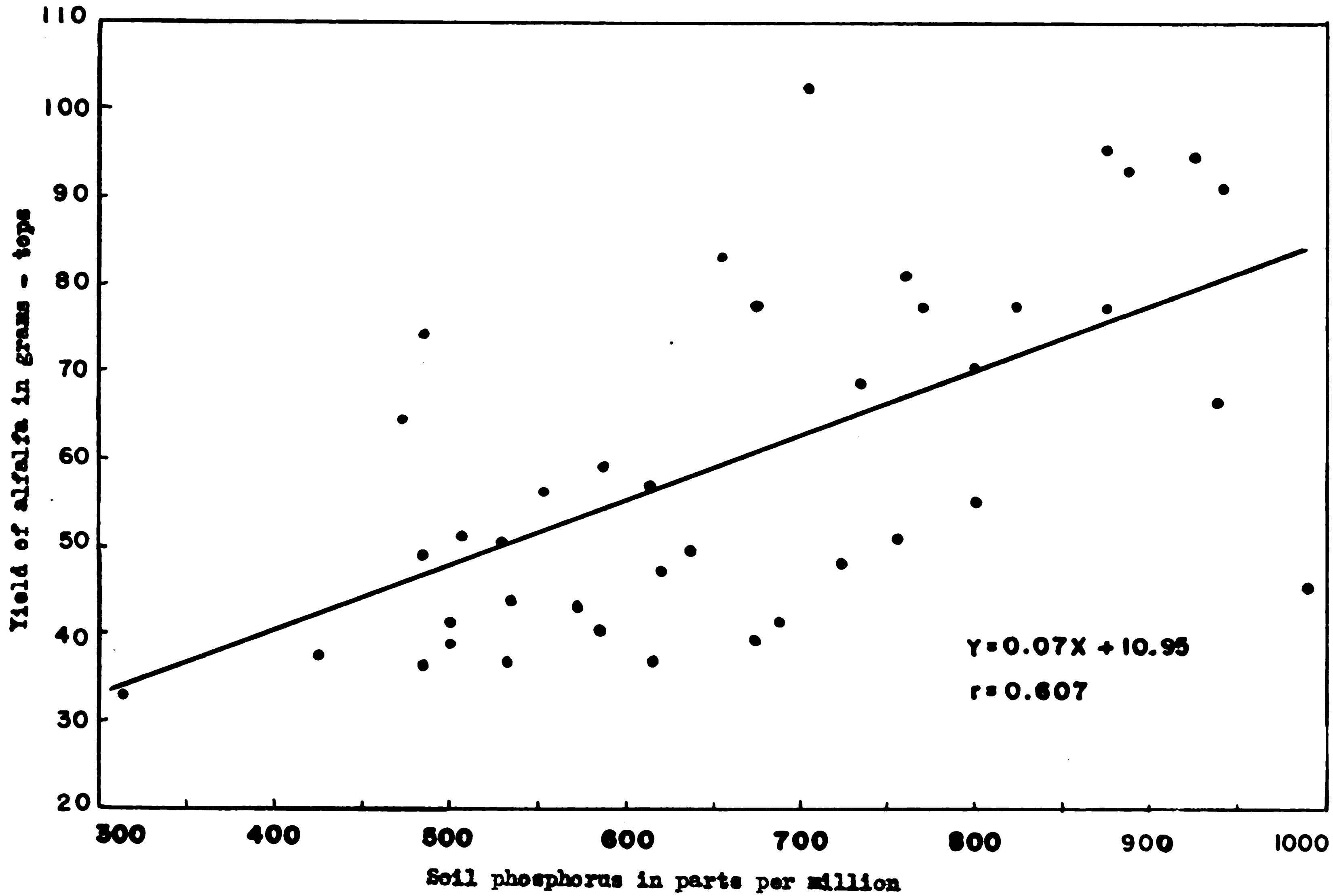

Figure 18. Relation between soil phosphorus and alfalfa yield as measured by the Bray Total Acid-Soluble, Adsorbed, and Organic Phosphorus Method.

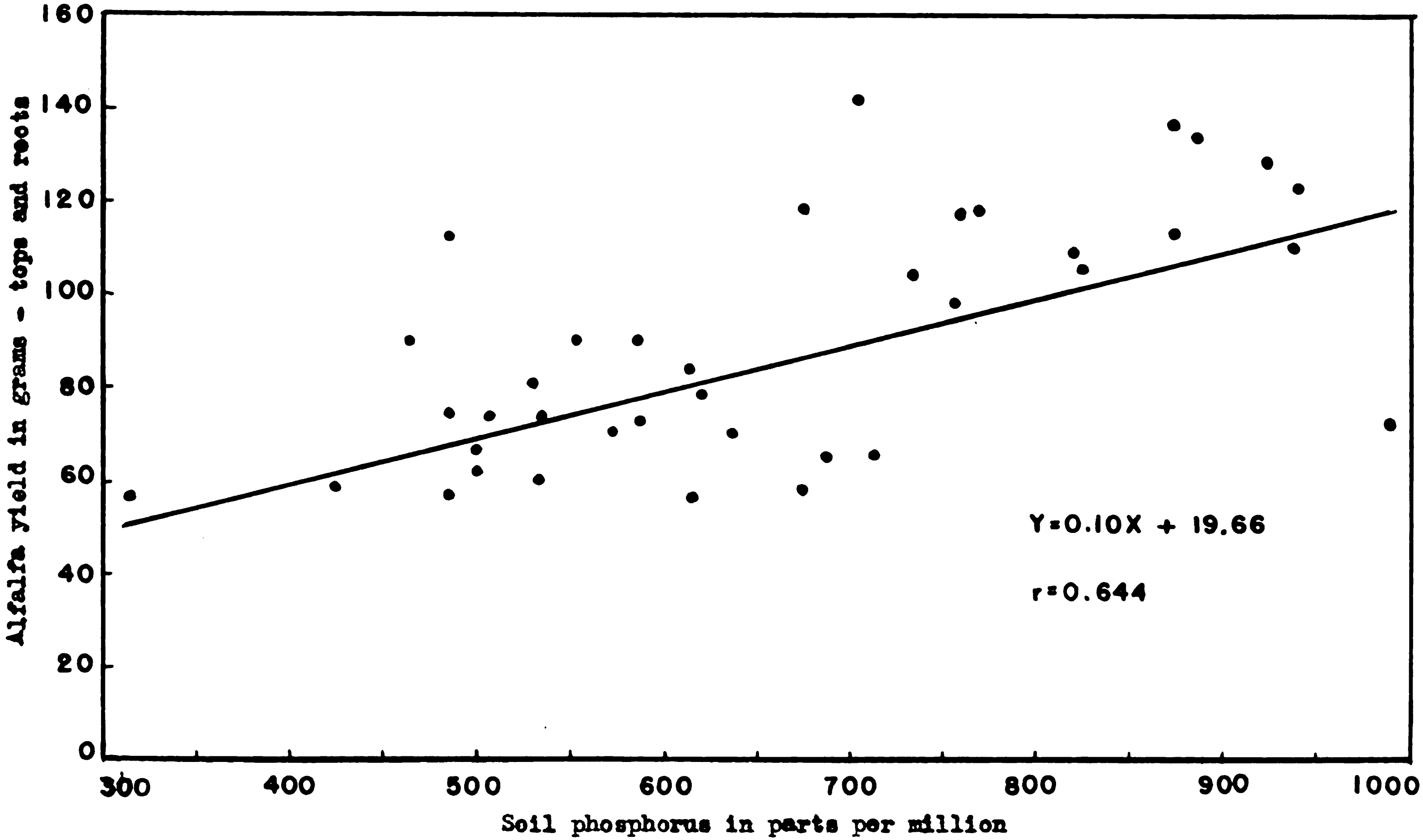

Figure 19. Relation between alfalfa yield and soil phosphorus as measured by the Bray Total Acid-Soluble, Adsorbed and Organic Phosphorus Method.

The coefficients of correlation are 0.607 and 0.644, respectively. With exception of two soils, 18 and 5, the correlations were very good. Soil number 18, as previously mentioned, is a light textured soil and gave proportionately low results as with the other tests. Soil number 5, an alkaline soil high in organic matter, gave high results.

From an examination of the results it is apparent that these quantitative methods for measuring the more resistant and less soluble forms of phosphorus are satisfactory for distinguishing between soils on the basis of their phosphorus contents and for predicting the phosphorus supplying powers of the soils.

Table XVII and XVIII present summaries of the relationships between the various tests for soil phosphorus and the yield results, total phosphorus uptake and percentage phosphorus compositions of alfalfa.

Relation Between Soil Phosphorus and Soil Properties

Careful examination of the data obtained with the various chemical tests failed to reveal any exact and definite relationship between any soil property and any particular fraction or fractions of soil phosphorus.

Generally, all of the tests measured relatively large amounts of phosphorus in the heavier textured soils. The amounts removed from the lighter textured soils were extremely variable. As previously shown, the variable amounts of chemically extractable phosphorus in

TABLE XVII

SUMMARY OF THE RELATIONSHIP BETWEEN SOIL PHOSPHORUS TESTS AND ALFALFA YIELDS

	Soil Phosphorus Test* (X)	Alfalfa Yield** (Y)	Coefficient of Correlation (r)
Rapid Tests	Spurway Reserve	Tops	0.312
	Spurway Reserve	Tops and Roots	0.302
	Bray's Adsorbed	Tops	0.754
	Bray's Adsorbed	Tops and Roots	0.796
	Bray's Available	Tops	0.635
	Bray's Available	Tops and Roots	0.599
Quantitative Tests	Bray's Adsorbed and Acid-Soluble	Tops	0.499
	Bray's Adsorbed and Acid-Soluble	Tops and Roots	0.501
	Bray's Organic	Tops	0.487
	Bray's Organic	Tops and Roots	0.532
	Bray's Total Adsorbed, Acid-Soluble, and Organic	Tops	0.607
	Bray's Total Adsorbed, Acid-Soluble, and Organic	Tops and Roots	0.644

* Soil phosphorus in parts per million on a soil basis.
** Yield in grams of dry plant material per pot.

TABLE XVIII

SUMMARY OF THE RELATIONSHIP BETWEEN SOIL PHOSPHORUS TESTS AND PHOSPHORUS UPTAKE

AND PHOSPHORUS COMPOSITION OF ALFALFA

	Soil Test (X)*	Coefficient of Correlation (r): Total Uptake of Phosphorus in Milligrams (Y)	Coefficient of Correlation (r): Percentage Phosphorus in Alfalfa Tops (Y)
Rapid Tests	Spurway Reserve	-0.142	0.046
	Bray's Adsorbed	0.416	0.749
	Bray's Available	0.073	0.472
Quantitative Tests	Bray's Adsorbed and Acid-Soluble	0.230	0.354
	Bray's Organic	0.292	0.306
	Bray's Total Adsorbed, Organic, and Acid-Soluble	0.264	0.394

* Soil phosphorus in parts per million on a soil basis.

the lighter soils were responsible for reduced linear correlations with yields. These same lighter textured soils are responsible for the lack of a clear relationship between certain chemical properties and soil phosphorus. Generally, high percentages of clay, high exchange capacities, and relatively high percentages of organic matter are associated with relatively high levels of phosphorus. However, in some instances, the soils high in sand and silt gave high tests for phosphorus. Despite the variability of the lighter textured soils, a somewhat general relationship was found to exist between the amounts of phosphorus removed by Bray's adsorbed phosphorus test and the percent sand. The soils having large proportionate amounts of sand in most instances contained large amounts of adsorbed phosphorus.

The amounts of soil phosphorus removed by the various tests showed little relationship to the hydrogen-ion concentration of the soils. As previously discussed, the highest levels of plant availability for phosphorus are thought to be between pH 6.5 and 8.0. However, the chemical availability of phosphorus as measured by soil tests did not indicate increased availability in that range. The only clue to a possible relationship is shown in the data from the rapid test for adsorbed phosphorus. All of the soils above pH 7.0 contained low to medium amounts of adsorbed phosphorus.

The inability to establish clear relationships between the chemical and physical properties of the soils and the available soil phosphorus as determined by any one of five different methods serves to re-emphasize the concept that each soil is an entity in itself and must be judged as such. The accuracy of each test method has been shown by correlation with the yield results. The failure to establish relationships between physical properties and test results does not discredit the tests nor decrease their usefulness.

Relation Between Phosphorus Fixation and Alfalfa Yields

No direct relationship existed between fixation of added phosphorus by the soils and the yields of alfalfa hay produced on them. The high rate of phosphorus application which perhaps came close to satisfying the fixation capacities of the soils possibly precluded the establishment of such a relationship. This is brought out not only by the values obtained for adsorbed phosphorus after plant growth but by the good growth throughout the experiment. Possibly, at a lower rate, the difference in abilities of the soils to fix phosphorus would be more apparent.

The total amounts of phosphorus fixed by the untreated soils in Table XVI provide a comparison of the relative fixing capacities of the soils. In Table XIX the soils were again arranged in descending order of the amounts of phosphorus fixed but were also grouped into "Low", "Medium", and "High" categories. Comparison of the arrangement in Table VII with the grouping in Table XIX indicated that though there is no evidence of a direct relationship between the requirements for phosphorus as indicated by alfalfa growth and the amount of phosphorus fixed, a somewhat general relationship did exist. Close

TABLE XIX

RELATIVE PHOSPHORUS FIXING CAPACITIES OF FORTY MICHIGAN SOILS

Low			Medium			High		
1.	Bellefontaine sand	(17)*	15.	Kent sandy clay loam	(21)	31.	Plainfield sandy loam	(15)
2.	Kalkaska sand	(20)	16.	Kalkaska sand	(19)	32.	Kent clay loam	(22)
3.	Fox sandy loam	(18)	17.	Conover sandy clay loam	(37)	33.	Waukesha sandy loam	(10)
4.	Plainfield loamy sand	(30)	18.	Conover sandy clay loam	(38)	34.	Napanee sandy clay loam	(28)
5.	Emmet sandy loam	(25)	19.	Toledo clay loam	(29)	35.	Isabella sandy clay loam	(24)
6.	Fox loam	(13)	20.	Conover loam	(8)	36.	Bellefontaine sandy loam	(14)
7.	Selkirk loam	(39)	21.	Miami clay loam	(3)	37.	Conover loam	(9)
8.	Fox loamy sand	(12)	22.	Hillsdale sandy loam	(11)	38.	Warsaw loam	(16)
9.	Miami sandy loam	(1)	23.	Isabella sandy clay loam	(23)	39.	Wisner sandy clay loam	(34)
10.	Brookston sandy clay loam	(7)	24.	Kawkawlin sandy clay loam	(33)	40.	Granby sandy loam	(5)
11.	Miami clay loam	(2)	25.	Wisner sandy clay loam	(36)			
12.	Brookston sandy loam	(4)	26.	Selkirk sandy clay loam	(40)			
13.	Brookston sandy clay	(27)	27.	Brookston loam	(32)			
14.	Wisner sandy loam	(21)	28.	Miami loam	(26)			
			29.	Macomb sandy loam	(6)			
			30.	Clyde clay loam	(35)			

* Original soil numbers.

examination revealed that a large number of the soils in the "Low" fixing group fell in the "Least" and "Moderate" categories of Table VII. Also a greater percentage of the soils with "Greatest" and "Marked" requirements for phosphorus fell in the "High" and "Medium" fixing groups. This somewhat general relationship appeared to indicate that the relative amount of phosphorus fixed by a soil is perhaps a fair index of its ability to supply phosphorus.

A comparison of the relative fixing capacities with the levels of available phosphorus as measured by the chemical tests showed that there was little relationship between the magnitude of phosphorus fixation and the existing level of chemically available phosphorus.

The Phosphorus Supplying Powers of Forty-one Michigan Soils

The greenhouse and laboratory studies conducted throughout this investigation were designed primarily to secure a better understanding of the ability of the various soils to supply phosphorus. The final measure of the capacity of a soil to deliver a given nutrient element is obtained through actual plant growth on the soil. Other methods, such as soil tests and fixation studies, are useful but their value is assessed in terms of the plant growth. When several methods are used, such as was done in this experiment, a reliable estimate can be made of the nutrient supplying powers of a given soil.

Consideration of the yields, phosphorus uptake, and percentage composition, soil tests, and fixation studies made possible an evaluation of the phosphorus supplying powers of the forty-one soils under investigation. Presented in Table XX is an arrangement of what was considered to be the phosphorus supplying powers of these representative Michigan soils. The soils were arranged in descending order of their phosphorus supplying power and were grouped into "High", "Medium", and "Low" categories. The soils in the "High" category gave high phosphorus tests, low yield response to added phosphorus, and produced plants which were generally higher in phosphorus than the mean percentage phosphorus content. On the other hand, the soils in the "Low" category gave low soil phosphorus tests, marked increases in yield to added phosphorus, and supported plants whose phosphorus contents were generally lower than the mean phosphorus content. The soils in the "Medium" group generally gave intermediate results by each method of evaluation.

TABLE XX

THE PHOSPHORUS SUPPLYING POWERS OF FORTY-ONE MICHIGAN SOILS*

High			Medium			Low		
1.	Emmet sandy loam	(25)**	14.	Brookston sandy clay loam	(7)	24.	Bellefontaine sandy loam	(14)
2.	Fox sandy loam	(18)	15.	Miami clay loam	(3)	25.	Warsaw loam	(16)
3.	Hillsdale	(31)	16.	Macomb sandy loam	(6)	26.	Toledo clay loam	(29)
4.	Brookston sandy clay	(27)	17.	Granby sandy loam	(5)	27.	Fox loamy sand	(12)
5.	Fox loam	(13)	18.	Conover loam	(8)	28.	Conover sandy clay loam	(37)
6.	Clyde clay loam	(35)	19.	Kalkaska sand	(20)	29.	Isabella sandy clay loam	(23)
7.	Bellefontaine sand	(17)	20.	Brookston loam	(32)	30.	Miami clay loam	(2)
8.	Plainfield sandy loam	(15)	21.	Wisner sandy clay loam	(34)	31.	Kawkawlin sandy clay loam	(33)
9.	Waukesha sandy loam	(10)	22.	Brookston sandy clay	(41)	32.	Wisner sandy clay loam	(4)
10.	Hillsdale sandy loam	(11)	23.	Kent clay loam	(22)	33.	Wisner sandy clay loam	(36)
11.	Kent clay loam	(21)				34.	Napanee sandy clay loam	(28)
12.	Plainfield loamy sand	(30)				35.	Conover sandy clay loam	(38)
13.	Selkirk sandy clay loam	(40)				36.	Miami sandy loam	(1)
						37.	Miami loam	(26)
						38.	Selkirk sandy clay loam	(39)
						39.	Conover loam	(9)
						40.	Isabella sandy clay loam	(24)
						41.	Kalkaska sand	(19)

* An evaluation based on comparative yields of alfalfa, soil tests, and phosphorus fixation.
** Original soil numbers.

SUMMARY

An investigation was undertaken to determine the phosphorus supplying powers of several representative Michigan soils. Forty-one different soils representing approximately eleven million acres of agricultural land in the southern half of the lower peninsula were selected for greenhouse and laboratory studies. Alfalfa, a phosphorus responsive crop, was grown on each of the soils for eleven months under controlled conditions in the greenhouse. Available soil phosphorus was measured by several arbitrary chemical soil analyses making use of both rapid tests amd more quantitative laboratory methods. Phosphorus fixation by the soils was evaluated by two different methods. One method measured the fixation of phosphorus at different rates of application and the other measured the amount of fixation with and without the free iron oxides. The results are summarized in the succeeding paragraphs.

Forty-one Michigan soils varied greatly in their ability to produce alfalfa without added phosphorus. Yields of seven harvests of alfalfa ranged from 33.1 grams to 103.7 grams, with an average yield of 60.9 grams. Based on yield response to added phosphorus, the soils were arranged into what appeared to be their relative need for phosphorus fertilization.

Yields were increased on all of the soils by added phosphorus. The dry weights of seven harvests were from 88.4 grams to 123.1 grams. The average yield was 100.5 grams. Percentage yield increases prod ced by added phosphorus varied from 3.0 percent to 216.8 percent

with an average increase of 65 percent.

The percentage phosphorus composition of the alfalfa harvests on the unphosphated soils averaged 0.167 percent whereas alfalfa grown on the phosphorus treated soils averaged 0.323 percent phosphorus.

The total amounts of phosphorus removed by alfalfa averaged 133.0 and 427.6 milligrams for the plants grown on the unphosphated and phosphated soils respectively.

The recovery of applied phosphorus ranged from 20.3 percent to 60.6 percent as measured by the difference in method. The average percentage recovery was 38.4.

The amount of chemically available phosphorus removed by the several rapid tests varied with the soil and with the extracting agent of the test. Spurway's reserve test removed a proportion of the acid-soluble forms of phosphorus, the amounts of which ranged from 3 parts per million to 81 parts per million. There was apparently no relationship between the amounts of phosphorus removed by this test and any of the soil properties.

Bray's adsorbed phosphorus test is believed to remove the adsorbed phosphorus and perhaps some of the easily acid-soluble phosphorus from the soils. There appeared to be some general relationship between soil texture and the amounts removed by this extractant, with soils high in sand usually, giving medium to high tests for adsorbed phosphorus. The amounts of phosphorus removed from the soils by this method ranged from 5 parts per million to 68

parts per million.

Bray's available phosphorus test removed proportionate amounts of both the acid-soluble and adsorbed phosphorus. The amounts removed ranged from 11 parts per million to 93 parts per million.

Bray's more quantitative method for acid-soluble and adsorbed phosphorus removed considerably larger quantities from the soils than did the rapid tests. However, the amounts removed were proportionate to the amounts removed by the rapid tests. No clear relationship between soil properties and soil phosphorus as measured by this method could be established.

Organic phosphorus determinations by Bray's hydrogen peroxide method indicated that relatively large quantities of the total soil phosphorus existed in the soil in organic combinations. The amounts varied from 73 parts per million to 652 parts per million and generally followed the organic content of the soil.

Definit e relationships were established between soil phosphorus and alfalfa yields which clearly showed that chemically available phosphorus as measured by the several methods was a good index of the soils phosphorus supplying-powers. Correlation coefficients between the dry weights of seven harvests of alfalfa and soil phosphorus as measured by rapid soil tests were 0.312, 0.754, and 0.635, for Spurway's reserve test, Bray's adsorbed phosphorus, and Bray's available phosphorus respectively. Considering the relationship between total dry weight of seven harvests and roots and extractable phosphorus, the coefficients of correlation were 0.302, 0.796, and

0.599 for the above three soil tests.

With the more quantitative methods for determing soil phosphorus, the tests for adsorbed and acid-soluble, organic, and total adsorbed, acid-soluble, and organic gave correlation coefficients of 0.499, 0.487, and 0.607, with the yields of seven harvests of alfalfa. With the total yield of harvests and roots the correlation coefficients were 0.501, 0.532, and 0.644.

The high degree of linear correlation between alfalfa yields and soil phosphorus extracted with reagents containing the fluoride ion showed very definitely that fluoride aids in the removal and measurement of soil phosphorus which is available for plant utilization.

Phosphorus fixation studies of twenty-two selected soils using several rates of applied phosphorus revealed no apparent direct relationship with any of the measured soil properties. The quantities of retained phosphorus varied with the soil and also with the amount of applied phosphorus. The character of the fixation curves for the individual soils suggested that the mechanisms of fixation also differed with the soils.

The removal of free iron oxides reduced phosphorus fixation from 0.6 percent to 75 percent. No relationship, however, could be established between the amount of phosphorus fixation or the decrease in fixation and free iron oxide content. On the basis of the quantities of phosphorus fixed, the soils were arranged in order of their need for phosphorus fertilization. Comparison of the yield

results and the fixation studies revealed that plant response and phosphorus fixation as methods were equally satisfactory in evaluating the need for phosphorus fertilization or conversely, the ability of soils to supply phosphorus.

A classification of the forty-one Michigan soils as to their phosphorus supplying powers was presented based on the yield and composition of continuously cropped alfalfa, soil tests, and the phosphorus fixation studies for chemically available phosphorus.

LITERATURE CITED

(1) Arnold, C. Y., and Schmidt, W. A. 1951 Soil tests as a measure of phosphorus available to tomatoes on heavy soils. Soil Sci. 71:105-115.

(2) Attoe, O. J., and Truog, E. 1949 Correlation of yield and quality of alfalfa and clover hay with levels of available phosphorus and potassium. Soil Sci. Amer. Proc. 14:249-253.

(3) Black, C. A. 1942 Phosphate fixation by kaolinite and other clays as affected by pH, phosphate concentration, and time of content. Soil Sci. Amer. Proc. 7:123-133.

(4) Bouyoucos, G. J. 1951 A recalibration of the hydrometer method for making mechanical analysis of soils. Agron. Jour. 43:434-438.

(5) Bowers, A. H. 1947 The relation between forms of soil phosphorus and response of alfalfa and small grain to added phosphate. M.S. Thesis, Michigan State College.

(6) Bradfield, R., and Allison, W. H. 1933 Criteria of base saturation in soils. Trans. Second Comm. Internatl. Soc. Soil Sci. A:63-69.

(7) Bray, R. H., and Wilhite, F. M. 1929 Determination of total replaceable bases in soils. Ind. and Eng. Chem., Anal. Ed. 1:144.

(8) __________, and Dickman, S. R. 1941 Adsorbed phosphates in soils and their relation to crop response. Soil Sci. Amer. Proc. 6:312-320.

(9) __________ 1942 Tentative fluoride extraction methods for soil phosphorus. Ill. Agr. Exp. Sta. Agron. Dept. Pamphlet AG-1006.

(10) __________ 1942 tests for measuring and differentiating between adsorbed and acid soluble forms of phosphate in soils. Ill. Agr. Exp. Sta. Agron. Dept. Pamphlet AG-1028.

(11) __________, and Kurtz, L. T. 1945 Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59:39-45.

(12) __________ 1949 Correlation of soil tests with crop response to added fertilizers and with fertilizer requirements. Diagnostic Techniques for soils and crops. The American Potash Institute, Washington, D. C.

(13) Chandler, W. V. 1941 Phosphorus adsorption by five Alabama soils as influenced by reaction, base saturation, and free sesquioxides. Jour. Amer. Soc. of Agron. 33:1-12.

(14) Coleman, Russell 1944 The mechanism of phosphate fixation by montmorillonitic and kaolinitic clays. Soil Sci. Soc. Amer. Proc. 9:72-78.

(15) Davis, L. E. 1935 Sorption of phosphates by non-calcareous Hawaiian soils. Soil Sci. 40:129-158.

(16) Deb, B. C. 1950 The estimation of free iron oxides in soils and clays and their removal. Jour. of Soil Sci. 1:212-220.

(17) Hibbard, P. L. 1935 Factors influencing phosphate fixation in soils. Soil Sci. 39:337-358.

(18) Kelly, J. B., and Midgeley, A. R. 1943 Phosphate fixation -- An exchange of phosphate and hydroxyl ions. Soil Sci. 55:167-176.

(19) Kurtz, T., and DeTurk, E. E., and Bray, R. 1946 Phosphate adsorption by Illinois soils. Soil Sci. 61:111-124.

(20) Lawton, K., Robertson, L. S., Cook, R. L., and Rood, P. J. 1947 A study of correlation between rapid soil tests and response of legume hay to phosphorus and potassium fertilization on some Michigan soils. Soil Sci. Amer. Proc. 12:353-358.

(21) Mattson, S. 1927 Anionic and cationic adsorption by soil colloidal materials of varying $Si\ O_2/Al_2\ O_3\ /\ Fe_2\ O_3$ ratio. Proc. 1st Int. Cong. Soil Sci. 2:199-211.

(22) __________ 1930 The laws of soil colloidal behavior: III Isolectric precipitation. Soil Sci. 30:459-495.

(23) __________ 1931 The laws of soil colloidal behavior: IV Amphoteric behavior. Soil Sci. 32:343-365.

(24) Metzger, W. H. 1940 Significance of adsorption or surface fixation of phosphates by some soils of the prairie group. Jour. Amer. Soc. Agron. 32:513-526.

(25) Millar, C. E. 1948 Soils of Michigan. Michigan Ext. Bul. 290.

(26) Miller, L. B. 1928 Retention of phosphate by hydrated alumina and its bearing on phosphate in the soil solution. Soil Sci. 26:435-439.

(27) Murphy, H. F. 1939 The role of kaolinite in phosphate fixation. Hilgardia 12:341-382.

(28) Peech, M., Alexander, L. T., Dean, L. A., and Reed, J. F. 1947 Methods of soil analysis for soil fertility investigations. U.S.D.A. Cir. 757.

(29) Perkins, A. T., Wagoner, C. E., and King, H. H. 1942 Phosphorus fixation by soil separates and fractions. Soil Sci. 53:37-41.

(30) Piper, C. S. 1944 Soil and plant analysis. Interscience Publishers Inc., New York, N. Y.

(31) Prince, A. L., Toth, S. J., and Bear, F. E. 1948 Phosphorus-supplying powers of 20 New Jersey soils. Soil Sci. 65: 297-308.

(32) Pugh, A. J. 1934 Laws of soil colloidal behavior: III Colloidal phosphates. Soil Sci. 38:315-334.

(33) Rich, C. I. and Attoe, O. J. 1950 Phosphorus supplying powers of soils for oats. Soil Sci. Amer. Proc. 15:219-222.

(34) Roszmann, C. A. 1927 Retention of phosphorus by soil colloids. Soil Sci. 24:465-474.

(35) Russell, E. J., and Prescott, J. A. 1916 The reaction between dilute acids and the phosphorus compounds of the soil. Jour. Agr. Sci. 8:65-110.

(36) Scarseth, G. D., and Tidmore, J. W. 1934 The fixation of phosphates by soil colloids. Jour. Amer. Soc. Agron. 26:138-151.

(37) ______________ 1935 The mechanism of phosphate retention by natural alumino-silicate colloids. Jour. Amer. Soc. Agron. 27:596-616.

(38) Smith, F. W. 1949 A study of the availability of native and added phosphorus in several Michigan soils as measured by chemical analysis and plant growth response. Ph.D. Thesis, Michigan State College.

(39) Spurway, C. H. and Lawton, K. 1949 Soil testing. Michigan Agri. Exp. Sta. Tech. Bul. 132 (4th rev.)

(40) Swenson, R. M., Cole, C. V., and Sieling, D. H. 1949 Fixation of phosphates by iron and aluminum and replacement by organic and inorganic ions. Soil Sci. 67:3-22.

(41) Teakle, L. J. H. 1928 Phosphate in soil solution as affected by reaction and cation concentration. Soil Sci. 25:143-162.

(42) Toth, S. J. 1937 Anion adsorption by soil colloids in relation to changes in free iron oxides. Soil Sci. 44: 299-314.

(43) __________, and Bear, F. E. 1947 Phosphorus adsorbing capacities of some New Jersey soils. Soil Sci. 64:199-211.

(44) Turner, R. C., and Rice, H. M. 1952 Role of the fluoride iron in release of phosphate adsorbed by aluminum and iron hydroxide. Soil Sci. 74:141-148.

(45) Veatch, J. O. 1941 Agricultural land classification and land types of Michigan. Mich. Exp. Sta. Spec. Bul. 213 (1st rev.) 1941.

(46) Voelcker, A. 1863 On the absorption of soluble phosphate of lime by different soils of known compositions; and remarks on the application of superphosphate and other phosphate manures. J. Royal Agri. Soc. 24:37-65.

(47) Waksman, S. A. 1938 Humus. Williams and Wilkins, Baltimore, Md.