A STUDY OF THE AVAILABILITY OF NATIVE AND ADDED PHOSPHORUS IN SEVERAL MICHIGAN SOILS AS MEASURED BY CHEMICAL ANALYSES AND PLANT GROWTH RESPONSE

Thesis for the Degree of Ph. D.

MICHIGAN STATE COLLEGE

Floyd William Smith

1949

THESIS

3 1293 10504 8932

MSU
LIBRARIES

RETURNING MATERIALS:
Place in book drop to remove this checkout from your record. FINES will be charged if book is returned after the date stamped below.

P 114 V
APR 22 '85

NOV. 06 1996

MAR 27 2007

0 3 2 4 07

A STUDY OF THE AVAILABILITY OF NATIVE AND ADDED PHOSPHORUS IN SEVERAL MICHIGAN SOILS AS MEASURED BY CHEMICAL ANALYSES AND PLANT GROWTH RESPONSE

by

FLOYD WILLIAM SMITH

A THESIS

Submitted to the School of Graduate Studies of

Michigan State College of Agriculture and

Applied Science in partial fulfillment

of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

Department of Soil Science

1949

THESIS

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Dr. R. L. Cook for his guidance and assistance throughout the course of this investigation and in the preparation of the manuscript. The photographs included in the manuscript ware also taken by Dr. Cook.

Acknowledgement is also due Dr. L. M. Turk for his helpful assistance in the preparation of the final manuscript.

337943

TABLE OF CONTENTS

A STUDY OF THE AVAILABILITY OF NATIVE AND ADDED PHOSPHORUS IN SEVERAL MICHIGAN SOILS AS MEASURED BY CHEMICAL ANALYSES AND PLANT GROWTH RESPONSE

INTRODUCTION

It is a well established fact that various soils differ considerably in their ability to render available to plants both the native and added phosphorus. It was observed that in the case of several of the soils included in this investigation a great variation did exist in connection with the growth of certain floriculture crops. Furthermore, it was not easy to explain these variations with the available data relative to the chemically available forms of phosphorus in these soils.

Watson (18) made extensive use of Spurway's (14) active soil extracting solution in the establishment and maintenance of various levels of nutrients in connection with tomato production. This method is widely used in measuring the availability of nutrients, including phosphorus, especially for greenhouse soils.

Recently Bray (6) has made an extensive study of the availability of potassium in the soils of Illinois. This investigator has found a very close correlation between the exchangeable potassium content of a soil and plant growth response, provided that the latter is considered in terms of percentage yield rather than absolute yield. These correlations have been presented in several scientific

presentations (6, 10).

Bray (5) has spent considerable time in evaluating the various methods for measuring the chemical availability of phosphorus in the soil. This author has pointed out that in the past such methods have been based on an acid extraction of the phosphorus. Recently much time has been devoted by this investigator to the development of a satisfactory method for the measurement of the adsorbed forms of phosphorus in the soil. As a result of this research Dickman and Bray (11) and Bray and Dickman (3, 4) have made an extensive study of the use of the fluoride ion for the replacement of adsorbed phosphorus from the anion exchange complex of the soil. A proposed method involving these considerations has been published by Bray (5).

Workers at the Illinois Station have spent considerable time in developing photometric methods for measuring the amount of phosphorus and potassium in soil extracts. Arnold and Kurtz (1) have perfected a photometer method for this particular purpose. Similarly Bray (7) has published a method for measuring available potassium in the extract by photometric means.

As mentioned previously Bray has published data relative to the correlation between exchangeable potassium and plant growth response. Subsequently this author (9) published additional work relative to correlations between available forms of phosphorus and plant growth response.

The published data were considerably less comprehensive in the case of phosphorus than in the case of potassium but nevertheless an apparently satisfactory relationship was found and thus the same principles are being applied in actual practical application in the Illinois Soils Extension program.

Lawton, et al. (12) attempted to correlate the response of legume hay to both phosphorus and potassium fertilization with the chemically measured available forms of these two elements. These investigators used the methods of Spurway (14), Bray (5) and Peech and English (13). They were unable to find any high degree of linear correlation between crop response and soil test value with either phosphorus or potassium. Similarly the correlation between plant growth response as measured upon a percentage basis and exchangeable potassium did not appear to be significant.

In light of the preceeding more or less confusing picture which has been presented with regard to the correlation or lack of correlation between chemically measured phosphorus availability and plant growth response, a detailed investigation of the phosphorus fertility of a number of Michigan soils was undertaken by the author. Presented in the succeeding pages is a detailed discussion of this study.

METHODS OF EXPERIMENTATION

The various soils used in this experiment were collected during the fall of 1948 from various areas in lower Michigan as described in Table 1.

Table 1. Identification of Soils Used in Phosphorus Availability Studies.

Soil No.	Soil Type	County	Legal Description
1	Brookston silt loam	Macomb	NW¼ Sec.5-T2N-R14E
2	Brookston silt loam	Macomb	NW¼ Sec.10-T1N-R13E
3	Brookston loam	Saginaw	NW¼ Sec.33-T9N-R3E
4	Brookston loam	Kent	NW¼ Sec.29-T8N-R12W
5	Brookston loam	Gratiot	NW¼ Sec.26-T12N-R2W
6	Brookston loam	Gratiot	NW¼ Sec.26-T12N-R2W
7	Brookston loam	Clinton	SW¼ Sec.21-T6N-R2W
8	Brookston loam	Tuscola	SE¼ Sec.28-T14N-R8E
9	Miami loam	Clinton	SW¼ Sec.21-T6N-R2W
10	Miami loam	Tuscola	NE¼ Sec.31-T14N-R11E
11	Isabella loam	Kent	SW¼ Sec.20-T8N-R12W
12	Isabella sandy loam	Isabella	NE¼ Sec. 4-T13N-R4W
13	Conover loam	Clinton	SW¼ Sec.21-T6N-R2W
14	Conover clay loam	Macomb	SW¼ Sec. 5-T1N-R13E
15	Napanee loam	Macomb	NE¼ Sec.31-T3N-R14E
16	Kent silt loam	Kent	NW¼ Sec.33-T7N-R11W
17	Clyde clay loam	Macomb	NW¼ Sec.31-T3N-R14E
18	Oshtemo loamy sand	Clinton	NE¼ Sec.27-T5N-R1W
19	Emmet sandy loam	Leelanau	NW¼ Sec. 8-T31N-R11W
20	Muck	Eaton	North west of Eaton Rapids

Veatch (17) has provided the following descriptions of the various soil series utilized in this investigation:

<u>Brookston</u>: Soils of this series are predominantly loams and clay loams with dark colored plow soil, underlain by wet mottled gritty clay to depths of several feet. The organic matter content and fertility of such soils is high. The clay is highly retentive of moisture and is generally found moist or wet.

The topography is that of level plains and valleys and the soil is wet or semi-swampy in character. Originally such soils were covered with hardwood forest such as elm, soft maple, ash, shag bark hickory, bass wood, swamp white oak, etc.

These soils are regarded as of high value for hay, corn, small grains, beets, beans and alfalfa when artificially drained.

<u>Miami</u>: These soils are light brownish loams and silt loams over brownish, compact and retentive but granular gritty clay. A clay substratum extends to depths of several feet. These soils are moist but not excessively wet and the surface is acid but changes to a limy condition at shallow depths. In general these soils are of relatively high fertility.

The topography is that of rolling upland clay plains, associated swales of wet darker colored clay

land, lakes and muck swamps. Locally the slopes are steep. The original vegetation was dense forest of sugar maple and beech with variable proportions of oaks and hickory.

This soil is of high value for agricultural use and extensively used for general farming purposes.

Conover: Soils of this series are comprised of dark colored loams and silt loams underlain by yellowish and mottled gray massive, gritty clay to depths of several feet. The soils are generally non-acid or only slightly acid. These soils are of high fertility.

The topography of this series of soils is that of smooth upland and swales which are intermediate in drainage between Miami and Brookston series. The original vegetation was hardwood forest consisting of large individual tree growth, mainly of elm, hickory, ash and basswood.

Agriculturally these soils are suitable for hay, grain, beets, alfalfa and pasture and return medium to high yields.

Napanee: These soils consist of grayish and light brown silt and clay loam surface soils over very compact yellowish clay. The surface soil is lighter colored and more compact and plastic clay than that under the Miami series.

These soils consist of level and rolling uplands, clay plains and level strips adjacent to streams in association with the Brookston series. Locally, the topography may be of steep slopes and bluffs.

These soils are utilized agriculturally for hay and small grain production. Tillage operations are more difficult than for the Miami soils.

Kent: These soils are comprised of light brownish and grayish heavy silt and clay surface soils underlain by plastic compact and relatively impervious pale and reddish clay. Soils of this series are medium or low in organic matter but relatively high in other elements of fertility.

The topography of areas occupied by the Kent soil series consists of level, upland clay plains and these are generally associated with swales of wet clay land and some muck.

These soils are regarded as first class agricultural land for hay and small grains and are largely in cultivation.

Clyde: The soils of this series are generally of loam or clay loam texture and are underlain by plastic highly retentive bluish gray and mottled clay. These soils contain a very high percentage of organic matter

and may be mucky at the surface. Such soils are of high fertility and are limy at shallow depths but not in the surface layer.

These soils occur in swampy and marsh land. The native vegetation consists of hardwoods, elm, ash, maple, and in part open land with grasses and sedges.

These soils are of high agricultural value when drained for hay, beets, beans and grain.

<u>Oshtemo</u>: This soil material is a light brown sand and is underlain by pervious sand with small admixtures of clay and gravel. This soil is characteristically dry, low in nitrogen and intermediate to low in fertility.

This material occurs on level or pitted dry sandy plains and terraces. The native vegetation is open type of forest consisting mainly of oaks and hickory.

The general agricultural value is low. The soil included in this investigation is so nearly pure sand in nature that it is not utilized for agricultural purposes.

<u>Emmet</u>: These soils are deep, penetrable sandy soils, characterized by a light gray leached sand at the surface and brown to umber brown sand or sandy loam at 6 to 12 inches. The surface layers are acid, but soil is limy at depths of about three feet.

The topography of such areas as are occupied by soils of this series is that of hilly uplands, including smooth crests and steep slopes of ridges. Both dry and swampy valleys are associated. The native vegetation consists of hardwood forest, sugar maple, beech, yellow birch, hemlock and white pine.

The smoother land of this series may be regarded as first class for potatoes and of fair value for hay, oats, sweet clover and alfalfa. The steeper slopes are of small agricultural value.

Muck: This sample of soil material (Soil 20) was not a truly representative muck in the usual sense. This material was obtained from a low lying area northwest of Eaton Rapids, Michigan. The material was of a definite red color and had a much higher volume weight than ordinary muck material. The surrounding upland mineral soil carried a considerable number of iron concretions and apparently much of this iron in the oxide form had found its way into the muck deposit.

This particular area was apparently quite productive. The material was used in this experiment because it was felt that perhaps there would be evidence of extreme phosphorus deficiency due to the presence of such a large amount of iron.

In general, the various soils used in this study can be regarded as representative of the various series descriptions as presented above. Several distinguishing features of soils were noted and are summarized briefly as follows.

Sample 4, the Brookston silt loam from Kent county, can be regarded as of characteristic of that series only insofar as surface topography and texture are concerned. The color is not the same dark color as prevailed in the other members of this series which were included in this study. The soil possessed a distinct reddish cast both in the surface soil and in the subsoil layers. In this respect it was somewhat similar to sample 11, the Isabella loam also from a nearby location in Kent county.

Samples 7, 9 and 13 which are respectively members of the Brookston, Miami, and Conover series were collected from a single farm in Clinton county and are, therefore, representatives of a catena frequently found in southern Michigan.

Samples 5 and 6 were collected from the same farm and are essentially identical except that number 5 was taken from a field used for general agricultural purposes whereas sample 6 was collected from an adjoining fence row which was under grass vegetation and had no history of recent cultivation.

The remainder of the samples were taken from fields used for the production of cultivated crops except for the following. The Oshtemo sand, sample 18, was not being utilized for any agricultural purpose. The Kent silt loam, sample 16, was collected from a grassed area near Grand Rapids and from all observations of the surrounding land it appeared unlikely that this land had ever been cultivated, at least not for a number of years. The Clyde clay loam, sample 17, was taken from a small wood lot and apparently this area had never been cultivated due to its low lying position and accompanying very poor drainage.

The initial laboratory phases of this investigation consisted of the establishment of various levels of chemically available phosphorus in the soil of each series. This was accomplished by adding to each of the soils four specified amounts of $Ca(H_2PO_4)_2 \cdot H_2O$ and allowing this added phosphorus to come to a state of equilibrium with the soil during a three week interval in which the soil was maintained at optimum moisture. After this interval of time the various experimental samples were dried to an air dry state and extracted by chemical means so that the available phosphorus could be measured colorimetrically in an aliquot of the soil extract by means of the Evelyn photoelectric colorimeter, using the Corning No. 660 filter in this instrument. In addition to the various samples of soil to which an addition of $Ca(H_2PO_4)_2 \cdot H_2O$ had been made, a sample of each soil was taken through the same procedure except for the addition of no phosphorus compound. The amounts of

phosphorus added to each soil were according to the schedule indicated in Table 2.

Table 2. The Amounts of $Ca(H_2PO_4)_2 \cdot H_2O$ Added to 150 Grams of Air Dry Soil for the Establishment of Various Levels of Chemically Available Phosphorus.

Phosphorus added to soil as elemental P		Equivalent amount of superphosphate (pounds/acre of 0-20-0)
ppm	Grams/150 grams of soil	
0	0	0
20	.0030	450
40	.0060	900
80	.0120	1800
160	.0240	3600

The 150 gram quantity of soil for each sample was placed in a glass tumbler and maintained in such throughout the course of the investigation„ The added phosphorus was weighed individually for each sample of soil on an analytical balance and added dry to the soil in which it was carefully mixed by hand manipulation. Following the return to the air dry condition each sample of soil was crushed by gentle rolling so as to facilitate more accurate sampling and to eliminate large aggregates of soil.

A total of 8 extraction procedures was employed during the course of the laboratory investigations. The procedures may be summarized as follows:

(1) <u>Spurway's Active Extraction</u>: This extracting solution consists of .018N acetic acid. Five grams of soil were extracted with 20 ml. of the solution by means of shaking the suspension for exactly one minute after which the suspension was placed on a filter and the clear aliquot obtained was used for phosphorus measurement. This method is exactly as outlined by Spurway (14), except for the use of the colorimeter.

(2) <u>Spurway's Active Extraction (1:10 extraction ratio)</u>: The extracting solution used was the same as for method 1 above. However, 5 grams of soil were extracted with 50 ml. of extracting solution. The suspension was shaken for exactly one minute.

(3) <u>Spurway's Active Extraction (One hour shaking)</u>: This extracting solution was also the same as for method 1 and the ratio of soil to extracting solution was likewise the same. However, the suspension was subjected to 1 hour of end over end shaking on a mechanical shaker.

(4) <u>Spurway's Reserve Extraction</u>: In this procedure 5 grams of soil were shaken for exactly one minute in .135N HCl as outlined by Spurway (14) for the removal of the so-called "reserve" portion of available phosphorus.

(5) Bray's Total Available Phosphorus: This procedure is according to that of Bray (5) and other Illinois associates (1). The extracting solution consists of .03 N NH_4F in .10 N HCl. Five grams of soil were shaken 40 seconds with the solution and then poured upon a filter.

(6) Bray's Adsorbed Phosphorus: This procedure is likewise according to the methods outlined by Bray (5) and others (1). The extracting solution consists of .03 N NH_4F in .025 N HCl. Five grams of soil were shaken 40 seconds with the extracting solution and then the suspension was filtered.

(7) Bray's Total Available Phosphorus (1:50 ratio): This method of extraction was identical with method 5 above except that a ratio of 1 part of soil to 50 parts of extracting solution was used. Bray (5) has recommended this ratio as being more desirable for certain research purposes in the calibration of plant growth response than method 5 and for this reason this ratio was employed.

(8) Bray's Adsorbed Phosphorus (1:50 ratio): This method of extraction was identical with method 6 above except that a ratio of 1 part of soil to 50 parts of extracting solution was employed. This ratio was suggested by Bray (5) as being better suited for research purposes than method 6.

associates (1). The extracting solution consists of .03 N NH_4F in .10 N HCl. Five grams of soil were shaken 40 seconds with the solution and then poured upon a filter.

<u>Bray's Adsorbed Phosphorus</u>: This procedure is likewise according to the methods outlined by Bray (5) and others (1). The extracting solution consists of .03 N NH_4F in .025 N HCl. Five grams of soil were shaken 40 seconds with the extracting solution and then the suspension was filtered.

<u>Bray's Total Available Phosphorus (1:50 ratio)</u>: This method of extraction was identical with method 5 above except that a ratio of 1 part of soil to 50 parts of extracting solution was used. Bray (5) has recommended this ratio as being more desirable for certain research purposes in the calibration of plant growth response than method 5 and for this reason this ratio was employed.

<u>Bray's Adsorbed Phosphorus (1:50 ratio)</u>: This method of extraction was identical with method 6 above except that a ratio of 1 part of soil to 50 parts of extracting solution was employed. This ratio was suggested by Bray (5) as being better suited for research purposes than method 6.

The various soils described in Table 1 were also used in the greenhouse for the measurement of actual growth response of wheat and tomato plants. Soil samples 1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 16, 17, 18 and 20 were utilized for the production of Henry Spring wheat. The various cultures were established exactly in accordance with the addition of phosphorus as outlined in Table 2 for the laboratory investigations. The quantity of each soil used was 4,000 grams in a one gallon jar and thus the amount of phosphorus added was according to the schedule in Table 3.

Table 3. The Amounts of $Ca(H_2PO_4)_2 \cdot H_2O$ Added to 4000 Grams of Air Dry Soil for the Establishment of Various Levels of Available Phosphorus for Greenhouse Experiment Involving the Growth of Henry Spring Wheat.

Phosphorus added to soil as elemental P		Equivalent amount of superphosphate (Pounds/acre of 0-20-0)
ppm	Grams/4000 grams of soil	
0	0	0
20	.08	450
40	.16	900
80	.32	1800
160	.64	3600

In addition to the above phosphate treatments each one gallon pot of soil was provided with 1.6 gms. of NH_4NO_3 and 1.0 gram of KCl so as to insure a uniform abundance of both nitrogen and potassium in every culture. Each treatment was established in duplicate.

The pots were planted to wheat on April 7 and by April 10 the seedlings had emerged. These were thinned to a uniform stand of 11 plants per jar on April 16 and eventually to a stand of only 10 plants per jar on April 24. Growth was quite rapid, especially on the pots which received the greater amounts of added phosphorus. No visual symptoms of either nitrogen or potassium deficiency become apparent during the course of the investigation. The wheat plants were harvested on June 18 at which time nearly all of the plants were at an advanced state of maturity. The heads of the grain were separated from the straw and separate weighings were made of each. No attempt was made to thresh the grain as it was badly shriveled and therefore it did not appear advisable to separate the grain from the chaff. The two portions of the plant material were ground separately and analyzed for total phosphorus content according to the method outlined by Ulrich (15, 16).

The ten following soils were utilized for a greenhouse experiment involving the use of only 1000 grams each of soil in one quart jars: Soils 4, 5, 6, 8, 11, 12, 14, 15, 18 and 19. The amounts of $Ca(H_2PO_4)_2 \cdot H_2O$ added to these were as presented below in Table 4.

Table 4. The Amounts of $Ca(H_2PO_4)_2 \cdot H_2O$ Added to 1000 Grams of Air Dry Soil for the Establishment of Various Levels of Available Phosphorus for Greenhouse Experiment Involving the Growth of Gloriana Tomatoes.

Phosphorus added to the soil as elemental P		Equivalent amount of superphosphate (Pounds/acre of 0-20-0)
ppm	Grams/1000 Grams of soil	
0	0	0
40	.04	900
80	.08	1800
160	.16	3600
320	.32	7200

These cultures were established in duplicate for each of the indicated levels of phosphorus. Additionally, .8 gm. of NH_4NO_3 and .5 gm. of KCl were added to each jar to insure an adequacy of nitrogen and potassium on each soil.

The jars were planted to tomatoes of the Gloriana variety on April 24, 1949. A single plant was allowed to remain until June 1 at which time the plants in all jars were harvested. These plants were subsequently dried, weighed and ground in the Wiley mill in preparation for the determination of total phosphorus as outlined by Ulrich (15, 16).

The jars involved in this experiment were replanted to tomatoes on June 6, 1949, so as to obtain a second growth

of this plant. The excess seedlings of this planting were utilized for planting the one gallon jars utilized in the wheat experiment so as to make observations relative to the response of residual phosphorus remaining after the removal of the wheat crop.

The second planting of tomatoes on all jars was harvested on July 19 and the plants were dried and weighed.

RESULTS AND DISCUSSION

The Chemical Availability of Phosphorus

The various amounts of available phosphorus extracted by each of the techniques already described are presented in Table 5. Graphic presentation of the results of four extraction procedures ((1) Spurway's Active extraction, (4) Spurway's reserve extraction, (7) Bray's total available phosphorus (1:50 ratio), and (8) Bray's adsorbed phosphorus (1:50 ratio)) are presented for each of the twenty soils in Figures 1 to 20 inclusive.

Table 5. The content of available phosphorus in the various soils as measured by different means of chemical extraction.

Soil	Phosphorus Added ppm	P.P.M. Available Phosphorus in Soil as extracted by: (1) Spurway's Active	(2) Spurway's Active (1:10)	(3) Spurway's Active (1 hr)	(4) Spurway's Reserve	(5) Bray's Total Available	(6) Bray's Adsorbed	(7) Bray's Total Avail- (1:50)	(8) Bray's Adsorbed (1:50)
(1) Brookston silt loam (Macomb County)	0	4.4	6	8.0	85	75	22	133	25
	20	5.2	7	7.8	94	90	25	160	42
	40	5.6	9	8.8	99	98	28	179	53
	80	9.2	13	11.6	134	112	39	190	68
	160	13.6	25	16.8	170	138	70	233	98
(2) Brookston silt loam (Macomb County)	0	6.0	15	7.4	99	86	22	113	35
	20	7.6	19	8.4	104	96	25	120	40
	40	7.8	20	9.0	125	106	32	145	44
	80	10.6	27	13.0	144	140	48	175	75
	160	22.8	57	19.0	170	228	82	203	138
(3) Brookston loam (Saginaw County)	0	4.1	7	6.8	49	68	13	83	25
	20	4.2	9	6.4	58	82	21	103	33
	40	5.2	10	7.4	66	84	26	113	39
	80	7.9	15	10.6	77	115	35	133	55
	160	16.4	28	19.6	122	152	61	190	105
(4) Brookston silt loam (Kent County)	0	3.0	3	5.0	6	19	13	19	19
	20	3.4	4	4.8	8	28	20	29	30
	40	4.0	6	5.3	12	35	28	48	39
	80	5.2	9	6.4	20	53	41	65	67
	160	10.2	20	10.0	54	81	80	125	121

Table 5. Continued

Soil	Phosphorus Added ppm	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(5) Brookston loam (Gratiot County)	0	6.4	16	7.6	49	60	17	67	28
	20	7.0	18	9.0	51	64	23	79	37
	40	9.6	24	10.4	65	82	34	98	52
	80	13.2	38	16.4	84	104	52	113	70
	160	33.6	84	4100	147	180	96	185	140
(6) Brookston loam (Gratiot County)	0	6.0	14	8.2	33	46	11	69	27
	20	7.7	16	8.2	46	58	18	77	37
	40	13.0	18	12.6	59	74	27	110	48
	80	27.5	40	35.2	104	120	60	162	78
	160	41.0	66	42.4	157	168	95	240	135
(7) Brookston loam (Clinton County)	0	3.2	6	7.2	39	37	11	37	30
	20	5.6	8	9.7	50	53	17	67	39
	40	7.6	13	10.6	63	57	25	80	58
	80	11.8	19	17.2	72	80	36	105	69
	160	23.4	36	31.6	115	122	79	150	103
(8) Brookston loam (Tuscola County)	0	8.4	14	10.6	99	88	19	145	38
	20	11.4	18	12.4	110	114	29	175	52
	40	13.0	23	14.6	115	132	38	205	70
	80	22.0	34	23.0	138	160	56	240	88
	160	43.2	61	45.5	182	228	88	300	140

Table 5. Continued

Soil	Phosphorus Added ppm	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
9. Miami Loam (Clinton County)	0	4.5	7	5.4	15	35	26	60	38
	20	5.5	8	6.2	20	45	33	67	44
	40	7.5	10	11.0	29	56	45	75	55
	80	18.5	24	20.4	63	88	75	113	87
	160	33.5	44	39.2	110	152	132	205	155
10. Miami Loam (Tuscola County)	0	6.2	10	8.0	36	45	23	53	30
	20	8.2	14	10.6	42	53	30	60	45
	40	9.2	21	11.2	50	63	39	74	55
	80	15.2	29	14.8	70	99	59	103	83
	160	42.4	59	30.4	126	159	96	175	138
11. Isabella Loam (Kent County)	0	1.2	2.5	2.6	6	24	18	20	19
	20	1.2	2.5	2.4	10	32	24	33	30
	40	1.4	3.	2.3	16	44	36	54	53
	80	1.6	3.	3.2	25	65	57	80	77
	160	2.2	6	3.2	50	140	102	150	132
12. Isabella Sandy Loam (Isabella County)	0	2.4	3	1.0	6	22	10	20	20
	20	5.2	6	1.6	14	28	21	33	30
	40	8.0	13	4.0	23	43	34	44	44
	80	17.2	27	9.6	54	82	64	85	79
	160	33.6	44	42.4	92	130	104	170	120

Table 5. Continued

Soil	Phosphorus Added ppm	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
13. Conover Loam (Clinton County)	0	5.3	10	8.3	25	38	17	58	30
	20	7.0	11	9.8	35	50	27	72	42
	40	11.5	19	15.2	42	65	36	84	64
	80	18.0	29	22.0	70	92	60	125	77
	160	39.5	52	42.4	126	158	114	175	140
14. Conover (Macomb County)	0	4.6	4	6.8	61	56	10	65	12
	20	5.4	6	6.5	69	68	14	80	17
	40	6.0	9	7.6	75	80	21	100	33
	80	9.0	14	10.4	94	100	34	125	58
	160	15.2	25	18.4	118	140	58	163	85
15. Napanee Loam (Macomb County)	0	3.6	6	6.6	30	37	16	48	35
	20	3.6	6	7.0	45	44	21	63	42
	40	4.4	8	7.8	45	53	30	80	48
	80	6.4	13	8.4	56	70	43	110	73
	160	11.6	23	13.0	92	126	76	170	125
16. Kent Silt Loam (Kent County)	0	4.8	10	9.2	26	44	18	37	43
	20	6.7	12	9.6	31	51	22	44	52
	40	7.4	14	9.8	36	56	24	55	67
	80	17.4	29	26.8	66	84	44	95	138
	160	24.8	36	31.6	92	130	72	128	170

Table 5. Continued

Soil	Phosphorus Added ppm.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
17. Clyde Clay Loam (Macomb County)	0	4.4	7	8.4	52	51	16	90	33
	20	5.2	8	8.4	56	60	17	98	40
	40	7.2	11	9.8	71	70	28	120	50
	80	9.2	12	11.2	74	78	31	123	53
	160	14.4	19	17.2	90	106	46	133	69
18. Oshtemo Sand (Clinton County)	0	2.0	4	.9	35	172	126	200	158
	20	2.3	5	.9	50	192	148	230	190
	40	2.8	7	.9	57	212	168	250	205
	80	5.0	8	1.2	75	252	180	290	233
	160	7.6	15	3.2	142	316	215	350	292
19. Emmet Sandy Loam (Leelanau County)	0	2.7	3	3.4	9	25	13	29	17
	20	4.2	6	4.6	17	38	23	40	30
	40	6.2	9	7.8	25	50	38	60	45
	80	13.8	20	16.4	44	75	66	80	74
	160	29.6	40	42.0	98	148	124	175	150
20. Muck (Eaton County)	0	5.4	15	3.6	22	50	28	100	60
	20	6.1	17	3.6	24	52	28	110	65
	40	6.4	19	4.2	25	62	30	120	73
	80	8.8	21	4.4	27	75	40	130	80
	160	10.4	27	9.0	30	85	58	160	113

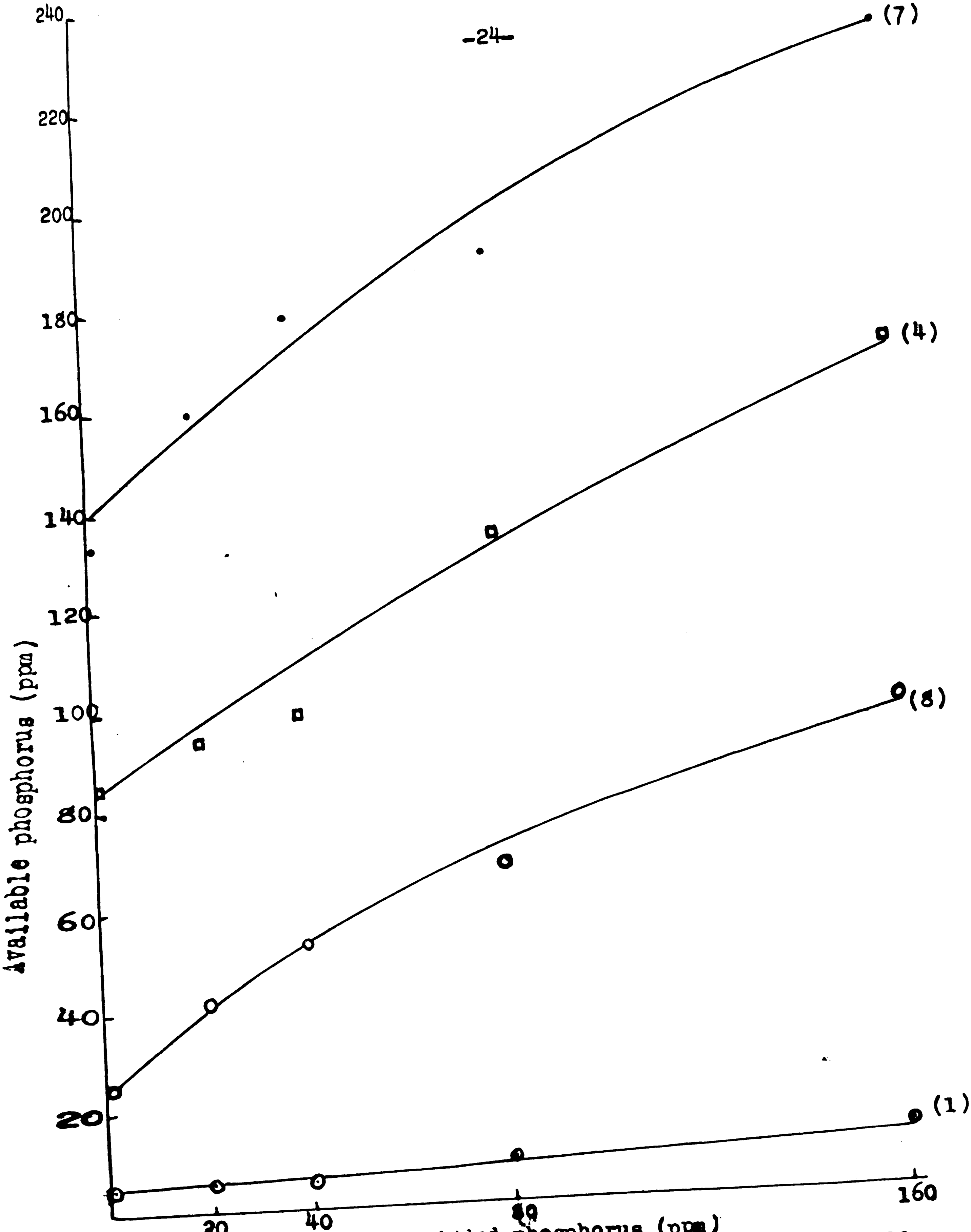

Figure 1. Relationship between added phosphorus and chemically available phosphorus in Brookston silt loam (1).

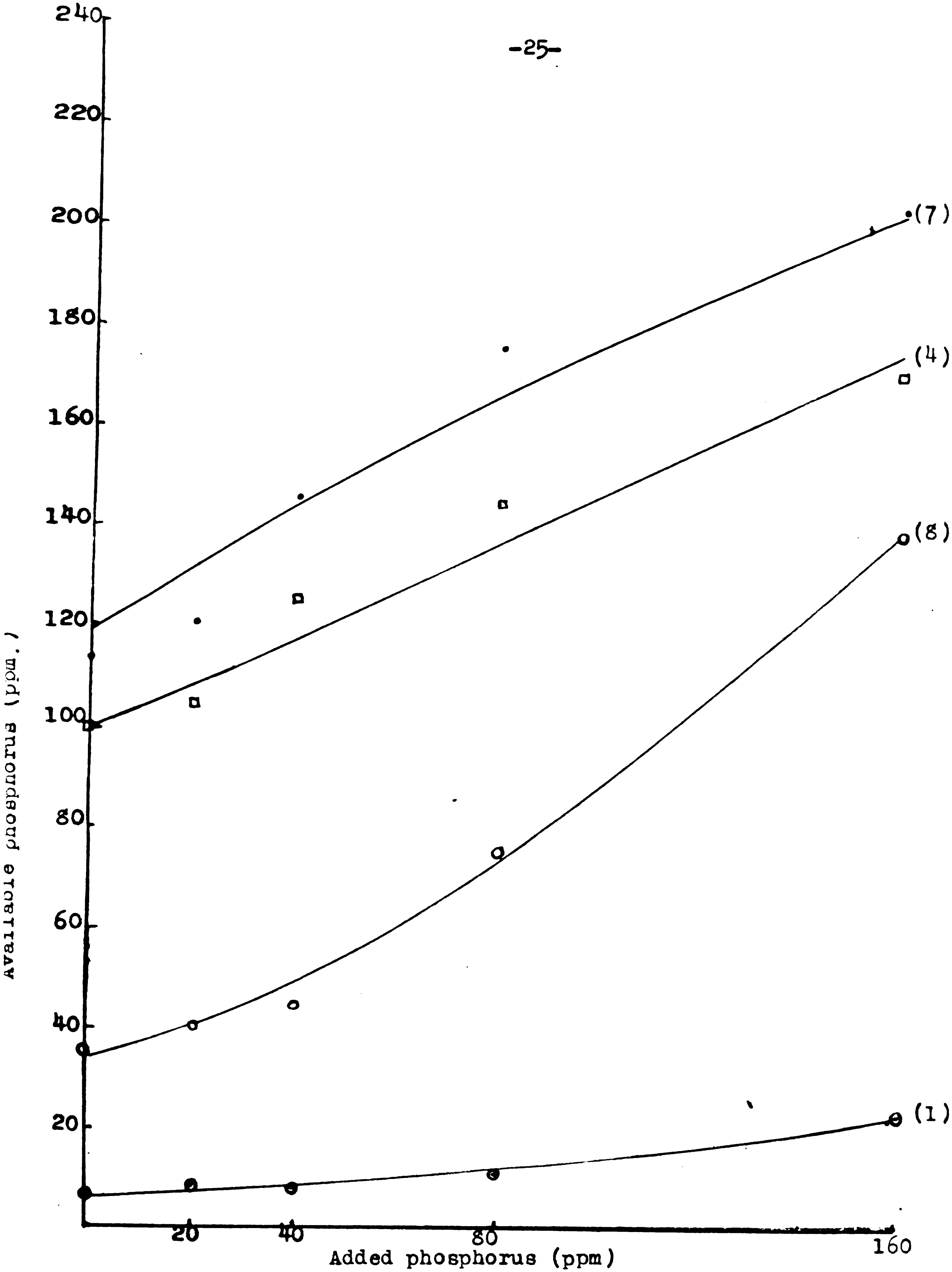

Figure 2. Relationship between added phosphorus and chemically available phosphorus in Brookston silt loam (2).

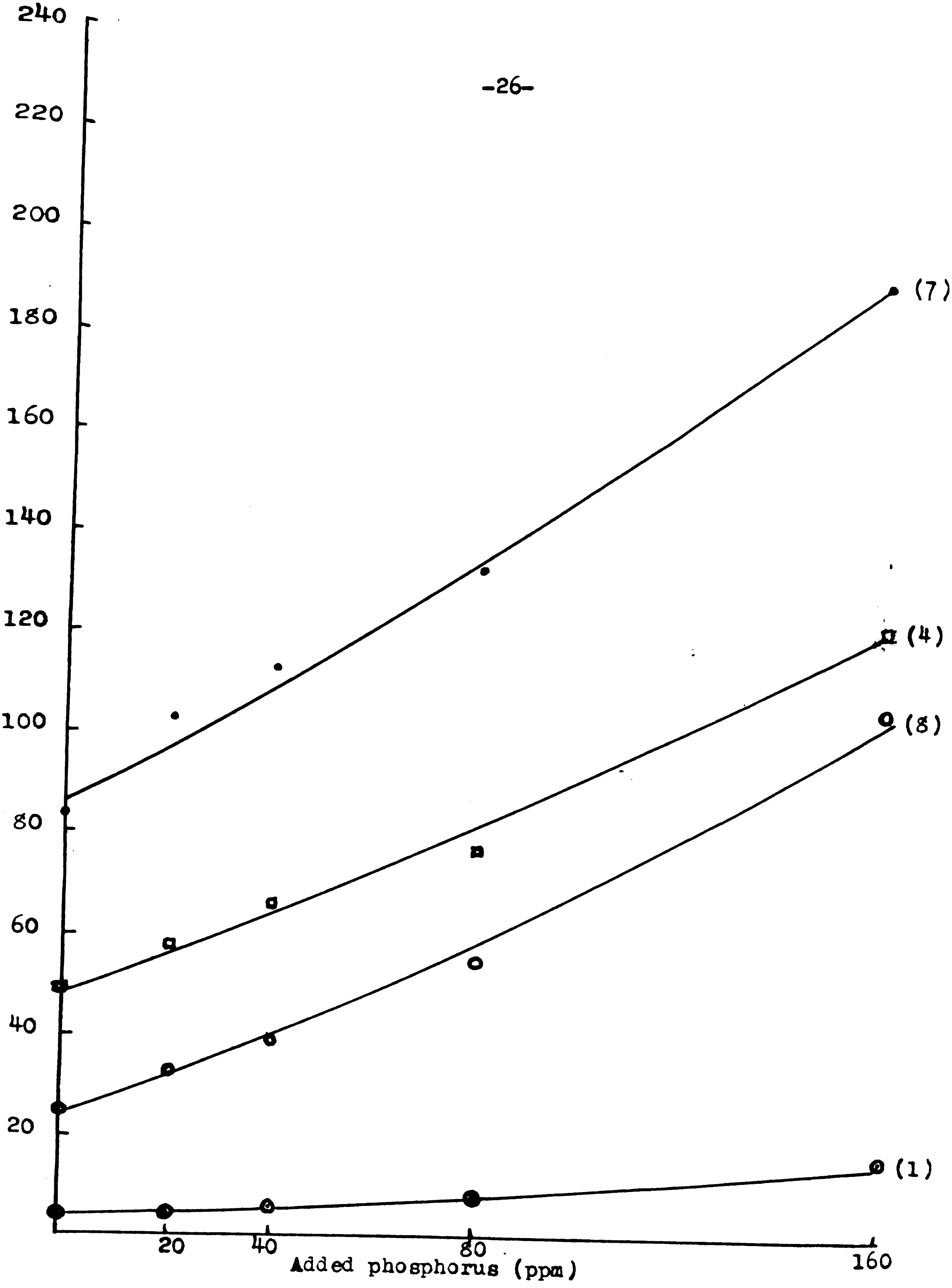

Figure 3. Relationship between added phosphorus and chemically available phosphorus in Brookston loam (3).

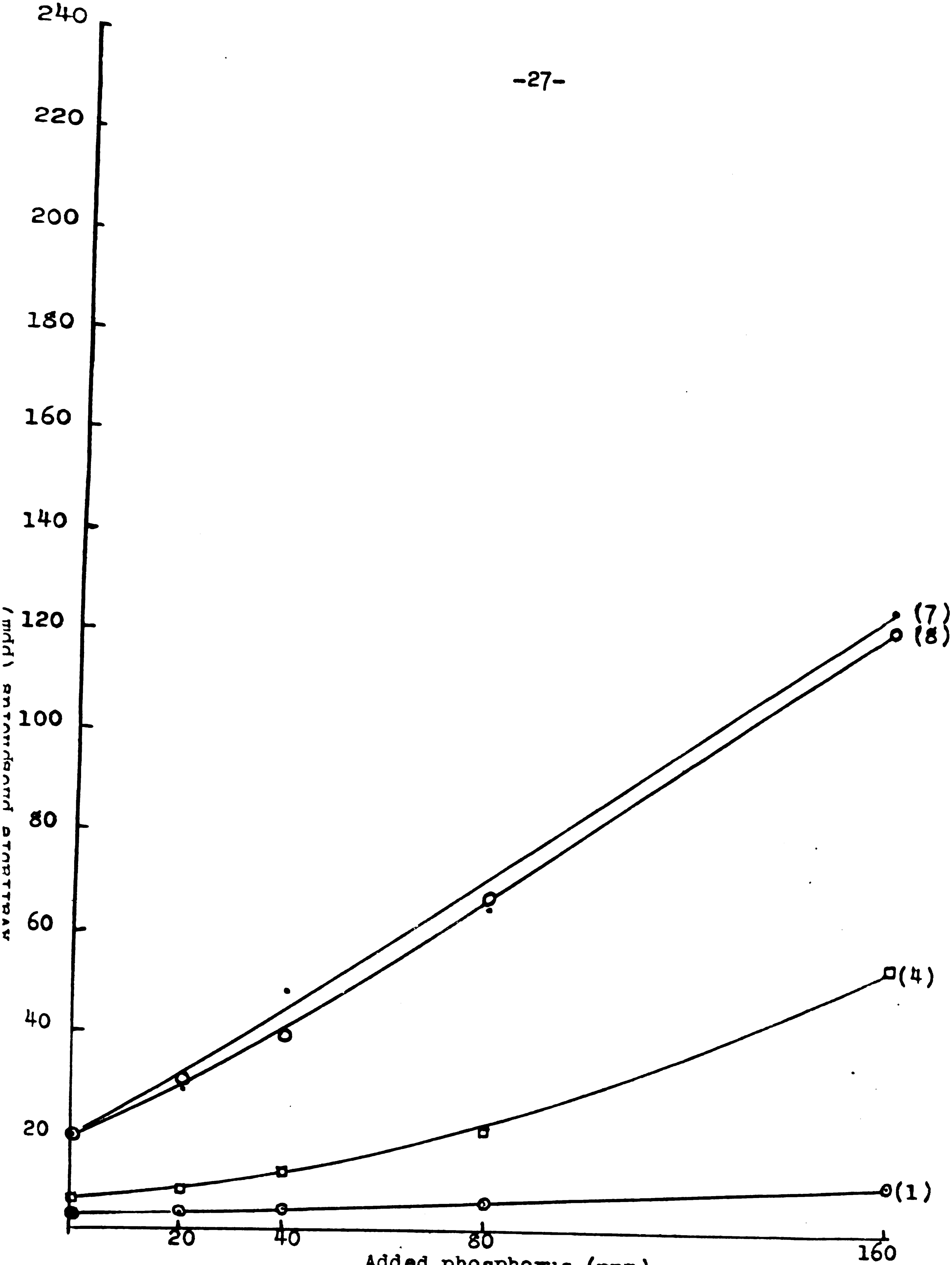

Figure 4. Relationship between added phosphorus and chemically available phosphorus in Brookston loam (4).

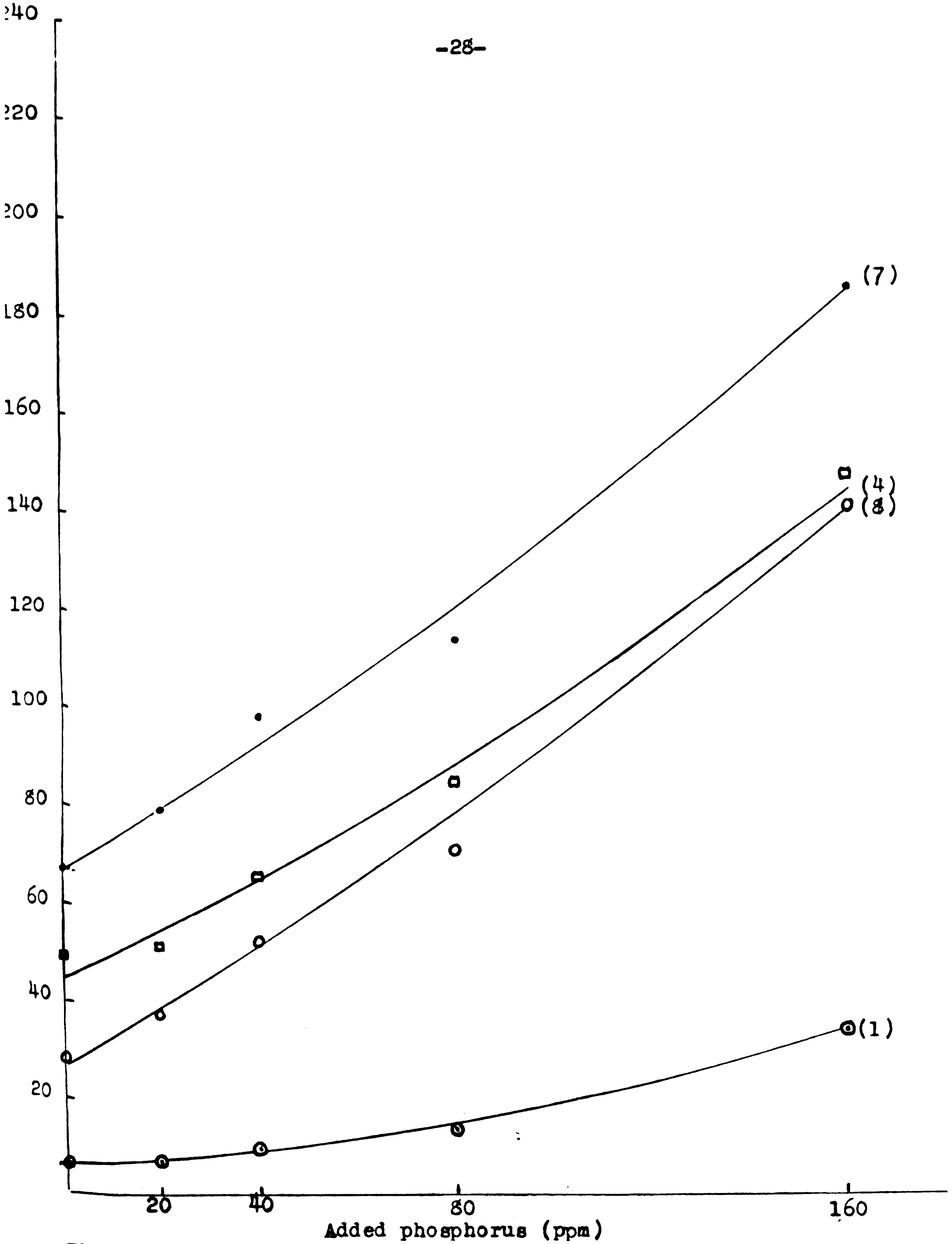

Figure 5. Relationship between added phosphorus and chemically available phosphorus in Brookston loam (5).

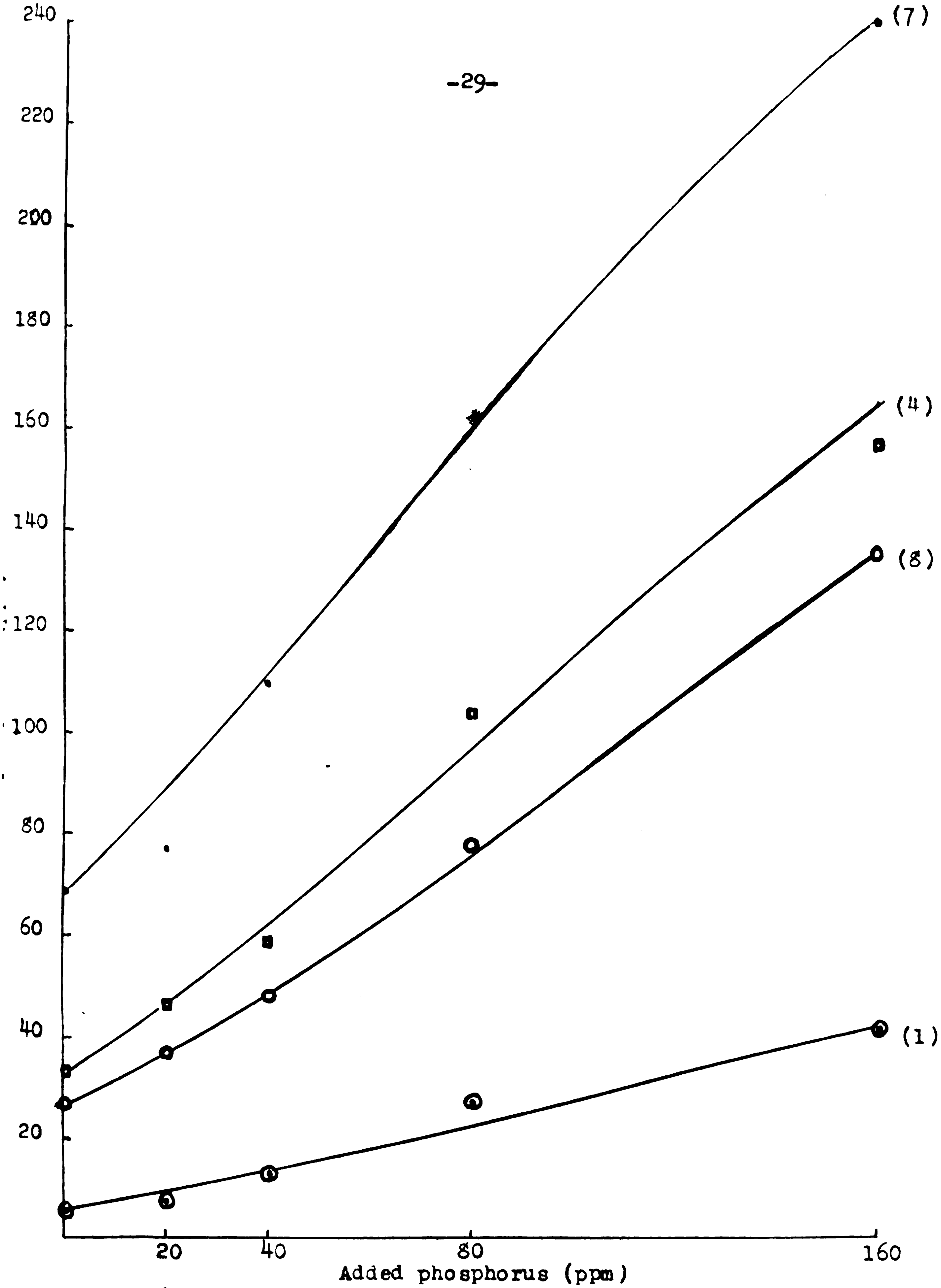

Figure 6. Relationship between added phosphorus and chemically available phosphorus in Brookston loam (6).

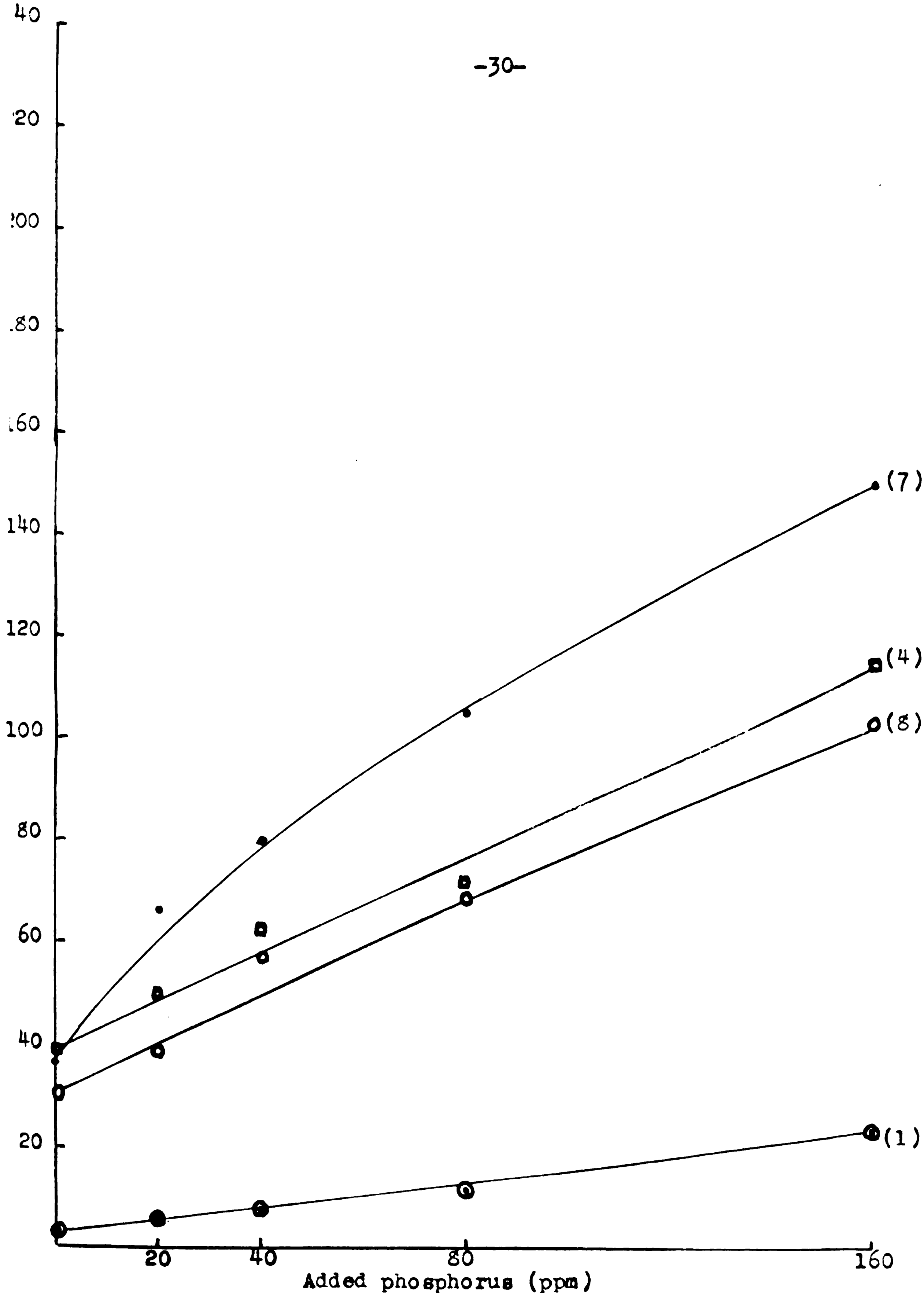

Figure 7. Relationship between added phosphorus and chemically available phosphorus in Brookston loam (7).

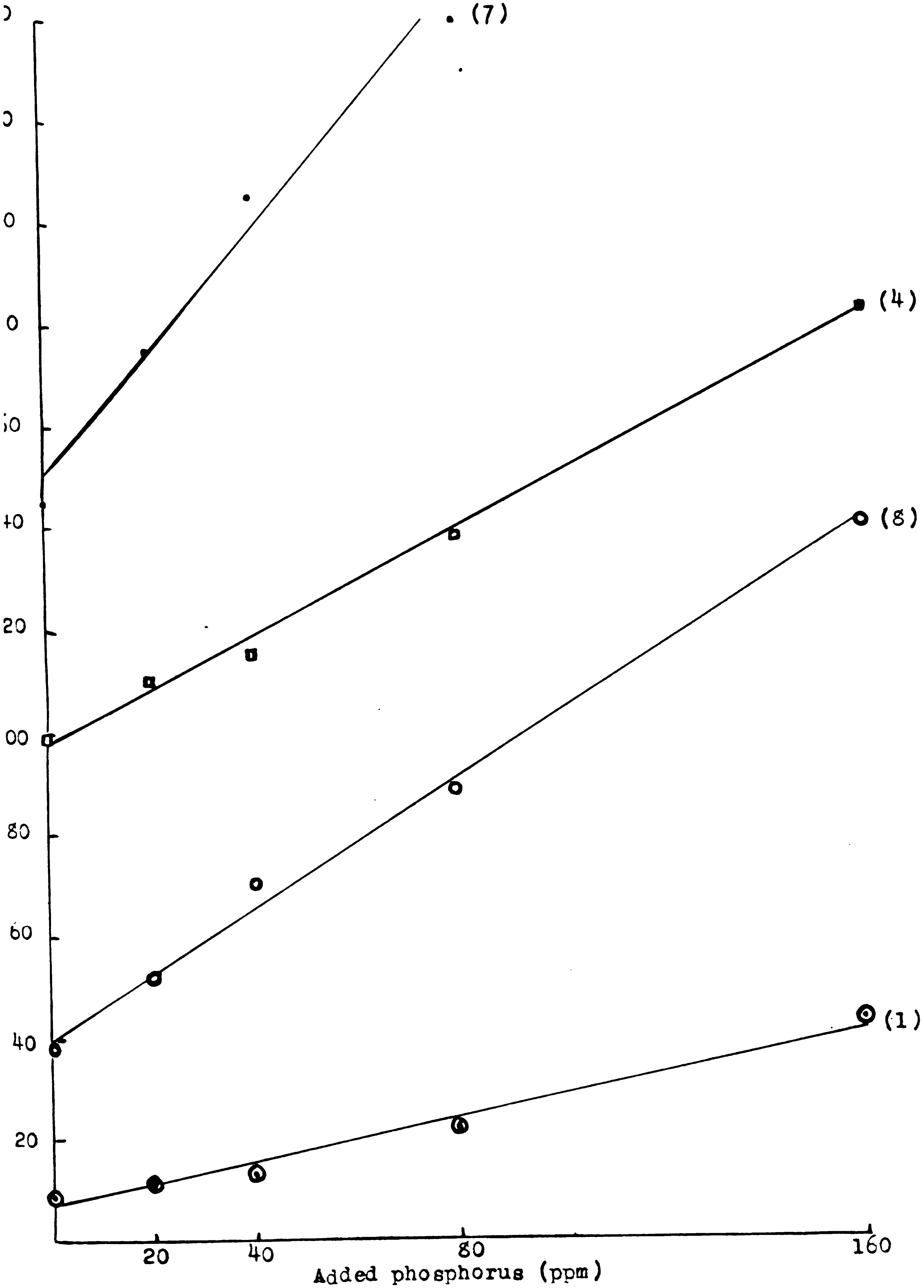

Figure 8. Relationship between added phosphorus and chemically available phosphorus in Brookston loam (8).

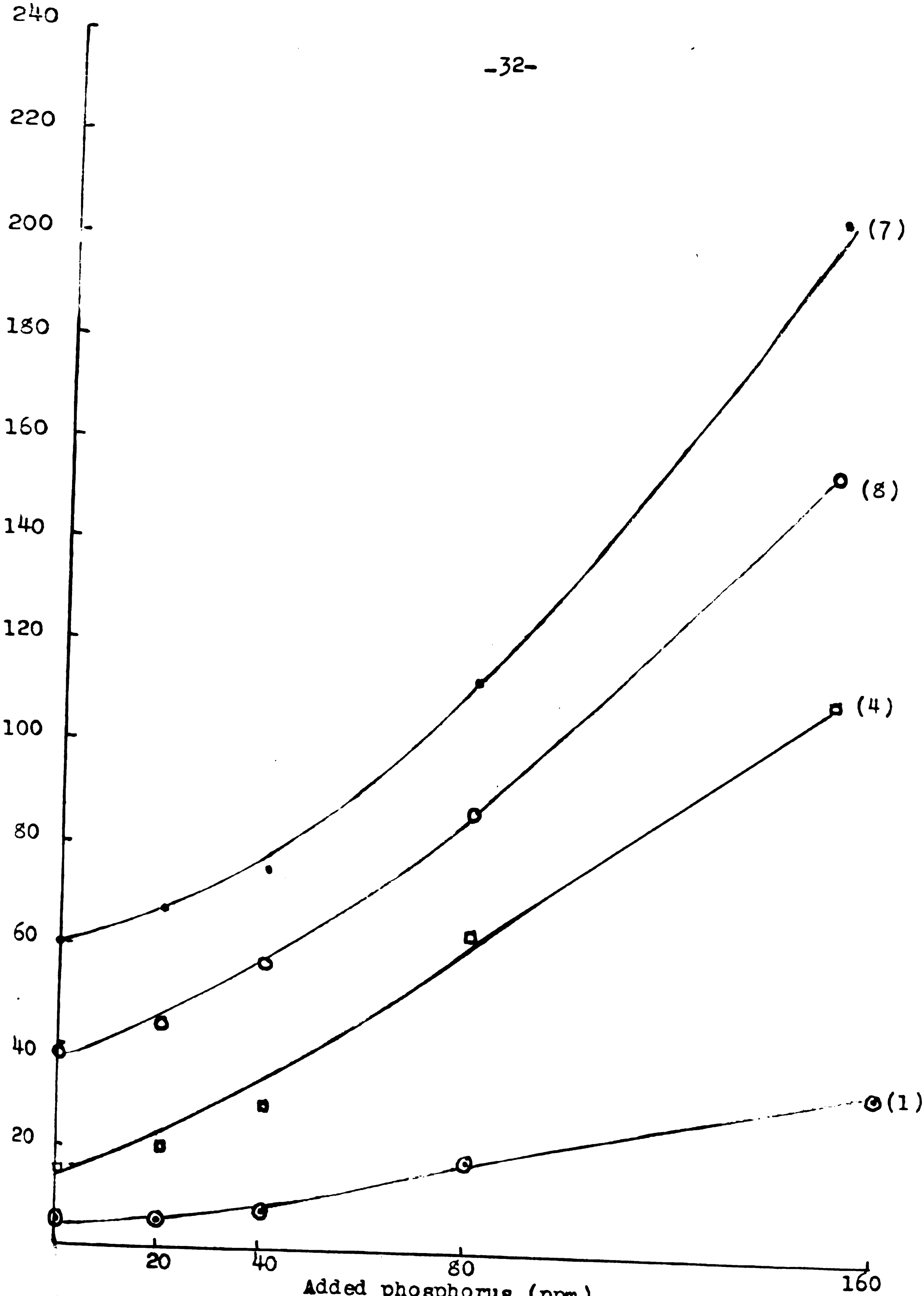

Figure 9. Relationship between added phosphorus and chemically available phosphorus in Miami loam (9).

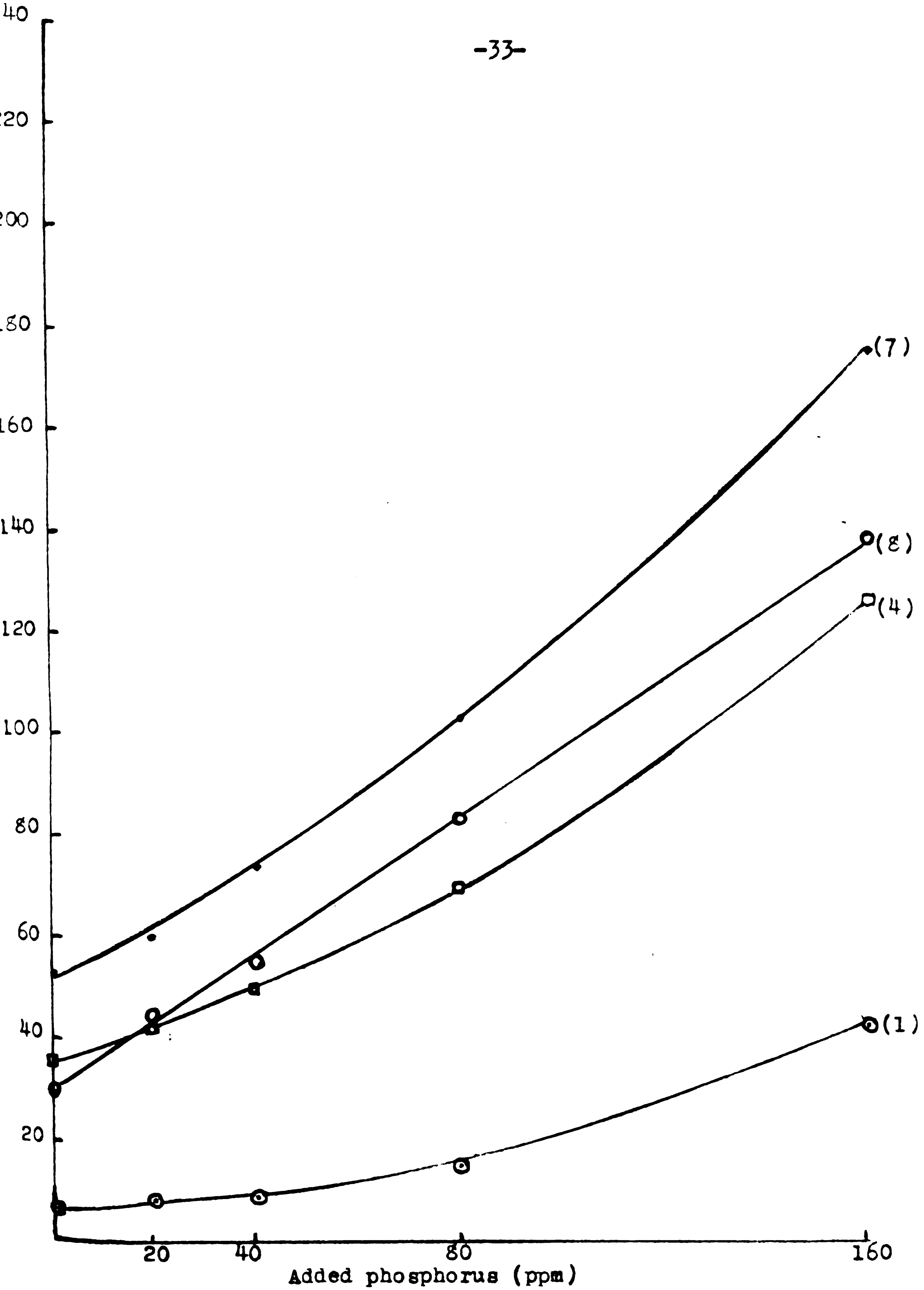

Figure 10. Relationship between added phosphorus and chemically available phosphorus in Miami loam (10).

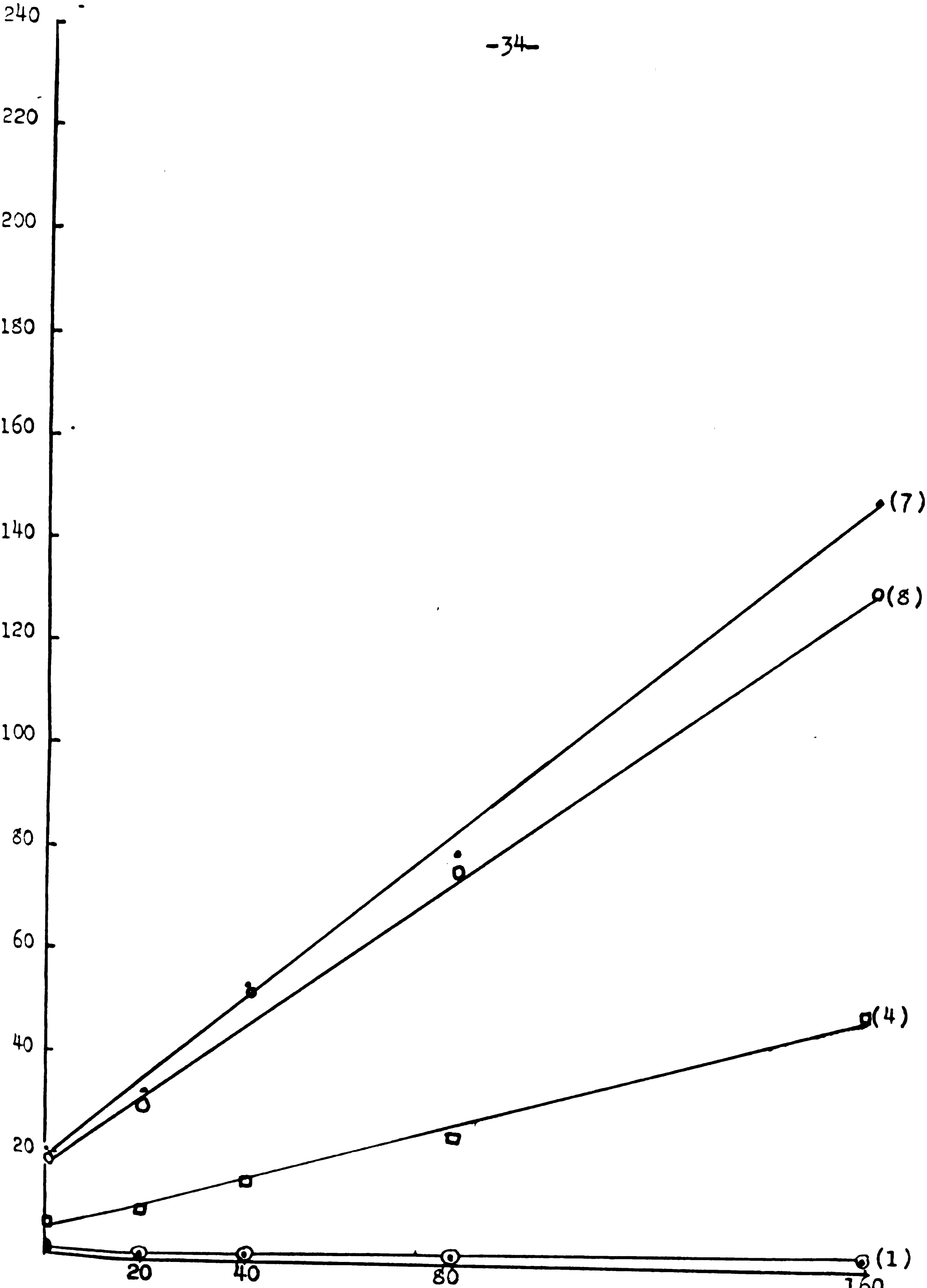

Figure 11. Relationship between added phosphorus and chemically available phosphorus in Isabella loam (11).

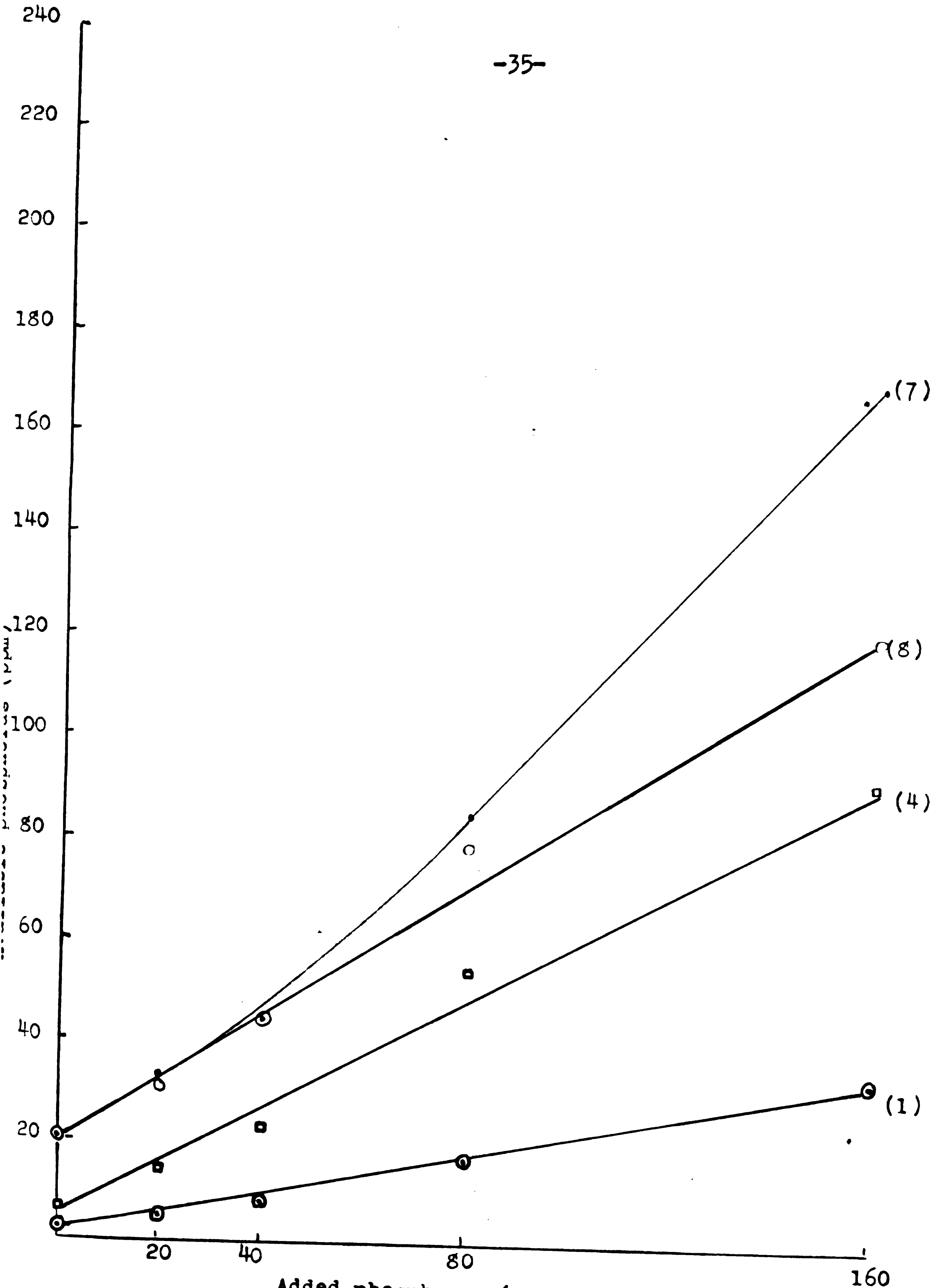

Figure 12. Relationship between added phosphorus and chemically available phosphorus in Isabella sandy loam (12)

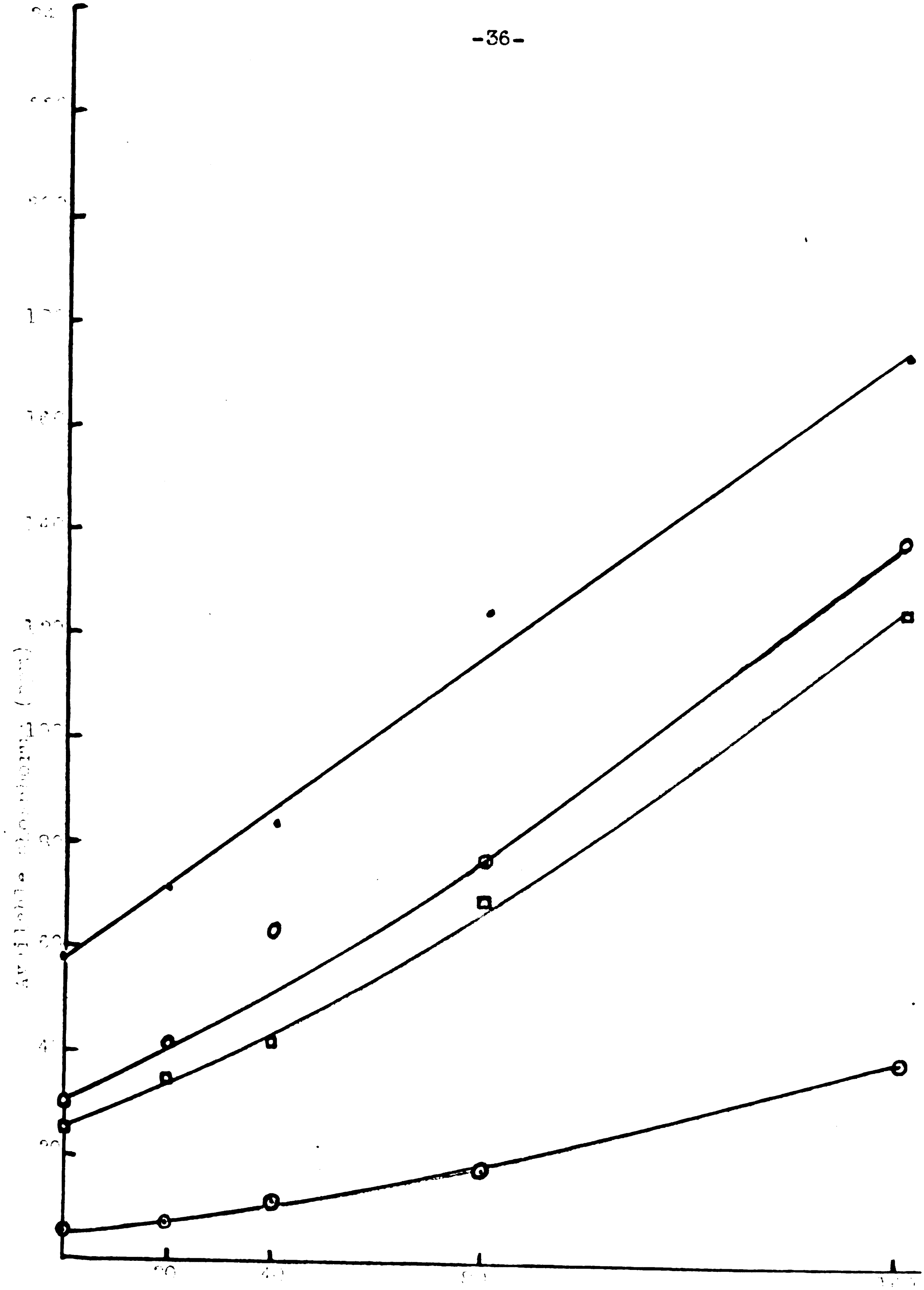

Figure 1[illegible]. Relationship between [illegible]

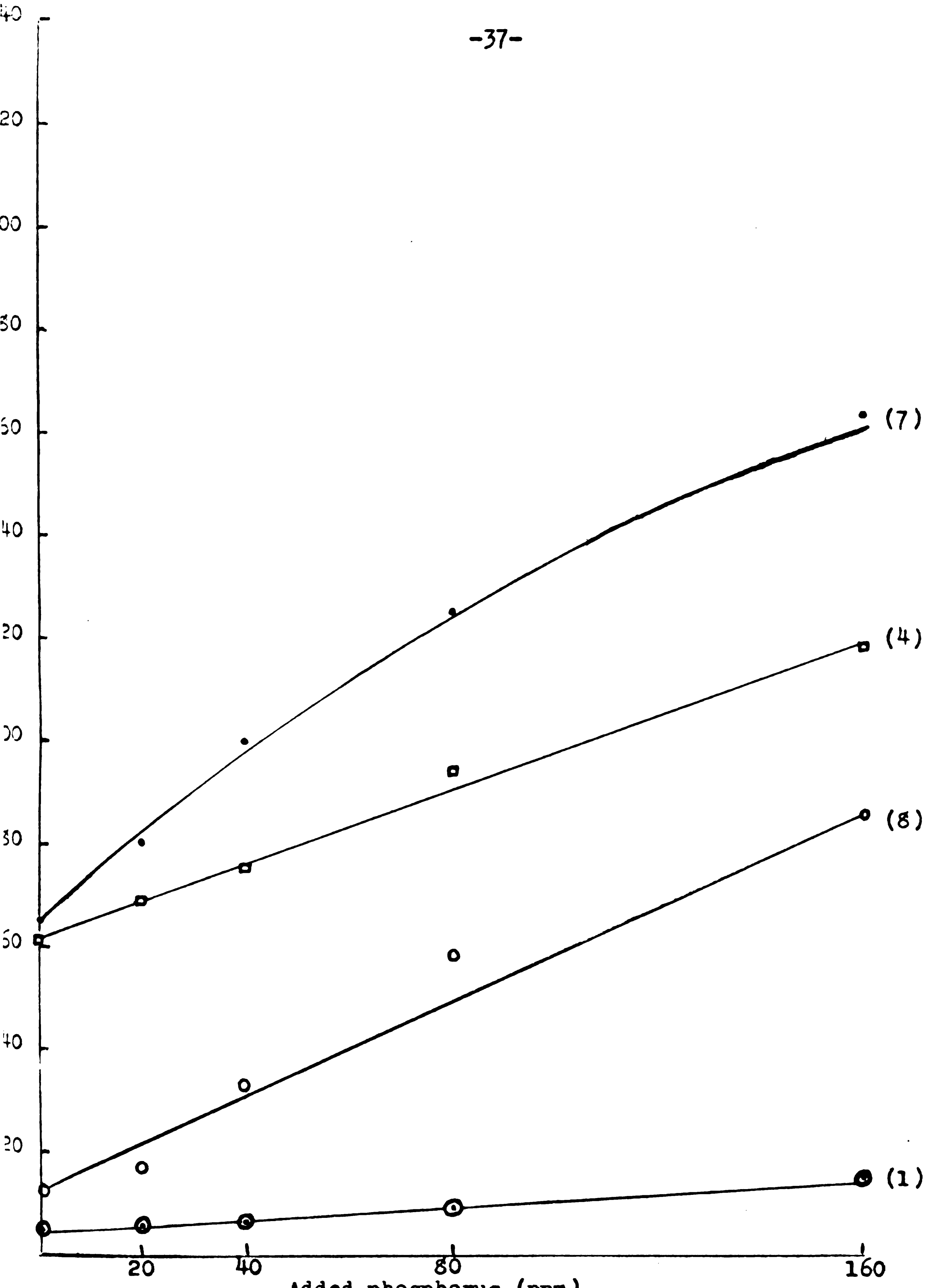

Figure 14. Relationship between added phosphorus and chemically available phosphorus in Conover clay loam (14).

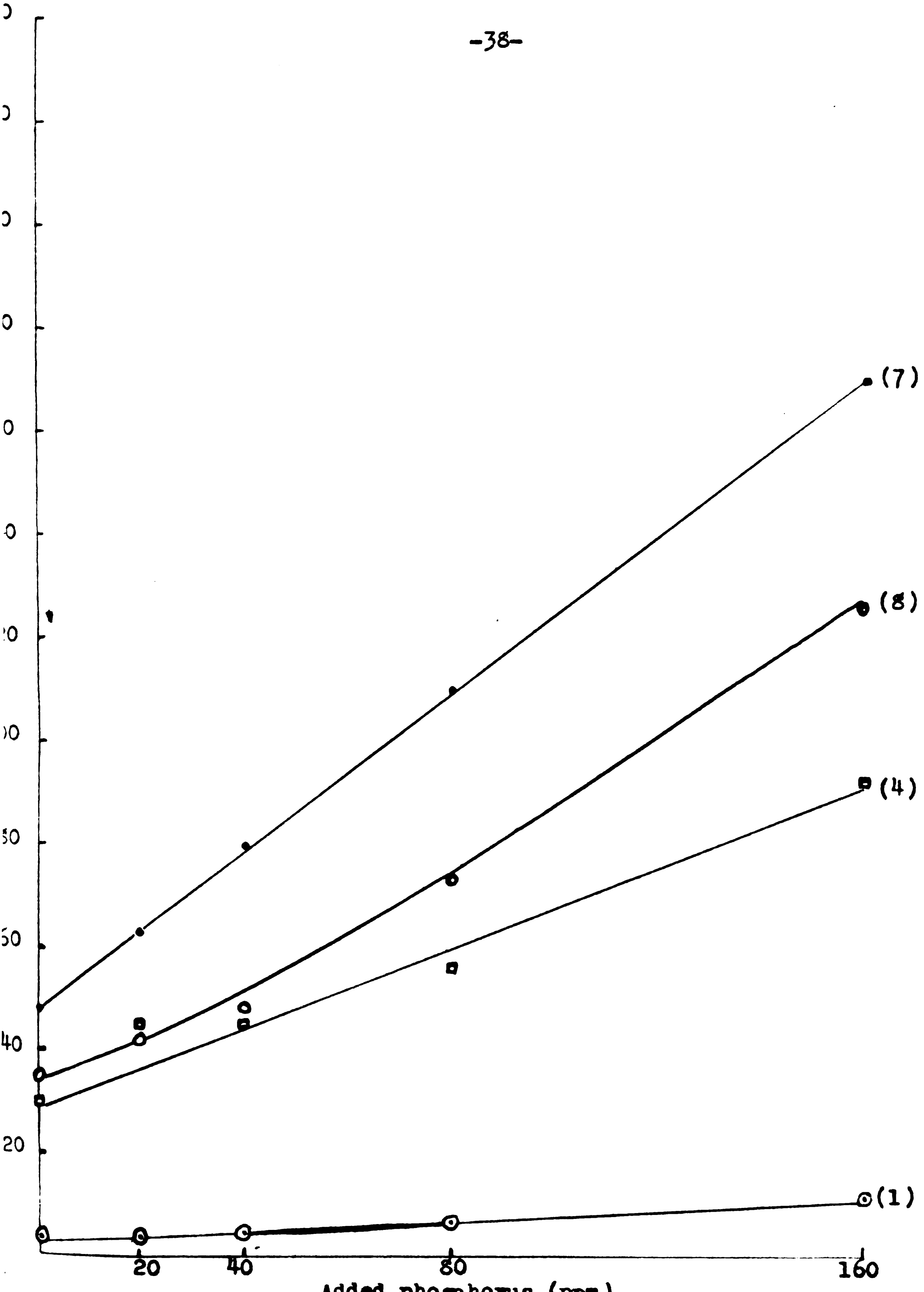

Figure 15. Relationship between added phosphorus and chemically available phosphorus in Napanee loam (15).

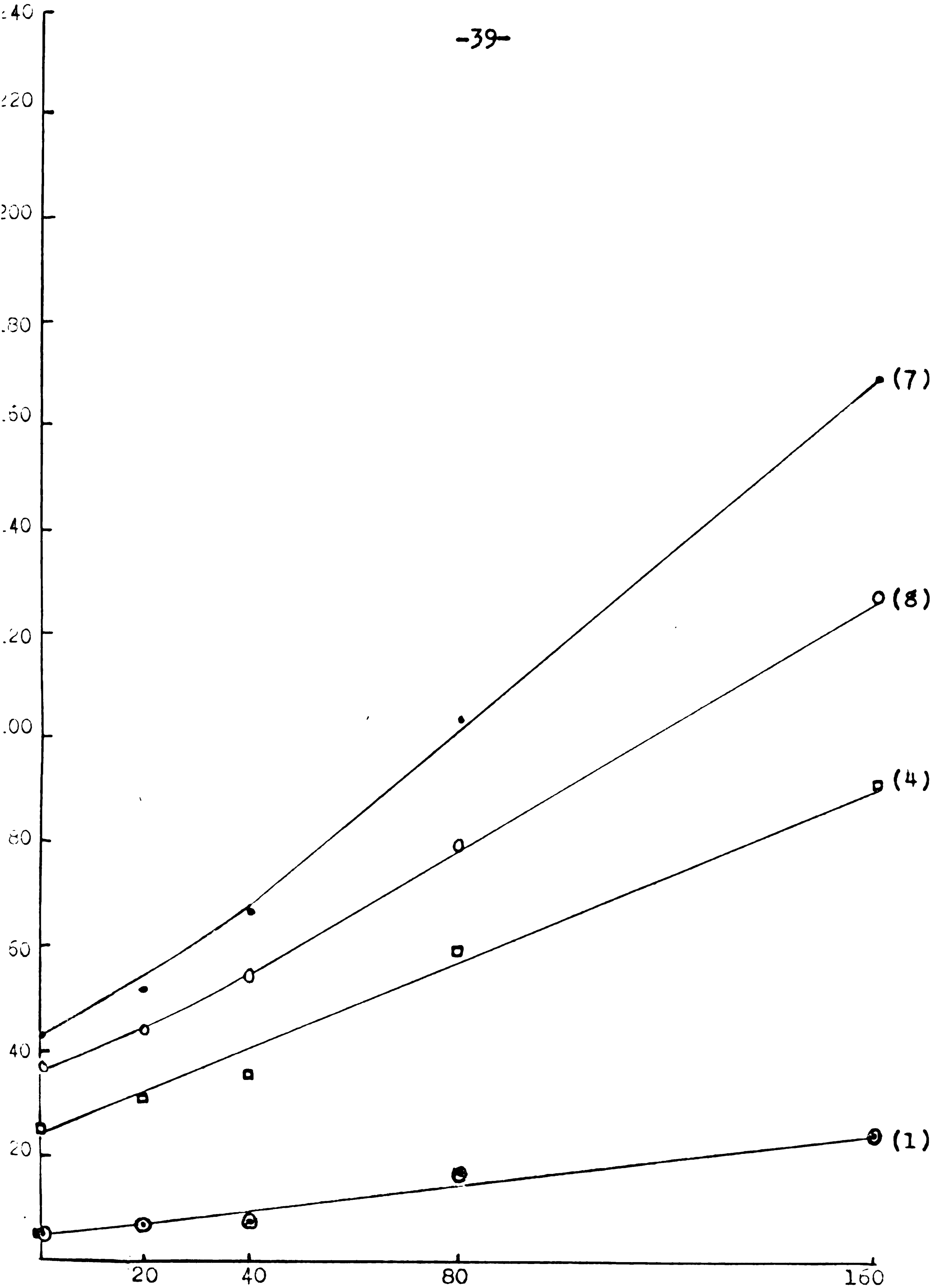

Figure 16. Relationship between added phosphorus and chemically available phosphorus in Kent silt loam (16)

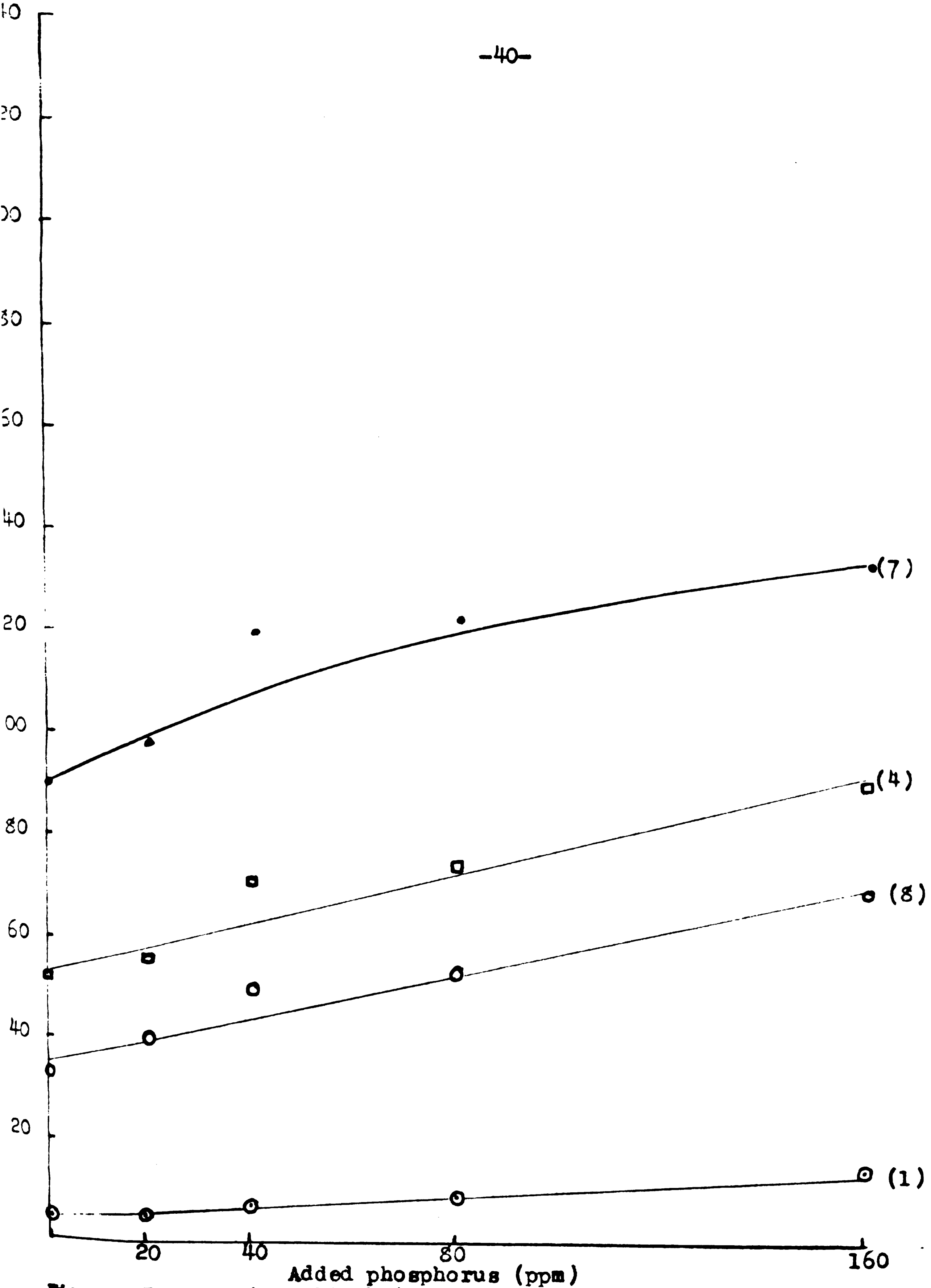

Figure 17. Relationship between added phosphorus and chemically available phosphorus in Clyde clay loam (17).

240
220
200
180
160

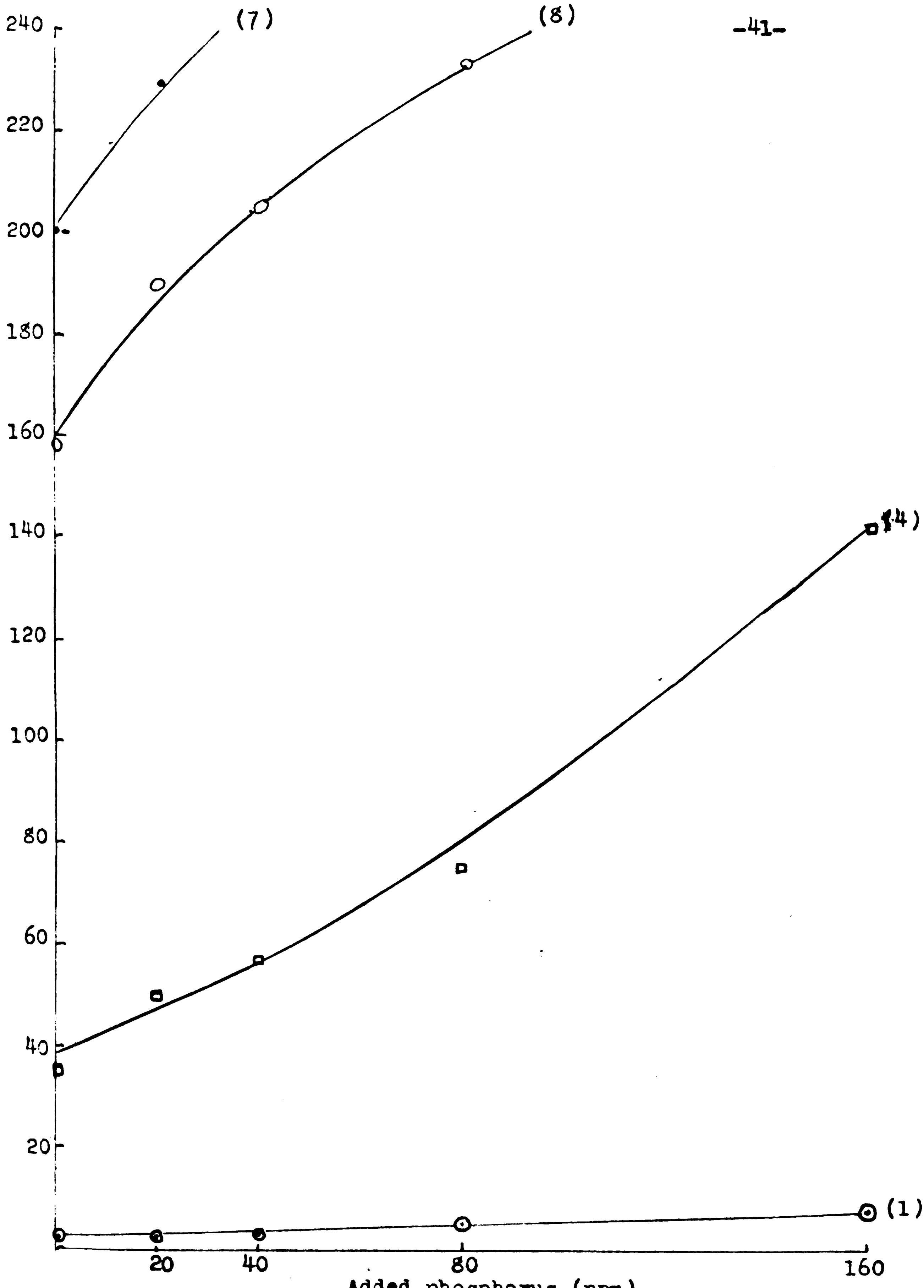

Figure 18. Relationship between added phosphorus and chemically available phosphorus in Oshtemo loamy sand (18).

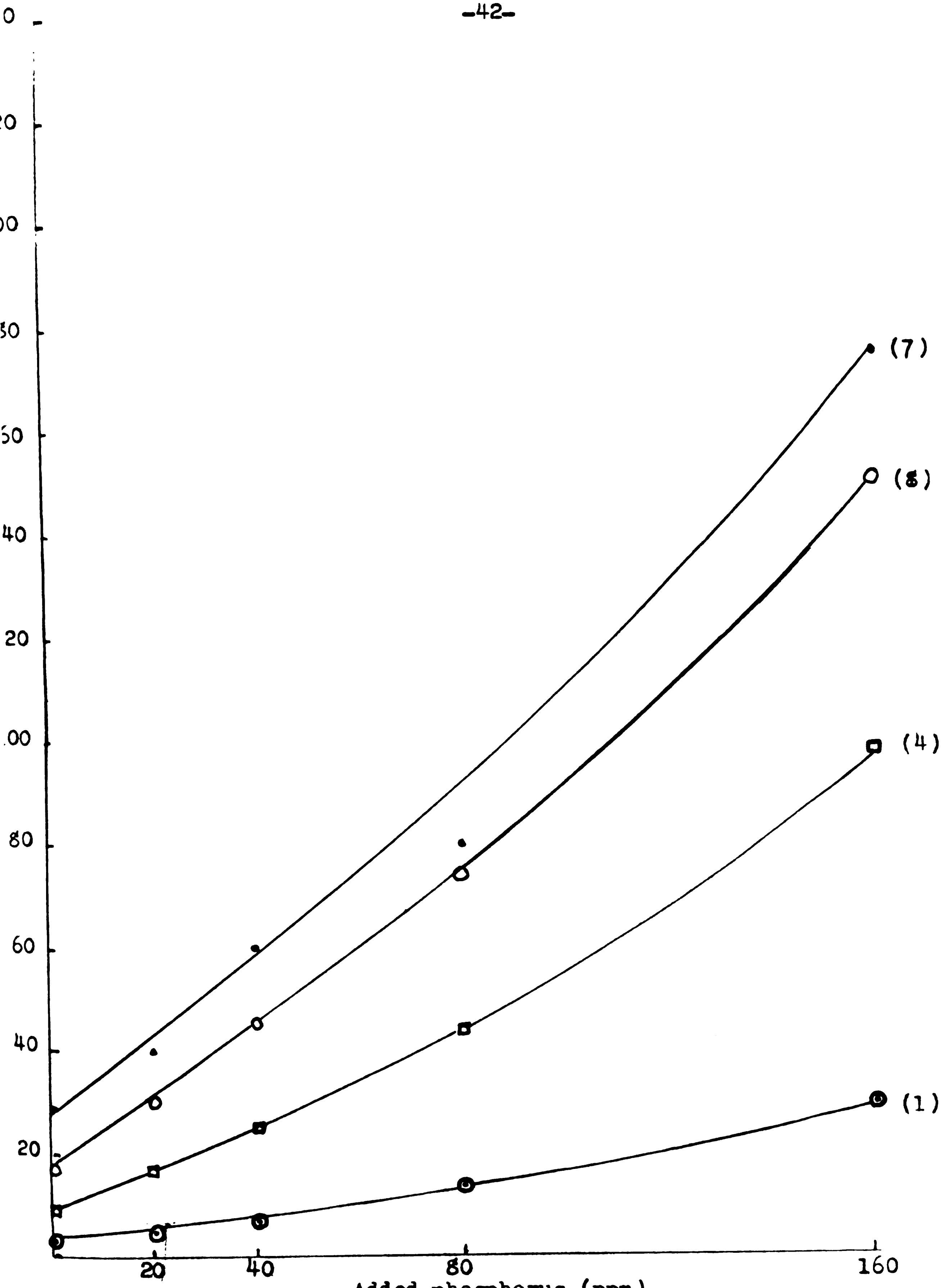

Figure 19. Relationship between added phosphorus and chemically available phosphorus in Emmet sandy loam (19).

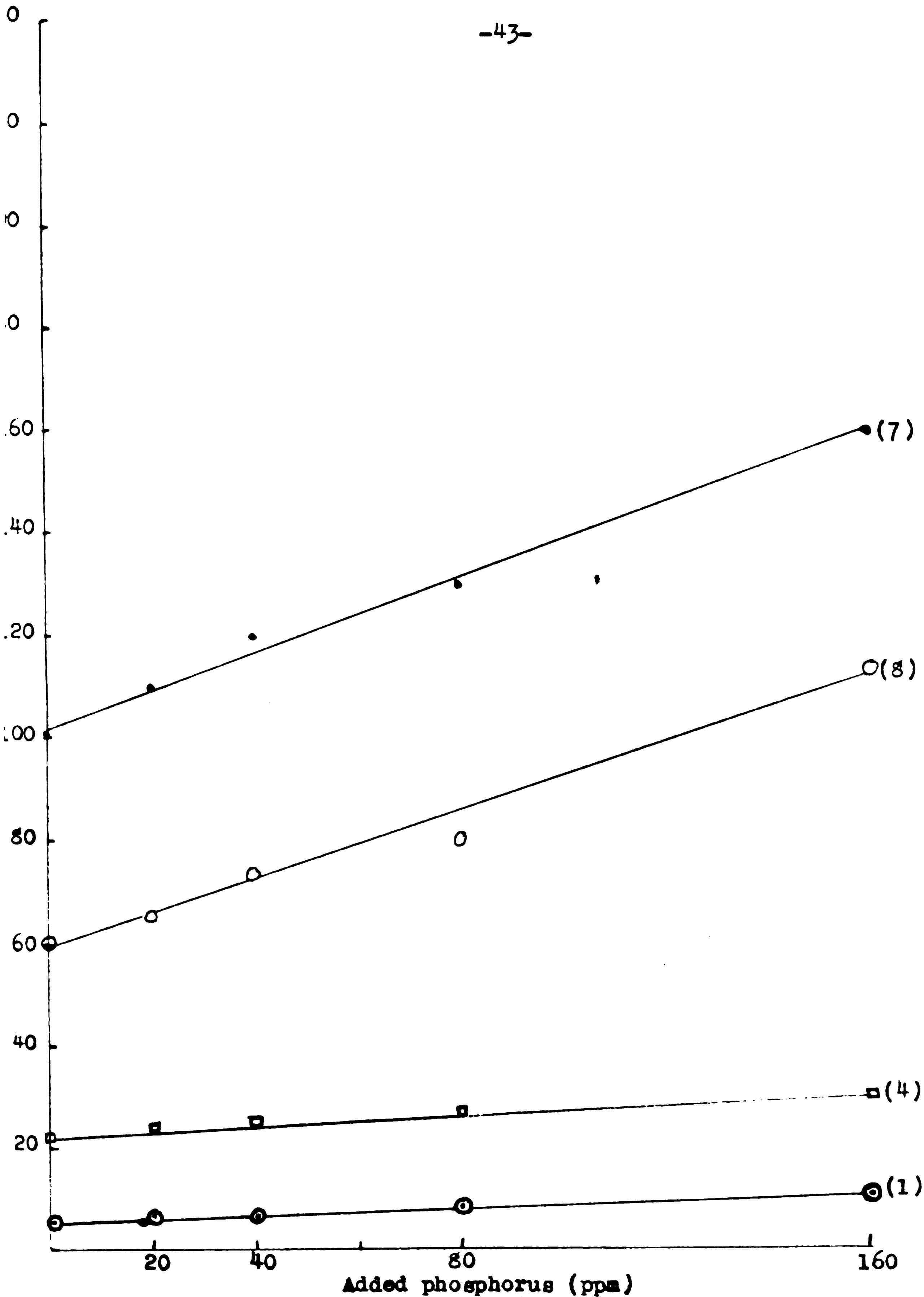

Figure 20. Relationship between added phosphorus and chemically available phosphorus in Muck (20).

In general the amount of phosphorus removed by the active extracting solution of Spurway (14) was quite low in comparison to that removed by the stronger acid extractants used in the reserve method of Spurway or in the techniques of Bray (5). This method of extraction did, nevertheless, tend to reflect an increasing amount of available phosphorus in the soils as the increment of added phosphorus became greater. In some cases the rise was not great, suggesting perhaps that the particular soil retained the added soluble phosphorus with such strength that this extraction was not effective in indicating its true availability. This was especially true on soil 4, 11, 14, 15, 17, 18 and 20. Inasmuch as it seemed that the true availability of the added phosphorus was not indicated in these particular soils it was decided that perhaps an increase in either the ratio of extracting solution to soil or in the time of shaking might improve the results of such chemical extractions. Thus the whole series of samples was subjected to two additional extractions in which Spurway's active extracting solution was used. Generally speaking, increasing either of these two previous mentioned factors resulted in an increased amount of phosphorus being removed from the soil except in certain instances where one or both of the revised techniques failed to result in any improvement. The increased ratio of extractant to soil was no more effective at the two lower levels of added phosphorus on the Brookston silt loam from Kent county (soil 4) than was the original extraction. The same relationship existed also for the Conover soil from Macomb county (soil 14). However, after as much as 80 ppm of soluble phosphorus had been added, each of these soils did release more phosphorus when subjected to the action of a greater volume of solution.

The increased shaking time was even less effective than was the increased amount of extracting solution. For example, in the case of the Isabella sandy loam soil (soil 12) the increased time resulted in a decided drop in the amount of phosphorus removed from the soil at all levels of added phosphorus except where as much as 160 ppm had been made. The decrease in amount extracted was even greater in the Oshtemo sand (soil 18) and the muck (soil 20). In various other instances it was apparent that at the lower levels of added phosphorus even less distinction was able to be detected between the increments than had been apparent previously with Spurway's original technique. There was some tendency such as on soils 1, 3, 4, 6, 11, 14, 18 and 20 for this procedure to reflect no more and in some cases even less available phosphorus in a given soil after the addition of 20 ppm soluble phosphorus than had been the case in the original sample.

In general the use of the weak acid extraction as outlined in either of the three above techniques produced a sufficiently colored extract so that the intensity of the blue was sufficient to be easily detected with the colorimeter, even at the lower levels of availability. Even the extracts from the soils containing the greatest amounts of soluble phosphorus contained so little phosphorus that it was seldom necessary to dilute the extract to obtain an intensity within the range of the Evelyn photoelectric colorimeter.

The use of Spurway's reserve extracting solution always resulted in a reflection of the various additions of soluble phosphorus and thus did not result in such exceptions as described for the active extraction, especially when the extraction time was one hour.

This method did result in great variability depending upon the soil. According to this method the original samples, before the addition of soluble phosphorus, had a range from a low of only 6 ppm of available phosphorus to as much as 99 ppm available phosphorus. This method was by far the more variable with respect to differences between individual soils. Furthermore, there are seemingly undesirable discrepancies in such techniques where only a strong acid extractant is used in the case of such soils as 4 and 11 where the amount of available phosphorus indicated is less after the addition of 160 ppm of soluble phosphorus than for a large number of the other soils even without the addition of soluble phosphorus. This method may also be criticized due to the inconvenience in measuring the amount of phosphorus in the extract. In the case of soils containing very large amounts it was frequently necessary to dilute several times and thus a considerable expenditure of time was made merely in a trial and error method of color development in the unknown samples. Due to the great variability in the amounts of phosphorus removed from untreated soils, no fixed dilution schedule could be adopted to provide for even the majority of samples.

The use of those techniques suggested by Bray (5) provided additional information relative to the apparent solubility of phosphorus in these soils. Bray (5) has recommended the use of a 1:10 ratio of soil to extracting solution in the neasurement of total available phosphorus or adsorbed phosphorus when ordinary field samples are being examined for fertilizer recommendations whereas the ratio of 1:50 has been recommended for research purposes.

The various samples of soil in this study were all initially subjected to an extraction ratio of 1:10. Upon the completion of the measurement of the so-called total available phosphorus it was at once apparent that this method had a distinct tendency to remove more phosphorus from the soil than did the use of the strong acid as employed by Spurway in the reserve extraction previously discussed. Only three exceptions to this were noted. In the case of three of the untreated Brookston soils (soils 2, 7 and 8) this technique did not remove as much as Spurway's extraction. However, in all other cases, including these three soils in those instances where soluble phosphorus had been added, this method did result in greater values.

This method did behave different than the previously described reserve extraction of Spurway in the sense that there was much less variability between soils. For example, the lowest value on an untreated sample using this technique was 19 ppm, and then for only one soil, as compared to a low value of 6 ppm for each of three soils using the reserve method. Excluding the Oshtemo sand, no value for any untreated soil exceeded 88 ppm whereas with the Spurway reserve extraction the corresponding value on this same untreated soil (soil 8) was 99 ppm of available phosphorus. Inasmuch as the same acid, HCl, is the acid involved in each of these extractions, it must be concluded that the presence of the fluoride ion has played a very significant role in causing the release of phosphorus from the soil to the extracting solution. In this way the exceedingly low values obtained where only the hydrochloric acid alone is used tend to be eliminated. The reason for the three soils (soils 2, 7 and 8) having greater values with the reserve extraction than with the method of Bray for measuring the total available phosphorus undoubtedly lies in the greater normality of the acid in the former extracting solution. This method of Bray was apparently quite capable of reflecting the presence of added soluble phosphorus in every case on every soil. This method also provided only one instance (soil 4) in which the measured available phosphorus after the addition of 160 ppm of soluble phosphorus was less than for the untreated samples of soils 2 and 8.

The use of Bray's extracting solution for the measurement of total available phosphorus also provided one other important advantage over Spurway's reserve extraction. As noted above, the range of measured values with Bray's technique was from 19 to 88 ppm on the untreated soils as compared to a range of 6 to 99 ppm on the untreated soils when using Spurway's procedure for removing the reserve phosphorus. This reduced range coupled with the fact that the Bray procedure utilizes a 10:1 extraction ratio as compared to 4:1 for Spurway's method meant not only a reduced range to contend with in working with the unknown samples but almost the complete elimination of the necessity for diluting unknown samples, particularly on untreated soils, so that a great saving of time was rendered.

Measurement of the adsorbed form of available phosphorus provided additional information about the tenacity with which added soluble phosphorus is retained by a given soil. For example, in the case of soils 4, 9, 11, 12 and 19 in particular, the amount of available phosphorus removed by either of Spurway's procedures was comparatively low and thus it might be suspected that in comparison to other soils which gave higher values where the same procedures were used these values are actually too low to reflect the true availability of phosphorus in these soils. No doubt the true availability of phosphorus in these soils was less than that of other soils receiving the same treatment but it is extremely doubtful if such wide variations could exist. It was noted previously that the addition of fluoride tended to eliminate these extreme variations between soils. The use of Bray's extracting solution for the removal of adsorbed phosphorus alone suggested that on several of these soils this form of phosphorus must be included in evaluating the available phosphorus in a given soil. Particularly with soils 4 and 11, both of which came from Kent county and to a lesser extent with such soils as the Miami loam (soil 9) and the Isabella sandy loam (soil 12) the content of available phosphorus was quite low when measured only by removing the strictly acid soluble fraction as is done in Spurway's method. The use of fluoride, even where it is in combination with such a dilute acid as 0.025N HCl as is used in Bray's adsorbed acid extracting solution effected the release of considerable additional non-acid soluble phosphorus. This conclusion must be made when it is apparent by examinatiom of the value for Bray's adsorbed phosphorus that on certain of these soils virtually as much phosphorus is removed by the fluoride in 0.025N HCl as in 0.1N HCl. Therefore, indirectly it is demonstrated that one of the major

reasons why Bray's total available phosphorus extraction technique eliminates the exceptionally low values observed with Spurway's methods is due to the action of the fluoride. Although only indirect evidence is available, it must be assumed that particularly in the case of the Isabella soils, the Miami soils and also the Brookston soil from Kent county as well as the Emmet soil that the quantity of adsorbed phosphorus is of no small importance particularly when considered as a proportion of the total available phosphorus present in such soils.

Additionally, the soils were subjected to extractions with the same solutions of Bray at the 1:50 ratio of soil to extracting solution. Bray(5) has suggested that this type of extraction is more desirable from the research standpoint and particularly in those instances where an attempt is being made to correlate such values with plant growth response. Furthermore, this same author has suggested that such extractions should more nearly remove all of the adsorbed phosphorus from a given soil whereas a 1:10 ratio removes only approximately one-half the entire adsorbed portion. Therefore, if a correlation between the adsorbed form and plant response does exist, it is more desirable to know the entire amount than only a fraction of it. In the case of the soils considered in this investigation the increased ratio always resulted in higher values for both the adsorbed forms and the total available phosphorus. However, the proportion removed by one ratio as compared to the other was by no means constant for the entire group of soils. For example, in the case of such samples as soils 1, 11, 14, 18, and 19, increasing the ratio of extractant to soil did not increase the value for adsorbed phosphorus nearly so much as it did in the case of soils 8 and 16, in particular, where the quantity removed as a result of a greater extracting ratio was nearly doubled in the latter. Therefore, inasmuch as no constant relation seemed to exist, even more importance might be placed upon using a relatively wide ratio of extracting solution to soil, particularly for research purposes where precise values representing a given fraction of phosphorus in the soil are of utmost significance.

The use of a wider ratio of extractant to soil also had the tendency to give even greater significance to the role of adsorption of phosphorus and removal by fluoride of phosphorus in chemical studies of this element in the soil. By comparing the last two columns of Table 5, it is apparent that in the cases of soils 4, 7, 11, 12, 16 and to a lesser extent with certain others that the equivalent of virtually all of the total available phosphorus can be extracted as adsorbed phosphorus if a ratio of 1:50 is employed. Thus additional clarification as to the exact status of the forms of phosphorus existing in the soil was provided. If only the values obtained as a result of a 1:10 extraction ratio had been considered, there probably would have been a tendency to have overlooked the true role of adsorption of the phosphorus for at least several of the above specified examples.

In general, the chemical studies of available phosphorus in the soil shed considerable light upon the phosphorus fertility of the various soils concerned. Seemingly the employment of the fluoride ion in extracting the adsorbed portion of phosphorus cannot be overlooked and therefore any attempt to evaluate the true status of phosphorus availability by means of either strong acid or weak acid extractants is not entirely acceptable on at least some of the soils included in this study.

Plant Growth Response

The Influence of Added Phosphorus on the Number of Wheat Heads Produced

Data relative to the mean number of wheat heads produced per individual treatment on each of the soils are presented in Table 6. There were obvious visual differences in the size of the plants according to both soil series and phosphorus treatment. Therefore, it was believed that a count of the number of wheat heads produced by each treatment might aid in explaining the plant response to phosphorus.

In general, there was some tendency for the addition of phosphorus to increase the number of wheat heads produced. This fact was usually most apparent for the first addition of phosphorus. On certain soils such as 2, 9, 12, 18 and 20 there was no apparent stimulation in the number of wheat heads produced as a result of the first addition of $Ca(H_2PO_4)_2 \cdot H_2O$. In the case of the Brookston silt loam from Macomb county (soil 2) this tendency was probably due to the fact that this soil in the untreated state was capable of producing a large number of wheat heads due to a high state of native fertility.

The other of the above soils had a much more pronounced tendency to produce a smaller number of wheat heads, especially in the case of soils 12 and 18. These two soils in particular seemed to be especially low in fertility and upon the basis of plant growth characteristics, including size of heads formed, were among the most responsive to added phosphorus, especially at the higher levels.

The data in Table 6 suggest that the various soil series had a definite tendency to vary probably even more than the levels of phosphorus within a given soil series. For example, the Clyde clay loam (soil 17) averaged more than double the number of wheat heads for each level of added phosphorus than did such soils as the two Isabella specimens (soils 11 and 12) and the Oshtemo series (soil 18). Similarly the two Brookston soils from Macomb county (soils 1 and 2) and the Kent silt loam (soil 16) were especially capable of producing large numbers of wheat heads, regardless of the added level of phosphorus. The Clyde and Kent soils were obtained from a wood lot and grassed area respectively and probably were of especially high fertility and therefore capable of producing a large amount of wheat heads. Likewise, the two Brookston soils were apparently in a high state of fertility as a result of soil management practices. Soil 1 was obtained from an area used for truck farming and Soil 2 was obtained from a grain stubble field which displayed an excellent growth of clover which suggested a relatively high level of fertility. Additionally, these two soils were in a well aggregated state as indicated by the apparent stability of the aggregates in the greenhouse cultures after several months of surface watering.

Table 6. The mean* number of wheat heads produced per treatment for the various soils according to the various levels of added phosphorus.

Added Phosphorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot C0.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.	(9) Miami loam Clinton Co.
0	20	21.5	16.5	10.5	11.5	10	11	13.5
20	24	21.5	17.5	11.5	15.5	17	15	13.5
40	20.5	22.5	18.5	14	13.5	17	16	15
80	24	22	21.5	12	16.5	15	13	18
160	22.5	25.5	24.5	18	16	17.5	18	18

Added Phosphorus ppm	(10) Miami loam Tuscola Co.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent Silt loam Kent Co.	(17) Clyde Clay loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(20) Muck Eaton Co.
0	16.5	9.5	10	13.5	23.5	25	10	16
20	15.5	11.	10	14	25.5	28	9	16
40	16.5	10.5	12	16	24.5	30	9.5	14
80	18.5	11.5	12	14.5	25.5	32	10.5	15.5
160	20	12.5	14.5	16	26	34	11.5	18

* Mean of 2 replicates

The Influence of Added Phosphorus on Yield of Plant Material

Yield of Wheat Straw

Data are presented in Table 7 relative to the mean weight of wheat straw produced by each treatment for the various soils studied in this investigation.. The weights, in general, showed a tendency to increase as the level of added phosphorus was increased, especially as the initial lower amounts of phosphorus were added. The first increment of phosphorus, 20 parts per million, produced an increase in all except two instances. One of these was on one of the apparently most fertile soils included in the study, the Kent silt loam (soil 16) and the Oshtemo loamy sand (soil 18) which, upon the basis of the appearance of plants and weight of material harvested, must be regarded as the least fertile of the soils in the study.

Comparatively speaking, the seemingly most infertile soils, upon the basis of chemically extractable phosphorus in the untreated samples, for instance the Isabella series (soils 11 and 12) and the Oshtemo sand (soil 18) gave the greatest percentage increase in weight of straw for the addition of phosphorus especially at the upper levels. This same general relationship also held for the Brookston soil from Kent county (soil 4) which behaved more like the

Table 7. The mean* weights expressed in grams of wheat straw produced per treatment for the various soils according to the various levels of added phosphorus.

Added Phosphorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co.	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.	(9) Miami loam Clinton Co.
0	19.7	18.7	14.7	8.0	11.0	7.3	14.8	14.5
20	22.3	19.4	15.4	11.2	14.4	16.6	14.9	15.2
40	21.3	17.0	14.3	14.3	15.3	20.1	20.4	16.7
80	24.4	21.9	19.7	13.5	16.2	26.0	24.4	18.0
160	23.7	27.1	23.0	17.4	16.3	37.8	19.7	18.3

Added Phosphorus ppm	(10) Miami loam Tuscola Co.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent silt loam Kent Co.	(17) Clyde clay loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(20) Muck Eaton Co.
0	13.0	2.6	5.2	13.6	24.4	23.6	2.7	17.4
20	15.2	6.6	10.6	15.5	21.1	27.6	2.3	16.4
40	16.2	7.9	12.1	16.0	23.7	26.6	5.4	13.5
80	17.6	11.1	13.6	15.5	26.3	27.3	7.4	17.6
160	19.4	12.2	14.0	16.7	25.1	28.6	8.8	17.8

* Mean of 2 replicates.

Isabella soil from the same county than like the majority of other Brookston soils included in this study. One other soil which gave a very marked increase in growth of straw according to the addition of phosphorus, especially at the upper levels, was the Brookston soil from Gratiot county (soil 7) which otherwise was similar to soil 6 except that it was taken from an uncultivated fence row. Apparently factors of fertility other than those associated with chemical availability of phosphorus enabled the uncultivated soil to respond much more favorably to a given addition of phosphorus.

The variability of plant growth as reflected by the weight of straw between the individual soil series was even more marked than that within a given soil. This behavior was quite similar to that noted for the number of wheat heads produced.

In a general sort of way those soils which apparently were of a high state of native phosphorus fertility as indicated by the chemical studies on the soil had a tendency to produce only slight response for a given addition of phosphorus.

Yield of Wheat Heads

Table 8 presents data relative to the influence of the various additions of $Ca(H_2PO_4)_2 \cdot H_2O$ upon the yield of wheat heads for the various soils. In general, the increased growth of the wheat plants was reflected more in the weight of the wheat heads than in the wheat straw. All of the soils were characterized by an increase in the weight of wheat heads produced for the first increment of added phosphorus.

The increase in the yield of wheat heads was particularly marked over the entire range of phosphorus additions on such soils as the Brookston loam from Kent county (soil 4), the two Isabella soils (soils 11 and 12) and in the case of the Oshtemo sand (soil 18). The response, though relatively somewhat less, was also quite marked upon both the Brookston soils from Gratiot county (soils 5 and 6).

It was also noted that, in general, even on the soils which have previously been pointed out as being of comparatively high phosphorus fertility there was more response in the yield of wheat heads than there was in the straw. Such was the case with the two Brookston soils from Macomb county (soils 1 and 2) and to a lesser extent with the Kent silt loam (soil 16) and the Clyde clay loam (soil 17). The only soil which perhaps showed no really pronounced tendency for an increased production of grain for the higher levels of available phosphorus was the muck soil (soil 20). The

Table 8. The mean* weights expressed in grams of wheat heads produced per treatment for the various soils according to the various levels of added phosphorus.

Added Phosphorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co.	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.	(9) Miami loam Clinton Co.
0	9.55	9.67	7.87	3.51	6.38	6.06	9.38	10.55
20	10.37	13.64	11.06	8.15	8.43	10.10	13.09	13.09
40	10.31	15.18	11.65	9.65	8.36	10.49	13.16	13.99
80	13.01	15.01	14.79	10.57	10.72	10.79	12.34	15.77
160	13.14	16.51	15.60	11.81	10.99	13.73	13.60	14.64

Added Phosphorus ppm	(10) Miami loam Tuscola Co.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent Silt loam Kent Co.	(17) Clyde Clay loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(20) Muck Eaton Co.
0	8.46	1.51	4.07	7.85	16.24	17.44	1.25	9.95
20	10.62	4.95	9.85	12.63	19.51	19.34	2.24	10.40
40	10.69	7.09	9.63	12.98	17.74	16.82	2.12	8.19
80	10.30	7.95	12.43	12.97	17.37	20.09	7.07	10.56
160	11.58	8.67	14.50	13.30	16.44	21.74	7.04	11.81

* Mean of 2 replicates.

same results were apparent in the straw production so that it may be assumed that under the conditions of this experiment phosphorus was not an important limiting factor in the growth of wheat plants on this particular soil.

Once again the very marked fluctuation between soils was quite apparent. The very highly fertile uncultivated soils such as the Kent silt loam and Clyde clay loam produced the greatest yields and the soils characterized by observed stable structure such as the two Brookston soils from Macomb county gave very good yields also. All of the Brookston soils were capable of producing relatively good yields provided the level of available phosphorus was sufficient. Only the Isabella loam from Kent county (soil 11) and the Oshtemo sand (soil 18) appeared to be rather inferior in productivity even after very large additions of readily available phosphorus.

Total Yield of Wheat Plant Material

The data presented in Table 9 give the mean weights for each treatment for the entire wheat plants. It happened that the particular sample of Henry Spring wheat was badly infested with smut. Probably the weight of heads was influenced somewhat more in certain treatments than in others by the presence of this disease. Also there was some tendency for a lack of uniformity in maturity. Therefore, the combined weight of straw and grain probably more

Table 9. The mean* total weights expressed in grams of wheat plants produced per treatment for the various soils according to the various levels of added phosphorus.

Added Phosphorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co.	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.	(9) Miami loam Clinton Co.
0	29.20	28.32	22.52	11.46	17.38	15.36	24.18	25.05
20	32.82	32.99	26.41	19.34	23.13	27.55	27.99	28.24
40	31.56	37.28	29.10	23.90	23.61	26.34	33.56	30.69
80	37.41	36.86	31.99	24.07	26.87	27.59	36.74	33.52
160	36.84	43.56	38.65	29.21	27.24	31.53	33.30	31.89

Added Phosphorus ppm	(10) Miami loam Tuscola Co.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent silt loam Kent Co.	(17) Clyde clay loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(20) Muck Eaton Co.
0	21.46	4.06	9.22	21.45	40.64	41.04	3.90	27.35
20	25.82	11.55	20.40	28.13	40.56	46.94	4.49	26.80
40	26.84	14.99	21.73	28.98	41.39	43.42	7.57	21.69
80	27.90	18.59	26.03	28.47	43.62	47.39	14.42	28.16
160	30.98	20.82	28.45	29.95	46.54	50.34	15.79	29.61

* Mean of 2 replicates

nearly reflect the true productive capacity of the various soils.

In a general manner, the total weight of plants, like the previously discussed factors, showed that certain soils were more responsive to added phosphorus than others and emphasized the fact that certain apparently highly fertile soils are much more productive than such soils as the Isabella soils and Oshtemo sand.

The data relative to yield of total plant material will be considered in detail in subsequent discussion in an attempt to correlate plant growth response to chemically measured available phosphorus. Therefore, detailed discussion is not presented at this point.

Photographs are presented in Plates 1 to 7, inclusive, of the wheat plants as of May 16, 1949. In general the photographs tend to illustrate the rather marked response to the various additions of phosphorus on such soils as the Isabella loam from Kent county (soil 11) and on the Oshtemo loamy sand from Clinton county (soil 18). The intermediate response noted on certain of the soils is characterized in Plates 1, 2 and 4. Such soils as the Kent silt loam from Kent county (soil 16) and the Clyde clay loam from Macomb county showed very little response to added phosphorus as of May 16.

Plate 1. Brookston silt loam from Macomb county (soil 1) showing effect of added phosphorus on growth of wheat May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 20, 3 = 40, 4 = 80, and 5 = 160.

Plate 2. Miami loam from Clinton county (soil 9) showing effect of added phosphorus on growth of wheat, May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 20, 3 = 40, 4 = 80, 5 = 160.

Plate 3. Isabella loam from Kent county (soil 11) showing effect of added phosphorus on growth of wheat May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 20, 3 = 40, 4 = 80, and 5 = 160.

Plate 4. Conover loam from Clinton county (soil 13) showing effect of added phosphorus on growth of wheat May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 20, 3 = 40, 4 = 80 and 5 = 160.

Plate 5. Kent silt loam from Kent county (soil 16) showing effect of added phosphorus on growth of wheat May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 20, 3 = 40, 4 = 80, and 5 = 160.

Plate 6. Clyde clay loam from Macomb county (soil 17) showing effect of added phosphorus on growth of wheat May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 20, 3 = 40, 4 = 80 and 5 = 160.

Plate 7. Oshtemo loamy sand from Clinton county (soil 18) showing effect of added phosphorus on growth of wheat May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 20, 3 = 40, 4 = 80 and 5 = 160.

Tomato Yields

The data reported in Table 10 provide additional information relative to the phosphorus fertility relationships of certain of the soils mentioned previously in connection with the wheat studies. Also included in this table of data are four additional soils, Brookston from Tuscola county (soil 8), Conover clay loam from Macomb county (soil 14), Napanee loam from Macomb county (soil 15) and Emmet sandy loam (soil 19). A photographic record of tomato plant response for this particular crop is presented in Plates 8 to 17, inclusive, for each of the soils and certain additional comparisons between soils of the same series and different series are presented in Plates 18 to 22, inclusive.

It was obvious early in the growth of the tomato plants that most of these soils were very much in need of added phosphorus for the successful growth of tomatoes. In the case of the Brookston loam from Kent county (soil 4) both Isabella soils (soils 11 and 12) and the Oshtemo sand (soil 18) the growth on the untreated cultures was hardly distinguishable after the first week and in some instances the plants were dead at the time of harvest. Each of these soils was previously determined to be quite phosphorus deficient as indicated by the growth of wheat plants and by at least one or more of the chemical methods used for measuring phosphorus availability.

Table 10. The mean dry weight expressed in grams of tomatoes produced per treatment for the various soils according to the various levels of added phosphorus.

Added Phosphorus ppm	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(8) Brookston loam Tuscola Co.	(11) Isabella loam Kent Co.
0	.08	.40	.87	2.01	.02
40	3.03	4.48	6.09	5.37	.80
80	4.43	4.60	6.24	5.09	1.95
160	4.46	4.41	7.05	6.40	3.37
320	4.44	4.80	6.29	6.02	5.09

Added Phosphorus ppm	(12) Isabella sandy loam Isabella Co.	(14) Conover clay loam Macomb Co.	(15) Napanee loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(19) Emmet sandy loam Leelanau Co.
0	.10	.80	.86	.27	.25
40	3.69	6.31	6.53	1.03	3.62
80	3.84	7.55	7.51	1.73	4.14
160	5.04	7.57	8.60	2.02	4.43
320	5.25	7.58	8.82	1.51	4.65

Plate 8. Brookston loam from Kent county (soil 4) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 9. Brookston loam from Gratiot county (soil 5) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus addition in ppm are 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 10. Brookston loam from Gratiot county (soil 6) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 11. Brookston loam from Tuscola county (soil 8) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 12. Isabella loam from Kent county (soil 11) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 13. Isabella sandy loam from Isabella county (soil 12) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 14. Conover clay loam from Macomb county (soil 14) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 15. Napanee loam from Macomb county (soil 15) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 16. Oshtemo loamy sand from Clinton county (soil 18) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 17. Emmet sandy loam from Leelanau county (soil 19) showing effect of added phosphorus on growth of tomatoes May 16, 1949. Phosphorus additions in ppm are: 1 = 0, 2 = 40, 3 = 80, 4 = 160 and 5 = 320.

Plate 18. A comparison between Brookston loam from a cultivated field in Gratiot county (bottom) and a corresponding soil sample collected from an adjoining fence row (top). Numbers correspond to phosphorus treatments as mentioned in Plates 9 and 10.

Plate 19. A comparison between Brookston loam from Tuscola county (top) and Brookston loam from Kent county (bottom). Numbers correspond to phosphorus treatments as mentioned in Plates 8 and 11.

Plate 20. A comparison between Isabella sandy loam from Isabella county (top) and Isabella loam from Kent county (bottom). Numbers correspond to phosphorus treatments as mentioned in Plates 12 and 13.

Plate 21. The comparative response of tomatoes on various soils to added phosphorus (bottom row received no phosphorus, top row 320 ppm). Soils are as follows: 1 = Brookston loam from Tuscola county (soil 8), 2 = Conover clay loam from Macomb county (soil 14), 3 = Brookston loam from Kent county (soil 4), 4 = Napanee loam from Macomb county (soil 15) and 5 = Brookston loam from Gratiot county (soil 6).

Plate 22. The comparative response of tomatoes on various soils to added phosphorus (bottom row received no phosphorus, top row 320 ppm). Soils are as follows: 1 = Brookston loam from Gratiot county (soil 5), 2 = Oshtemo loamy sand from Clinton county (soil 18), 3 = Isabella loam from Kent county (soil 11), 4 = Isabella sandy loam from Isabella county (soil 12) and 5 = Emmet sandy loam from Leelanau county (soil 19).

Even on the rather fertile heavy Brookston soils and such others as the Conover and Napanee, the growth on the untreated cultures was not great. However, these plants were apparently normal in appearance except due to the small stunted growth as a result of a lack of sufficient available phosphorus in the soil.

In most instances the greatest response to added phosphorus occurred with the first increment or the addition of 40 ppm of soluble phosphorus in the form of $Ca(H_2PO_4)_2 \cdot H_2O$. The only instances of appreciable response beyond this level were in the case of the Brookston soil from Kent county (soil 4), the Oshtemo sand (soil 18), both Isabella soils (soils 11 and 12) and to a minor extent with the Emmet sandy loam (soil 19). All of these soils except the Emmet had performed similarly in the production of wheat.

With the more fertile soils and even with the Brookston soil from Kent county, there apparently was no appreciable benefit after the addition of 160 ppm of phosphorus. In most of these cases the benefit was actually negligible after the addition of 80 ppm of phosphorus.

With the tomatoes, as with the wheat plants, great differences were noted among the soils. These differences were not as great between the soils as within a given soil especially after the first addition of phosphorus. The heavy Brookston soils and such related heavy soils as the Napanee and Conover soils were definitely superior to the lighter loams, and sands such as the Isabella soils, Oshtemo sand and Emmet sandy loam. However, with the exception of Oshtemo sand, satisfactory growth was possible on these provided an adequate supply of phosphorus was furnished the soil.

Chemical Analyses of Plant Material for Phosphorus

The Phosphorus Content and Total Phosphorus Removed by Wheat Plants from the Various Soils

The data presented in Table 11 show several interesting and significant facts. The percentage phosphorus content of the straw had a tendency to show a decline or no great increase in amount for most of the soils after the addition of the first increment of added phosphorus. There is a definite drop in percentage composition of phosphorus on such soils as the Brookston silt loam from Macomb county (soil 2), the Brookston loam from Kent county (soil 4), the Brookston loam from Clinton county (soil 7), the Miami loam from Clinton county (soil 9), the Isabella sandy loam from Isabella county (soil 12), the Conover loam from Clinton county (soil 13), the Kent silt loam (soil 16), the Clyde clay loam (soil 17), the Oshtemo sand (soil 19) and the muck (soil 20).

Reference to Table 8 shows that for each of these soils there occurred a marked stimulation in the weight of wheat heads produced on each of these soils and no doubt this pronounced stimulation in amount of wheat head formation accounted for the lowering of the phosphorus percentage in the straw. In the case of the Oshtemo sand another very marked depression occured in this percentage where the rate of phosphorus application was 80 ppm . This again coincides with a tremendous increase in the weight of wheat heads formed for this particular soil. Therefore, at least at the levels of phosphorus addition of 80 ppm or less, the actual percentage composition of the straw apparently depended more upon the stimulation of wheat level production than upon any other single factor. It cannot, however, be concluded that this stimulation of wheat head formation is related to the number of wheat heads formed. Reference to the data presented in Table 6 will reveal that, especially on the Oshtemo sand, there was no appreciable stimulation in number of heads. The same general condition holds for other of the above specified soils. Therefore, stimulation in the size of head and extent of grain development was undoubtedly of greater importance than actual numbers of heads formed.

For the majority of the soils a very marked stimulation in percentage composition of phosphorus in the wheat straw occurred, especially where 160 ppm of phosphorus had been

Table 11. Mean* percentage phosphorus expressed in terms of elemental P of wheat straw produced per treatment for the various soils according to various levels of added phosphorus.

Added Phos-phorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co.	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.	(9) Miami loam Clinton Co.
0	.164	.126	.176	.132	.100	.078	.096	.119
20	.178	.115	.176	.114	.148	.096	.088	.100
40	.208	.125	.180	.114	.172	.126	.148	.097
80	.187	.159	.186	.138	.177	.155	.148	.106
160	.244	.234	.204	.138	.226	.212	.240	.222

Added phos-phorus ppm	(10) Miami loam Tuscola C o.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent Silt loam Kent Co.	(17) Clyde clay loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(20) Muck Eaton Co.
0	.127	.129	.151	.133	.094	.120	.154	.158
20	.125	.129	.120	.113	.087	.090	.053	.145
40	.134	.123	.152	.104	.082	.124	.128	.204
80	.158	.134	.146	.115	.124	.106	.071	.162
160	.190	.143	.226	.256	.188	.172	.119	.159

* Mean of 2 replicates

added. This did not hold for the Brookston loam from Kent county (soil 4) and the Muck (soil 20) but in the case of the other soils the increase was very large.

There was some variation in percentage composition from one soil to another but this was much less than the other plant factors previously discussed.

The percentage phosphorus values for the wheat heads showed considerably less variation than did the corresponding data for the wheat straw. In the case of many of the values reported in Table 12, there was apparently little or no influence of added phosphorus upon the actual composition of the heads produced.

There were certain rather marked exceptions to this general statement. In the case of both of the Brookston loams from Gratiot county (soils 5 and 6) there was a pronounced tendency for an increased percentage of phosphorus to result with the increasing levels of added phosphorus to the soil. The same situation held for the two Isabella soils (soils 11 and 12) and for the Kent silt loam soil from Kent county (soil 16).

An interesting occurrence took place in the case of the Oshtemo sand. The addition of 20 ppm of phosphorus to the soil resulted in a very low content of this element in the heads. This seemingly can be explained upon the basis of the fact that this addition of phosphorus to the soil nearly doubled the formation of wheat heads as evidenced in Table 8.

Succeeding additions of phosphorus to this same soil resulted in an increase in the phosphorus content of the heads produced by this soil.

The weight of phosphorus taken up in the straw indicated that for most of the soils there was a tendency for the plants to contain more phosphorus in the straw in accordance with each increment of added phosphorus. This was very definitely true for the two upper levels of phosphorus on all except the muck soil.

There were certain exceptions to this tendency in the lower levels, however. Particularly for the first addition of 20 ppm in the case of such soils as the Brookston silt loam from Macomb county (soil 2), the Brookston loam from Clinton county (soil 7), the Miami loam from Clinton county (soil 9), the Conover loam from Clinton county (soil 13), the Clyde clay loam from Macomb county (soil 17), the Oshtemo sand (soil 18) and the Muck from Eaton county (soil 20), the straw actually contained less total phosphorus than the straw from the same soil where no phosphorus was added. All of these soils showed a marked increase in the weights of heads produced and it must, therefore, be assumed that this stimulation of head formation resulted in a heavy removal of phosphorus from the stems and leaves of the plant later in the growth period and thus the straw produced actually contained less total phosphorus than did that grown on untreated soil. On most of the other soils, however, there was a great increase in the total phosphorus

Table 12. Mean* percentage phosphorus expressed in terms of elemental P of wheat heads produced per treatment for the various soils according to various levels of added phosphorus.

Added Phosphorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co.	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.	(9) Miami loam Clinton Co.
0	.40	.36	.39	.41	.31	.38	.38	.43
20	.43	.40	.45	.44	.43	.42	.38	.42
40	.43	.42	.41	.43	.46	.47	.44	.42
80	.43	.41	.45	.48	.43	.48	.48	.43
160	.43	.38	.44	.45	.46	.48	.42	.45

Added Phosphorus ppm	(10) Miami loam Tuscola Co.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent Silt loam Kent Co.	(17) Clyde Clay loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(20) Muck Eaton Co.
0	.42	.31	.35	.43	.31	.34	.35	.42
20	.41	.37	.32	.41	.32	.33	.27	.41
40	.42	.42	.37	.41	.37	.37	.37	.41
80	.41	.45	.40	.45	.44	.37	.42	.43
160	.45	.45	.42	.47	.44	.46	.41	.43

* Mean of 2 replicates

content of the straw at this soil phosphorus level.

The major portion of the phosphorus contained in the plant was in the head portion as evidenced by comparing the data in Table 14 with that of Table 13 in all the soils except the Brookston silt loam from Macomb county (soil 1). Even in this case at all levels except the highest, 160 ppm, there was a slightly greater amount in the grain than in the straw.

The tendency for the straw of the wheat plants to contain less phosphorus after the addition of 20 ppm of phosphorus on certain soils did not persist in the case of the heads of the plants. In all cases the heads at this level contained more total phosphorus than did those grown on untreated soil. This clearly emphasizes the importance of phosphorus in the role of the head formation.

Generally speaking, the succeeding increments of added phosphorus resulted in a greater total accumulation of phosphorus in the heads although this tendency was by no means absolute nor always particularly pronounced. Therefore, it appeared that after a certain amount of phosphorus entered into the formation of heads, this portion of the plant did not take up excessively great additional amounts.

There was again great variation between the individual soils. This variation followed the same general trend as was usually noted for other characteristics of the wheat plants previously discussed.

Table 13. Mean* weight of phosphorus expressed in milligrams taken up by wheat straw per treatment for the various soils according to various levels of added phosphorus.

Added Phosphorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co.	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.	(9) Miami loam Clinton Co.
0	32.5	23.6	25.8	10.5	11.0	7.3	14.2	17.3
20	39.6	22.1	27.0	12.9	21.6	16.6	13.1	14.8
40	44.3	28.1	30.5	16.3	26.1	20.1	25.7	16.2
80	45.7	35.0	36.4	18.6	28.6	26.0	36.1	18.8
160	58.8	63.5	46.9	23.9	36.7	37.8	47.3	38.6

Added Phosphorus ppm	(10) Miami loam Tuscola Co.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent silt loam Kent Co.	(17) Clyde Clay loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(20) Muck Eaton Co.
0	16.4	3.0	7.9	18.5	23.1	28.3	4.2	27.5
20	19.0	8.7	12.6	17.6	18.3	24.8	1.3	23.9
40	22.6	9.7	17.9	16.8	20.2	33.0	7.0	26.2
80	27.9	14.7	19.8	18.0	32.5	28.9	5.2	28.8
160	36.7	17.5	31.5	42.7	47.1	49.2	10.2	28.3

* Mean of 2 replicates.

The total weight of phosphorus taken up by the plants, as presented in Table 15, more nearly reflects the actual uptake of phosphorus from each of the soils at the various levels than did either of the previous sets of data considered individually.

The various soils, except for the Muck, each had a tendency to release phosphorus in accordance with the level of added phosphorus. The Muck soil used in this experiment seemingly did not behave at all like the other soils, all of which are of mineral nature. The only other notable exception where the first increment of added phosphorus did not result in at least as much or more of this element in the plants was in the case of the Oshtemo sand. With this soil there was actually less total phosphorus in the plant material after the addition of 20 ppm of phosphorus than at any other level on any soil. This probably can be explained upon the basis of poor growth for the two replicates of this particular culture. Although ten plants were allowed to remain in each jar, only eight heads of wheat were produced on one jar. Therefore, it may have been the result of nothing more than abnormally poor plant growth that resulted in this particular exception. Only one other individual jar in the whole series produced so poorly in the entire series of jars and that was on an untreated jar of the Brookston loam from Kent county.

A consideration of the individual soils with regard to the total phosphorus released to plants indicates as great a variation as was true for the other factors previously considered. The Oshtemo sand, on the basis of these data, was the poorest soil for releasing phosphorus to plants. No doubt part of this is due to the tenacity with which the added phosphorus is held by the soil. This would be in accordance with the availability figures presented in Table 5 for this soil upon the basis of extraction with Spurway's active extracting solution. However, with the strong acid extraction of either Spurway or Bray this apparent unavailability was not in evidence. Therefore, the inability of this soil to release a large amount of phosphorus seemingly cannot entirely be attributed to a low phosphorus availability. The possibility of a lack of minor nutrient elements as a limiting growth factor cannot be entirely overlooked as this material was essentially pure sand. The possibility of unfavorable physical condition must also be considered as this material is entirely without compound soil structure and no doubt the possibility of poor aeration and other limiting physical factors does exist.

The remaining soils, with the exception of the Oshtemo sand and Muck as mentioned above behaved more or less in a regular fashion. There were soils such as the two Isabella soils (soils 11 and 12), the two Brookston loams (soils 6

Table 15. Mean* weight of phosphorus expressed in milligrams contained in the entire wheat plants per treatment for the various soils according to various levels of added phosphorus.

Added Phos-phorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co.	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.	(9) Miami loam Clinton Co.
0	70.7	58.4	56.6	25.0	30.8	30.1	49.8	62.5
20	84.4	76.8	76.7	49.3	57.2	59.0	62.8	69.2
40	88.7	92.1	76.8	57.3	64.2	69.5	64.4	74.3
80	101.5	96.4	102.2	68.8	74.6	77.2	95.3	85.8
160	109.3	126.3	115.2	77.0	87.2	103.0	104.4	103.7

Added Phos-phorus ppm	(10) Miami loam Tuscola Co.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent silt loam Kent Co.	(17) Clyde clay loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(20) Muck Eaton Co.
0	51.5	7.8	22.1	52.3	72.6	87.7	9.1	69.4
20	62.6	27.0	44.2	69.4	80.3	87.7	6.7	66.1
40	67.5	39.1	52.7	69.3	85.0	95.4	14.8	59.9
80	70.2	50.4	69.6	75.7	108.0	103.5	34.6	74.4
160	88.8	55.9	92.0	105.2	117.8	149.2	38.7	79.2

* Mean of 2 replicates

and 7) and the Brookston loam from Kent county (soil 4) which, expecially in the case of the untreated cultures, were able to release only comparatively small amounts of phosphorus. However, where soluble phosphorus was added, these soils were able to release a considerable amount at the upper levels and for the most part plant growth was at least moderately satisfactory. Therefore, the low supplying powers is at least in part due to an initial very low supplying power for these soils.

The Phosphorus Content and Total Phosphorus Removed by Tomato Plants From the Various Soils

Data relative to the percentage phosphorus composition and total phosphorus contained in the tomato plants are presented in Table 16. The tomato plants reflected much greater variation in both these values than did the wheat plants previously discussed.

It was previously noted that in the case of the yield of tomato plants the increase was actually rather small after the addition of 80 ppm of phosphorus to the soil. This same statement cannot be made for either the percentage phosphorus contained in the plant or the total accumulation of phosphorus by a plant.

Each addition of phosphorus resulted in an increased percentage of this element in the plant with the exception

Table 16. Mean* percentage composition and mean total uptake of phosphorus by tomatoes per treatment for the various soils according to various levels of added phosphorus.

Added Phosphorus ppm	(4) Brookston loam Kent Co.		(5) Brookston loam Gratiot Co.		(6) Brookston loam Gratiot Co.		(8) Brookston loam Tuscola Co.		(11) Isabella loam Kent Co.	
	%	Mgm.	%	Mgm	%	Mgm	%	Mgm	%	Mgm
0	.145	.115	.185	1.73	.185	1.60	.150	3.03	.150	.03
40	.215	6.50	.205	9.23	.210	12.80	.195	10.48	.150	1.20
80	.280	12.31	.425	19.70	.405	25.27	.400	20.55	.230	4.51
160	.400	17.80	.59	25.95	.605	42.50	.340	21.45	.310	10.45
320	.505	22.35	.78	37.50	.740	46.55	.500	29.60	.460	23.57

Added Phosphorus ppm	(12) Isabella sandy loam Isabella Co.		(14) Conover clay loam Macomb Co.		(15) Napanee loam Macomb Co.		(18) Oshtemo loamy sand Clinton Co.		(19) Emmet sandy loam	
	%	Mgm	%	Mgm	%	Mgm	%	Mgm	%	Mgm
0	.130	.12	.155	1.27	.190	1.60	.210	.52	.105	.26
40	.300	10.69	.160	10.04	.170	11.10	.220	2.26	.285	10.40
80	.365	14.33	.245	18.60	.215	16.12	.450	7.41	.470	19.48
160	.540	27.30	.385	29.30	.345	29.70	.550	11.25	.680	30.13
320	.740	38.93	.540	41.00	.540	47.50	.580	8.68	.820	38.15

* Mean of 2 replicates.

of two instances. In the case of the Isabella loam from Kent county (soil 11) the first increment of added phosphorus yielded plants with no higher percentage of phosphorus than those from the untreated soil. However, the plants on the untreated soil made almost no growth whereas those at the level of 40 ppm of added phosphorus made a significant growth. The other exception was the instance of a slight decrease in percentage composition of phosphorus at this same level in the case of the Napanee loam (soil 15). Here again a very marked increase in growth accompanied this addition so that the total recovery of added phosphorus was much greater than on the untreated soil.

The percentage composition of the tomato plants for phosphorus was over 0.70% in several instances and as high as 0.82% in one instance at the upper level of added phosphorus (320 ppm). This was probably much higher than was needed for maximum growth up to the stage of maturity to which these plants had progressed. It is somewhat difficult to predict from the data exactly where the minimum percentage composition for maximum growth did occur in tomatoes under these conditions. That is due to the fact that there was such a large increase in actual percentage composition for each added level and also because it is difficult to estimate the exact point where increased growth no longer resulted. However, in a general way it seems as though a percentage composition of approximately 0.40 - 0.45% phosphorus in the tomato plant was approximately enough to insure maximum growth up to the time of harvest. However, it should not be interpreted that such a level would be sufficient to insure maximum growth to a more advanced state of maturity.

Assuming a hypothetical desired percentage composition in the range of 0.40 - 0.45% for tomatoes, then it is possible to compare the relative phosphorus supplying powers of the soil. Such soils as the Brookston loam from Kent county (soil 4), the Conover clay loam from Macomb county (soil 14), the Napanee loam from Macomb county (soil 11) needed a considerably greater quantity of added phosphorus to attain this desired effect. Similar observations have previously been noted for this particular Brookston soil and the Isabella soil in the case of both the chemically measured phosphorus and the wheat yield results.

However, it cannot be concluded that either the Napanee or the Conover soil mentioned above were of inferior capability insofar as phosphorus supplying power is concerned. If the total milligrams of phosphorus contained in the plant are considered, it is seen that either of these soils compare favorably in this regard with either of the Brookston silt loams from Gratiot county (soils 5 and 6) and actually exceed the other Brookston soils included in this investigation.

Further consideration of the total recovery of phosphorus in the upper portions of the tomato plants suggested that again both the Brookston loam and the Isabella loam from Kent county as well as the Oshtemo sand must be ranked inferior to the other soils included in this study. However, at least some attention to factors other than phosphorus fertility, which may have entered into the picture, must be given the Oshtemo sand. The plants actually attained the previously mentioned desired level of 0.45% phosphorus with the addition of only 80 ppm of phosphorus to this soil yet plant growth increase was negligible beyond this point despite the fact that a higher percentage of phosphorus was contained. The possibility of minor element deficiency in this soil material or the presence of an undesirable physical condition has previously been mentioned and seemingly is once again indicated in the case of the tomato plant growth and phosphorus relationships.

The Yield of a Second Crop of Tomatoes on the Same Soils Previously Utilized for Tomato Production

Tomatoes were grown as a second crop on the same soils discussed in connection with Table 10. The mean weights of the plants produced as a result of this cropping are presented in Table 17.

The plants did not attain as much size during the course of this second growth as did the initial crop. No doubt this was due to a more or less general depletion of soil nutrients, including the available phosphorus.

In the case of the first crop it has already been noticed that there was a tendency for the tomatoes to attain maximum size at the addition of 80 to 160 ppm of phosphorus. However, such was not the case with the second crop. It can probably be concluded that four of the soils produced a maximum growth for this second crop at the 160 ppm level of added phosphorus. These soils are the two Brookston loams from Gratiot county (soils 5 and 6), the Brookston loam from Tuscola county (soil 8), and the Conover clay loam from Macomb county (soil 14). These soils are apparently the most productive ones included in this study since the greatest yield of tomatoes resulted for this crop at a lower level of added phosphorus than it did on the other soils.

The Napanee loam from Macomb county presented an interesting situation. This soil produced the largest yield of tomatoes at all levels of added phosphorus for the first crop and yielded especially well at the two highest levels. However, with regard to the second crop it was definitely inferior to several of the other soils. Apparently, this soil was able to make accessible to plant utilization at the time of the first crop a large percentage of its more available portion of phosphorus and thus the second crop of

Table 17. Mean* dry weight expressed in grams for tomatoes of the second crop per treatment for the various soils according to the various levels of added phosphorus.

Added Phosphorus ppm	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(8) Brookston loam Tuscola Co.	(11) Isabella loam Kent Co.
0	.3	.3	.5	1.0	.2
40	.6	1.3	4.5	3.9	.3
80	1.5	1.8	5.0	4.5	.5
160	2.9	3.9	5.4	5.0	.4
320	3.2	3.9	4.3	4.5	1.6

Added Phosphorus ppm	(12) Isabella sandy loam Isabella Co.	(14) Conover clay loam Macomb Co.	(15) Napanee loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(19) Emmet sandy loam Leelanau Co.
0	.4	.5	.4	.2	.3
40	1.0	3.1	2.5	.4	.8
80	1.8	4.4	2.0	.5	1.7
160	3.3	5.2	1.4	.8	1.9
320	4.3	4.3	1.2	1.3	3.1

* Mean of 2 replicates.

tomatoes was inadequately furnished with this element. The total uptake of phosphorus by the first crop was relatively large but not any more so than on the two Brookston loams from Gratiot county. Therefore, it appeared as though the Napanee was initially comparable to the Brookston soils insofar as supplying phosphorus, but at the time of the second crop some factor of fertility was lacking and thus the soil became definitely inferior to the Brookston soils mentioned above.

The inferior qualities of such soils as the Isabella loam from Kent county (soil 11) and the Oshtemo sand (soil 18) were again apparent in the growth of this second crop of tomatoes. The Brookston loam soil from Kent county (soil 4) though behaving much like the Isabella soil from the same county in previously discussed characteristics was definitely superior to the latter in this trial.

A photographic record is presented in Plates 23 to 32, inclusive of this second crop of tomatoes. The numbers of each jar in these photographes correspond to that of the original treatment as explained previously. A comparison of all soils is provided in Plate 33.

Plate 23. The second crop of tomatoes on Brookston loam from Kent county (soil 4).

Plate 24. The second crop of tomatoes on Brookston loam from Gratiot county (soil 5).

Plate 25. The second crop of tomatoes on Brookston loam from Gratiot county (soil 6).

Plate 26. The second crop of tomatoes on Brookston loam from Tuscola county (soil 8).

Plate 27. The second crop of tomatoes on Isabella loam from Kent county (soil 11).

Plate 28. The second crop of tomatoes on Isabella sandy loam from Isabella county (soil 12).

Plate 29. The second crop of tomatoes on Conover clay loam from Macomb county (soil 14).

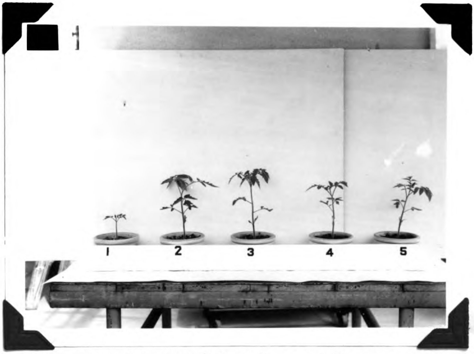

Plate 30. The second crop of tomatoes on Napanee loam from Macomb county (soil 15).

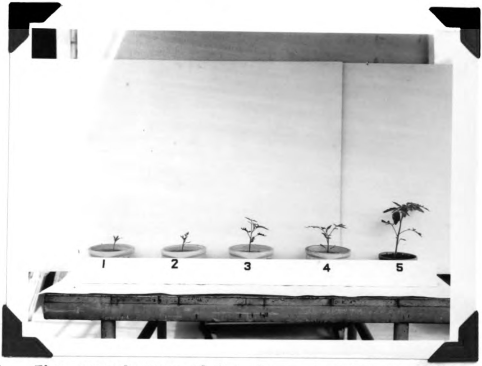

Plate 31. The second crop of tomatoes on Oshtemo loamy sand from Clinton county (Soil 18).

Plate 32. The second crop of tomatoes on Emmet sandy loam from Leelanau county (soil 19).

Plate 33. A comparison between tomatoes receiving the initial maximum amount of added phosphorus (320 ppm) for the various soils as follows:

Top row:
1.- Brookston loam from Tuscola county, (soil 8).
2.- Conover clay loam from Macomb county (soil14).
3.- Brookston loam from Kent county (soil 4).
4.- Napanee loam from Macomb county (soil 15).
5.- Brookston loam from Gratiot county (soil 6).

Bottom row:
1.- Brookston loam from Gratiot county (soil 5).
2.- Isabella loam from Kent County (soil 11).
3.- Oshtemo loamy sand from Clinton county (soil 18).
4.- Isabella sandy loam from Isabella county (soil 12).
5.- Emmet sandy loam from Leelanau county (soil 19).

The Yield of Tomatoes Following the Production of Wheat

Data are presented in Table 18 to indicate the dry weights of tomato plants produced following the growth of wheat. Due to considerable variability in the weights of plants as affected by treatment , it is doubtful whether or not these values indicate very much about the phosphorus fertility of a given soil.

There is some indication on such soils as 1, 2, 3, 5, 6, 9, 10, 11, 13, 16 and 17 that the yields tend to increase with each increment of added phosphorus and in this respect the behavior is perhaps similar to that previously noted. However, with certain of the other soils, especially the Oshtemo sand (soil 18) there is little evidence that the dry weight indicates any response to phosphorus. The growth was very poor in the various cultures of this soil suggesting once again the possibility of growth factors other than phosphorus fertility entering into the limitation of growth.

Probably the most significant fact indicated by the production of this crop was that of the considerable variation in the soils. As indicated above, the Oshtemo sand produced the poorest yield and also the Isabella loam from Kent county (soil 11) was a very poor growth medium. The Brookston loam from Kent county (soil 4) was comparatively inferior at the lower levels of phosphorus addition but at the upper levels this soil compared favorably with the other Brookston soils. Therefore, this soil behaved more favorably than did the Isabella loam from the same county.

An interesting comparison is afforded in the case of the two Brookston loam soils from Gratiot county. These soils are identical except for the fact that soil 6 was taken from an uncultivated fence row whereas soil 5 was obtained from a cultivated field. It was especially apparent in the case of this second crop of tomatoes following the wheat that the former was a much more favorable growth medium.

The Miami soils (soils 9 and 10), the Isabella sandy loam from Isabella county (soil 12) and the Conover loam from Clinton county (soil 13) all were satisfactory growth media at one or more of the various levels of added phosphorus. However, it was interesting to note that the Kent silt loam (soil 16) and especially the Clyde clay loam (soil 17) were somewhat superior to the majority of the soils. Both of these were collected from uncultivated areas. The Muck soil gave some little indication of response to added phorphorus at the time of this second cropping and this was the first indication of such response.

Plates 34 to 49, inclusive, provide a photographic record of the growth of tomato plants following wheat. The numbers for the various jars in each of these pictures indicate the following amounts of added phosphorus for the

Table 18. Mean* yield of tomato plants produced upon soils following the growth of wheat, expressed in grams of dry weight per treatment.

Added Phosphorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co.	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.	(9) Miami loam Clinton Co.
0	1.0	2.1	2.3	1.6	1.1	2.9	1.7	3.6
20	3.4	2.8	4.1	2.3	1.0	3.5	2.5	3.9
40	3.2	3.0	4.5	1.9	1.1	4.0	1.5	4.5
80	3.8	3.6	4.8	5.3	2.4	5.4	5.0	4.1
160	4.1	3.2	6.0	5.1	2.4	5.0	2.7	4.1

Added Phosphorus ppm	(10) Miami loam Tuscola Co.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent silt loam Kent Co.	(17) Clyde clay loam Macomb Co.	(18) Oshtemo loamy sand Clinton Co.	(20) Muck Eaton Co.
0	3.0	.2	1.5	1.6	3.7	2.3	.5	3.7
20	3.1	.4	1.8	3.0	3.4	5.0	.6	5.1
40	4.8	1.5	1.9	3.4	3.5	5.5	.7	4.9
80	4.8	1.7	1.6	3.1	6.0	6.9	1.7	5.9
160	5.8	2.5	4.5	4.7	6.0	10.4	.6	4.7

* Mean of 2 replicates.

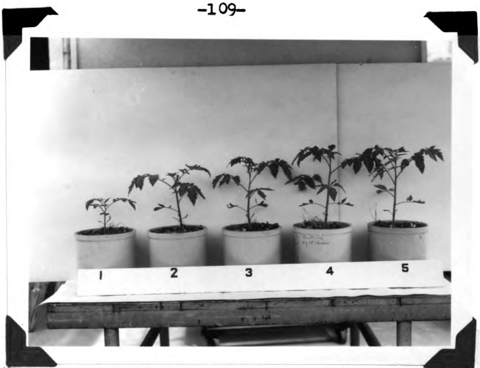

Plate 34. Tomatoes after wheat on Brookston silt loam from Macomb county (soil 1)

Plate 35. Tomatoes after wheat on Brookston silt loam from Macomb county (soil 2).

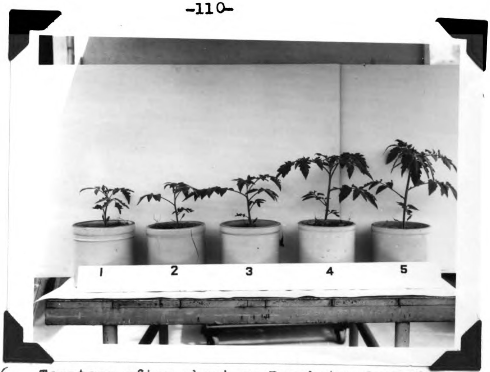

Plate 36. Tomatoes after wheat on Brookston loam from Saginaw county (soil 3).

Plate 37. Tomatoes after wheat on Brookston loam from Kent county (soil 4).

Plate 38. Tomatoes after wheat on Brookston loam from Gratiot county (soil 5).

Plate 39. Tomatoes after wheat on Brookston loam from Gratiot county (soil 6).

Plate 40. Tomatoes after wheat on Brookston loam from Clinton county (soil 7).

Plate 41. Tomatoes after wheat on Miami loam from Clinton county (soil 9).

Plate 42. Tomatoes after wheat on Miami loam from Tuscola county (soil 10).

Plate 43. Tomatoes after wheat on Isabella loam from Kent county (soil 11).

Plate 44. Tomatoes after wheat on Isabella sandy loam from Isabella county (soil 12).

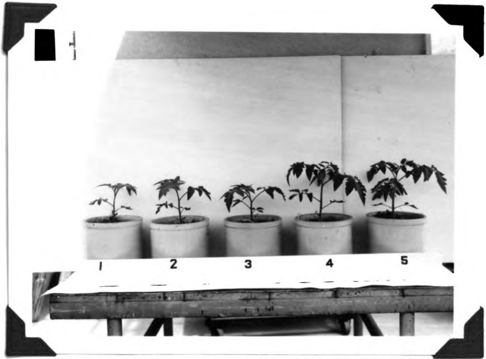

Plate 45. Tomatoes after wheat on Conover loam from Clinton county (soil 13).

Plate 46. Tomatoes after wheat on Kent silt loam from Kent county (soil 16).

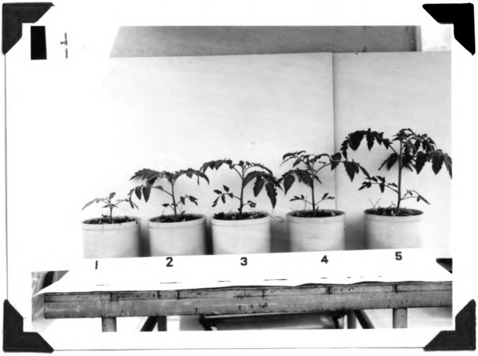

Plate 47. Tomatoes after wheat on Clyde clay loam from Macomb county (soil 17).

Plate 48. Tomatoes after wheat on Oshtemo loamy sand from Clinton county (soil 18).

Plate 49. Tomatoes after wheat on Muck from Eaton county (soil 20).

Plate 50. A comparison of tomatoes after wheat on Brookston loam from Gratiot county cultivated field (bottom row) with tomatoes on the same soil from an adjoining uncultivated fence row (top row).

initial crop of wheat: 1 = 0 ppm, 2 = 20 ppm, 3 = 40 ppm, 4 = 80 ppm and 5 = 160 ppm. Plate 50 provides a comparison between the cultivated and uncultivated field soils obtained from Gratiot county.

Relationship of Plant Growth Response to Available Phosphorus as Measured by Various Chemical Means.

The ultimate practical value of any chemical method for assaying soil fertility depends upon the suitability of that method for predicting plant growth response from the addition of a given quantity of the nutrient under consideration. Therefore, it was decided to measure the accuracy of certain of the chemical methods already described in terms of predicting plant growth response. Six of the chemical methods were considered in this manner. The two modified methods of Spurway's active extraction were not included because of their unsatisfactory behavior and because such modifications have never been actually used in a practical system of measuring the availability of soil phosphorus.

As pointed out by Bray (6) the German scientist Mitscherlich has carefully investigated plant growth response and shown that "the yield increases in proportion to the amount by which the current yield fails of the maximum yield, A". Mathematically this may be expressed:

$$\frac{dy}{dx} = (A - y)c \qquad (I)$$

where y = yield, x = amount of nutrient added per amount of soil, A = maximum yield, and c = proportionality constant. This equation may be intergrated and a "working equation" is provided as follows:

$$\text{Log } (A - y) = \text{Log } A - c(x + b) \qquad (II)$$

where A = maximum yield, y = yield obtained when x units of a nutrient are added to the soil, x = units of nutrient added per amount of soil, b = original nutrient content expressed in units of the added nutrient x, c = proportionality constant.

Equation (II) was found by Bray (6) to be unsatisfactory because of the inability to use the x value in his work because of insufficient data and, therefore he modified equation (II) as follows:

$$\text{Log } (A - y) = \text{Log } A - c_1 b_1 \qquad (III)$$

where c_1 = the proportionality constant, b_1 = the amount of nutrient in the surface soil as measured by the soil test, A = yield when potash is not deficient, y = yield when no potash is added. The value of this modified equation lies in the fact that it eliminates the value x, or fertilizer added, and can be applied directly to the experimental data where values for the chemically measured available portion of a nutrient are available. Bray originally applied the above concept to exchangeable potassium as related to plant growth response and subsequently to available phosphorus measurements as mentioned in the introduction of this paper. Therefore, it was decided to extend this concept to the phosphorus availability studies included in this investigation.

In order to calculate the c_1 value, it is necessary to evaluate A, y and b_1 in equation (III). Inasmuch as in the case of every soil there was one level of added phosphorus which produced a maximum yield it was decided to regard this as the yield obtainable when phosphorus was not deficient. This involves the assumption that sufficient added phosphorus had been applied to assure such a condition. Inasmuch as the equivalent of 3600 pounds per acre of 0-20-0 had been applied at the upper level, it does not seem illogical to make such an assumption. Also there were three instances where the maximum yield of wheat was attained before this point of application and in the other instances the trend of yields strongly suggests that the approximate ultimate maximum for each particular soil had been attained. Thus the yield at such levels was given the 100% yield value or became A in equation (III).

The value of y was in the case of each soil that value at each particular level of phosphorus availability below the maximum yield (100% yield) or the level of the A value. Therefore, all of the soils actually included in this evaluation are represented with four y values except three which have only three y values due to the fact that the maximum yield was attained with the level of 80 ppm of added phosphorus. The percentage yield values are presented in Table 19.

The b_1 values are the actual values for available phosphorus content as measured by the various methods previously mentioned. The values used are those obtained in the laboratory experiments as outlined under "Methods of Procedure".

By the use of equation (III) the c_1 values (proportionality constant values) were then calculated for each of the respective cultures where the yield was less than 100%.

The above calculations were made only for the wheat cultures and upon all soils except the Oshtemo sand and the Muck. The Oshtemo material is not a true soil in the usual sense and the muck material was not regarded as such and since little or no tendency to respond to added phosphorus was displayed by it these materials were omitted from mathematical consideration.

The yield of total wheat plant was used rather than either the straw or the head portion alone because it was believed that under the conditions of this greenhouse experiment the entire plant was a better criterion of growth response than either portion alone. The formation of heads was interfered with to a certain extent by the presence of smut and the maturity was somewhat irregular. Therefore, this portion was not used alone.

Graphical presentation is made of the plot of percentage yield versus actual content of chemically available phosphorus, as measured by each of the six mentioned methods, in Figures 21 to 26 inclusive. Also plotted in each case are the available phosphorus values for each soil corresponding to 100% yield. However, these b_1 values at 100% did not enter into the solving of the equation for the plot of the curve indicated.

The c_1 value was calculated for each yield (y) of less than 100% and these are presented in detail in Table 20. The mean of these was obtained and from this mean the curve for each plot was obtained.

Examination of each of the graphs suggests a more or less general correlation between available phosphorus content and percentage yield as indicated by the scatter of points in connection with the plot of the curve. This correlation does not appear to be outstanding in the case of either Figure 21 or 22 in which the two methods of Spurway were utilized. Considerable improvement is noted for the graphs in both Figures 23 and 24 where the field methods for extracting total available phosphorus and adsorbed phosphorus, respectively, at a ratio of 1 part of soil to 10 parts of solution were employed. Figure 25 in which a graph is made

Table 19. Percentage yield of total wheat plants for the various soils at various levels of added phosphorus.

Added Phosphorus ppm	(1) Brookston silt loam Macomb Co.	(2) Brookston silt loam Macomb Co.	(3) Brookston loam Saginaw Co.	(4) Brookston loam Kent Co.	(5) Brookston loam Gratiot Co.	(6) Brookston loam Gratiot Co.	(7) Brookston loam Clinton Co.
0	78.0	65.0	58.2	39.1	63.8	48.7	66.0
20	87.8	75.6	68.4	66.1	84.8	87.3	76.0
40	85.6	85.6	75.3	81.8	86.8	83.6	91.4
80	100.0	84.6	82.7	82.4	98.6	87.4	100.0
160	-	100.0	100.0	100.0	100.0	100.0	-

Added Phosphorus ppm	(9) Miami loam Clinton Co.	(10) Miami loam Tuscola Co.	(11) Isabella loam Kent Co.	(12) Isabella sandy loam Isabella Co.	(13) Conover loam Clinton Co.	(16) Kent silt loam Kent Co.	(17) Clyde clay loam Macomb Co.
0	74.8	69.4	19.5	32.4	72.7	87.4	81.5
20	84.3	83.4	55.4	71.7	94.0	87.1	93.4
40	91.6	86.8	71.9	76.3	96.8	88.8	86.2
80	100.0	90.1	89.2	91.6	95.2	93.8	94.0
160	-	100.0	100.0	100.0	100.0	100.0	100.0

Table 20. The c_1 values for the various soils used in calculating curves presented in Figures 21 to 26, respectively, according to method of chemical extraction.

Soil	(1) Spurway's Active	(2) Spurway's Reserve	(5) Bray's Total Available (1:10)	(6) Bray's Adsorbed (1:10)	(7) Bray's Total Available (1:50)	(8) Bray's Adsorbed (1:50)
(1) Brookston silt loam (Macomb Co.)	.1495	.0077	.0088	.0299	.0049	.0263
	.1755	.0097	.0102	.0365	.0057	.0217
	.1441	.0082	.0082	.0282	.0045	.0152
(2) Brookston silt loam (Macomb Co.)	.0760	.0046	.0053	.0207	.0040	.0130
	.0851	.0059	.0064	.0245	.0051	.0153
	.1078	.0067	.0079	.0263	.0058	.0191
	.0766	.0056	.0058	.0169	.0046	.0108
(3) Brookston loam (Saginaw Co.)	.0924	.0077	.0056	.0291	.0046	.0152
	.1192	.0086	.0061	.0238	.0049	.0152
	.1168	.0092	.0072	.0234	.0054	.0156
	.0964	.0099	.0066	.0218	.0057	.0139
(4) Brookston loam (Kent Co.)	.0720	.0360	.0114	.0166	.0114	.0114
	.1380	.0587	.0168	.0235	.0162	.0156
	.1850	.0616	.0211	.0264	.0154	.0189
	.1451	.0377	.0142	.0184	.0116	.0112

Table 20. Continued

Soil	(1)	(2)	(5)	(6)	(7)	(8)
(5) Brookston loam (Gratiot Co.)	.0690	.0090	.0074	.0260	.0066	.0158
	.1169	.0160	.0128	.0356	.0103	.0221
	.0916	.0135	.0107	.0259	.0090	.0169
	.1404	.0221	.0178	.0357	.0164	.0265
(6) Brookston loam (Gratiot Co.)	.0483	.0088	.0063	.0263	.0042	.0107
	.1165	.0195	.0155	.0498	.0116	.0242
	.0604	.0133	.0106	.0291	.0071	.0164
	.0327	.0086	.0075	.0150	.0056	.0115
(7) Brookston loam (Clinton Co.)	.1465	.0120	.0126	.0426	.0126	.0156
	.1107	.0124	.0117	.0364	.0092	.0159
	.1402	.0169	.0187	.0424	.0133	.0184
(9) Miami loam (Clinton Co.)	.1330	.0399	.0171	.0230	.0100	.0157
	.1461	.0402	.0179	.0243	.0120	.0183
	.1433	.0371	.0192	.0239	.0143	.0165
(10) Miami loam (Tuscola Co.)	.0827	.0142	.0114	.0228	.0097	.0171
	.0950	.0186	.0147	.0259	.0130	.0173
	.0956	.0176	.0140	.0225	.0119	.0160
	.0661	.0143	.0101	.0170	.0097	.0121

Table 20. Continued

Soil	(1)	(2)	(5)	(6)	(7)	(8)
(11) Isabella	.0785	.0157	.0039	.0052	.0047	.0050
loam	.2923	.0351	.0110	.0146	.0106	.0117
(Kent Co.)	.3935	.0344	.0125	.0153	.0102	.0104
	.6040	.0386	.0149	.0169	.0121	.0125
(12) Isabella	.0708	.0284	.0077	.0170	.0085	.0085
sandy loam	.1053	.0391	.0196	.0261	.0166	.0183
(Isabella	.0782	.0272	.0145	.0184	.0142	.0142
Co.)	.0620	.0197	.0130	.0166	.0124	.0135
(13) Conover	.1062	.0219	.0144	.0322	.0094	.0182
loam	.1746	.0350	.0244	.0452	.0170	.0291
(Clinton	.1299	.0356	.0230	.0415	.0178	.0234
Co.)	.0732	.0188	.0143	.0219	.0105	.0171
(16) Kent silt	.1873	.0346	.0204	.0499	.0209	.0243
loam	.1327	.0287	.0174	.0404	.0171	.0202
(Kent Co.)	.1285	.0264	.0170	.0396	.0142	.0173
	.0693	.0183	.0144	.0274	.0087	.0127
(17) Clyde clay	.1665	.0141	.0144	.0458	.0081	.0222
loam	.2270	.0211	.0197	.0694	.0121	.0295
(Macomb Co.)	.1195	.0121	.0123	.0308	.0072	.0172
	.1329	.0165	.0157	.0394	.0099	.0231

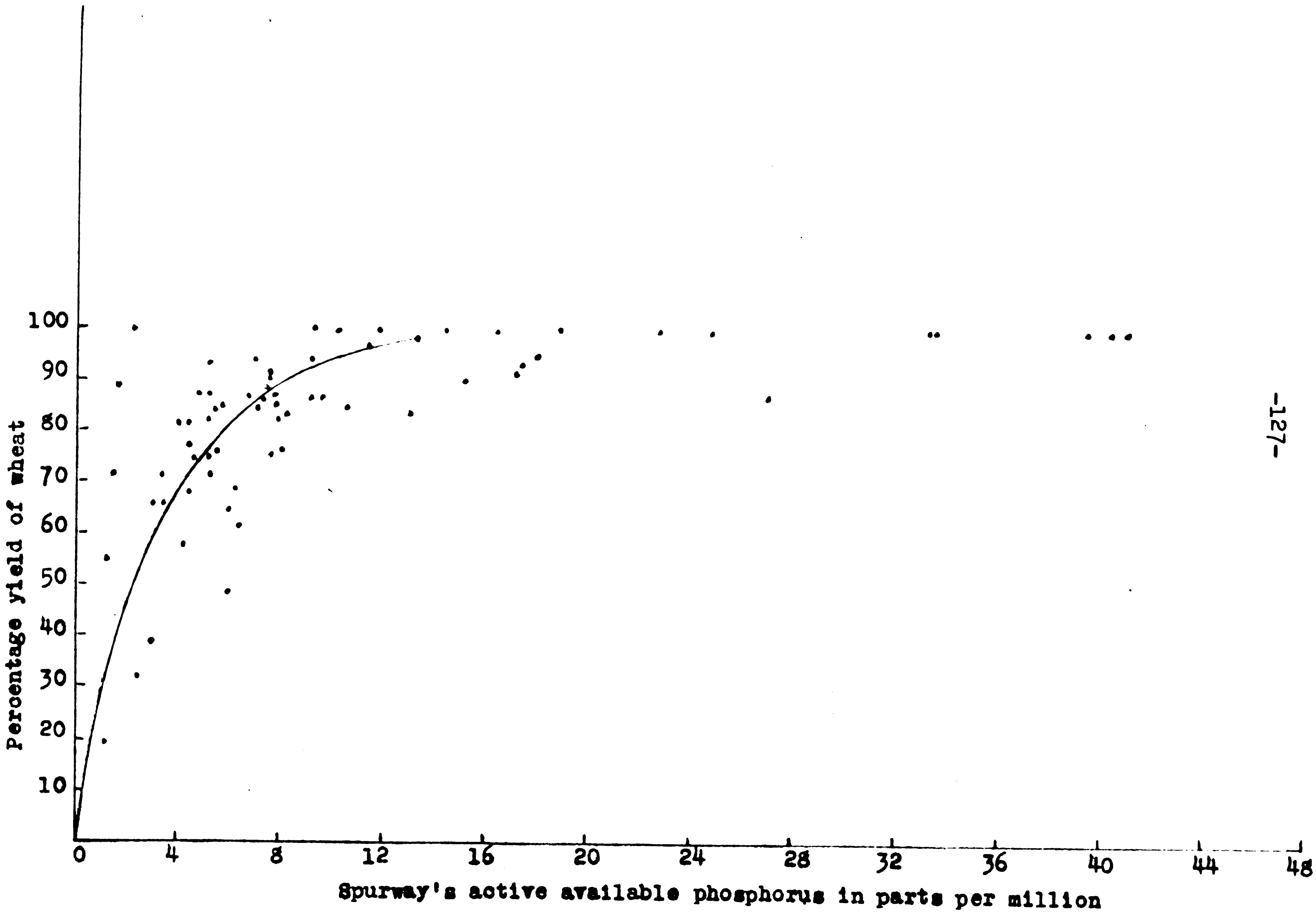

Figure 21. Relationship between active available phosphorus and total yield of wheat.

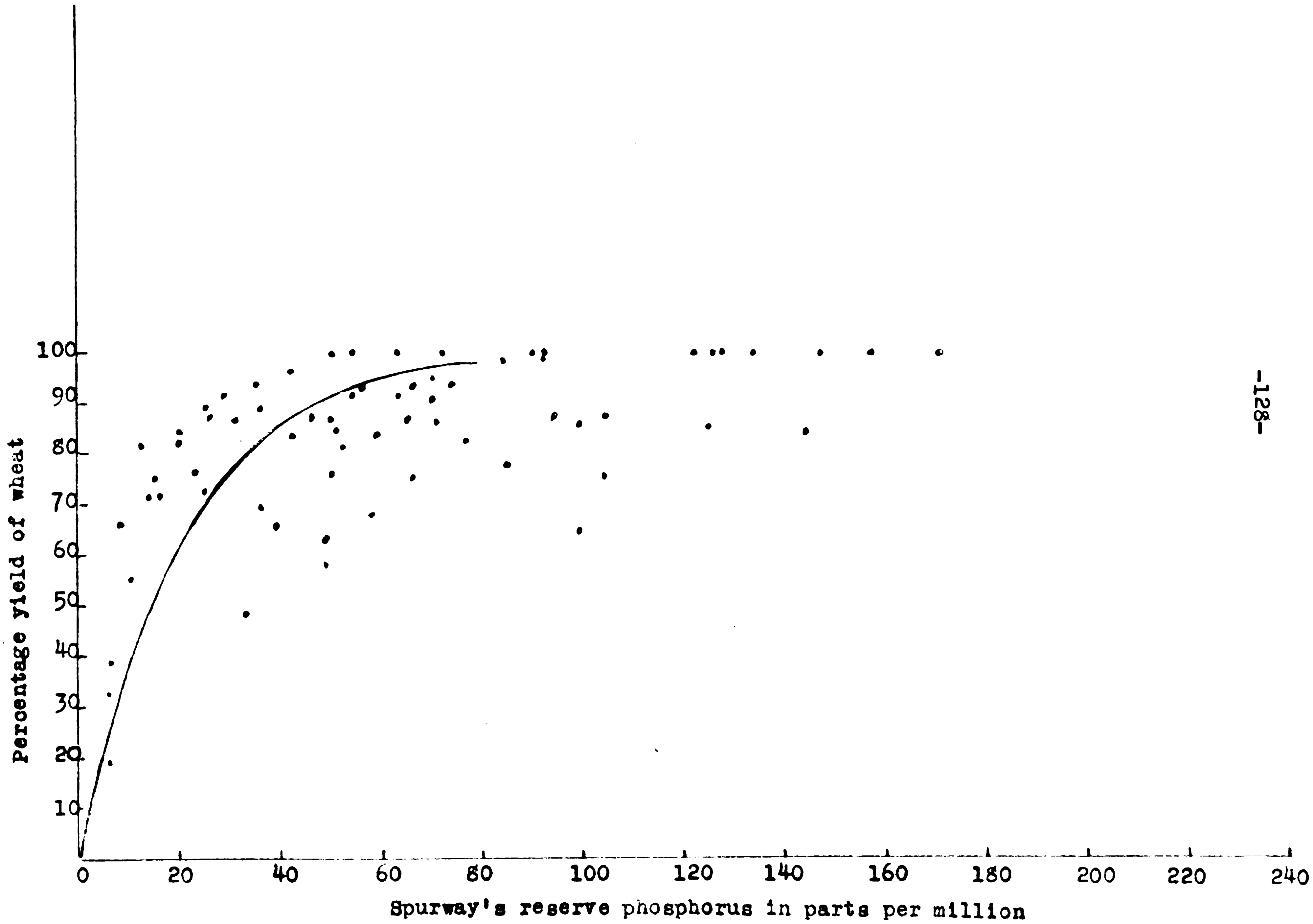

Figure 22. Relationship between reserve phosphorus and total yield of wheat.

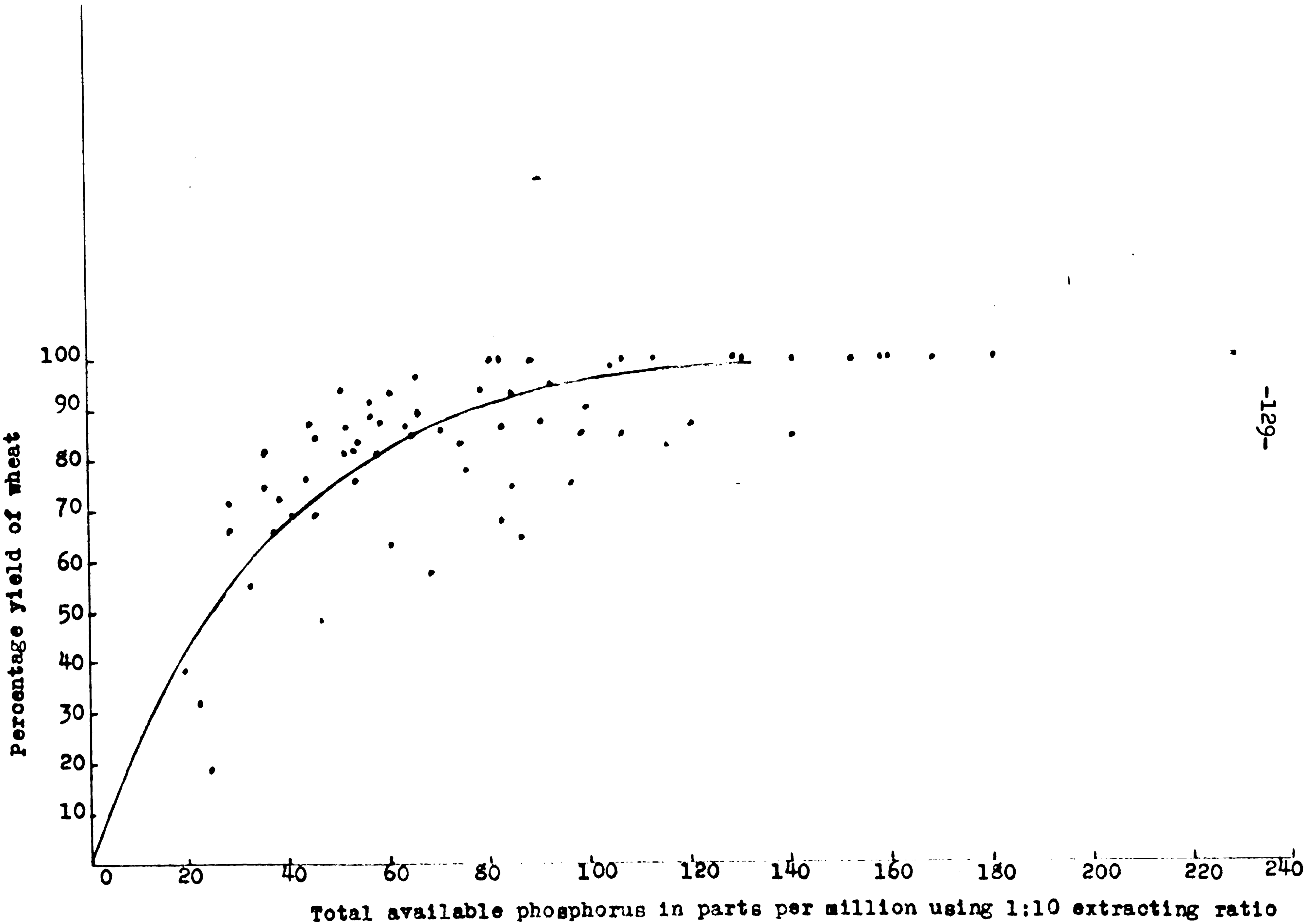

Figure 23. Relationship between total available phosphorus and yield of wheat.

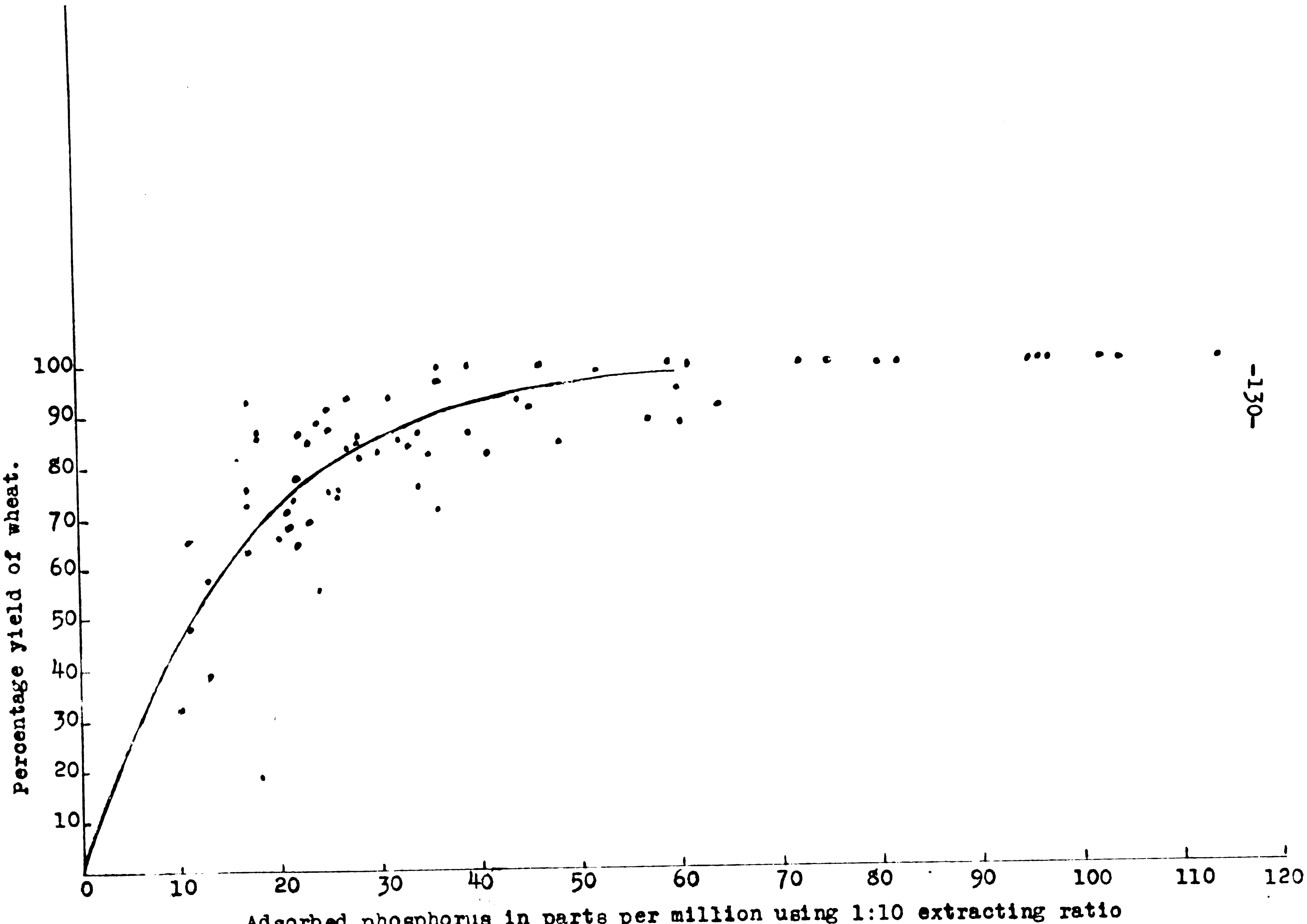

Figure 24. Relationship between adsorbed phosphorus and total yield of wheat.

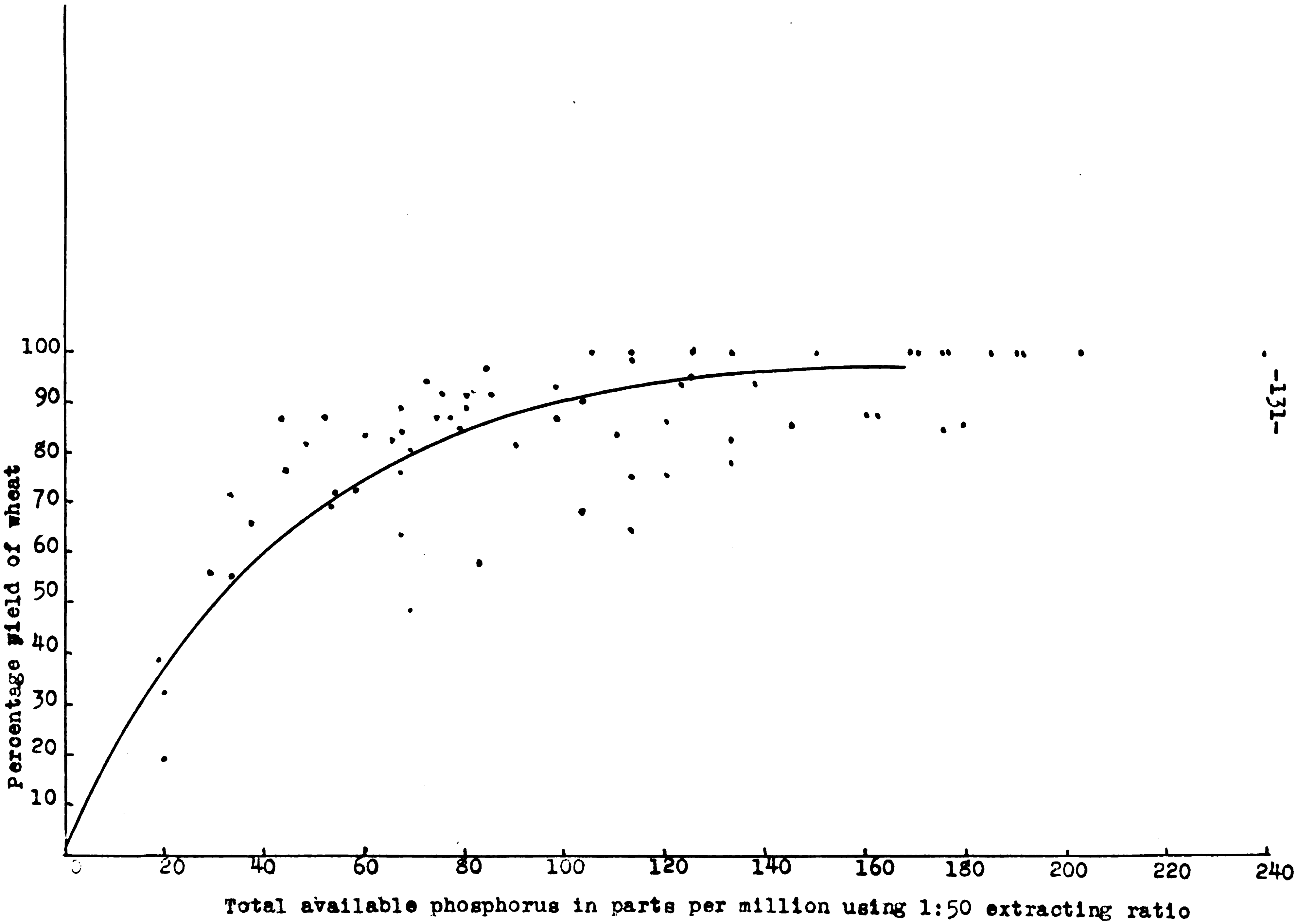

Figure 25. Relationship between total available phosphorus and yield of wheat.

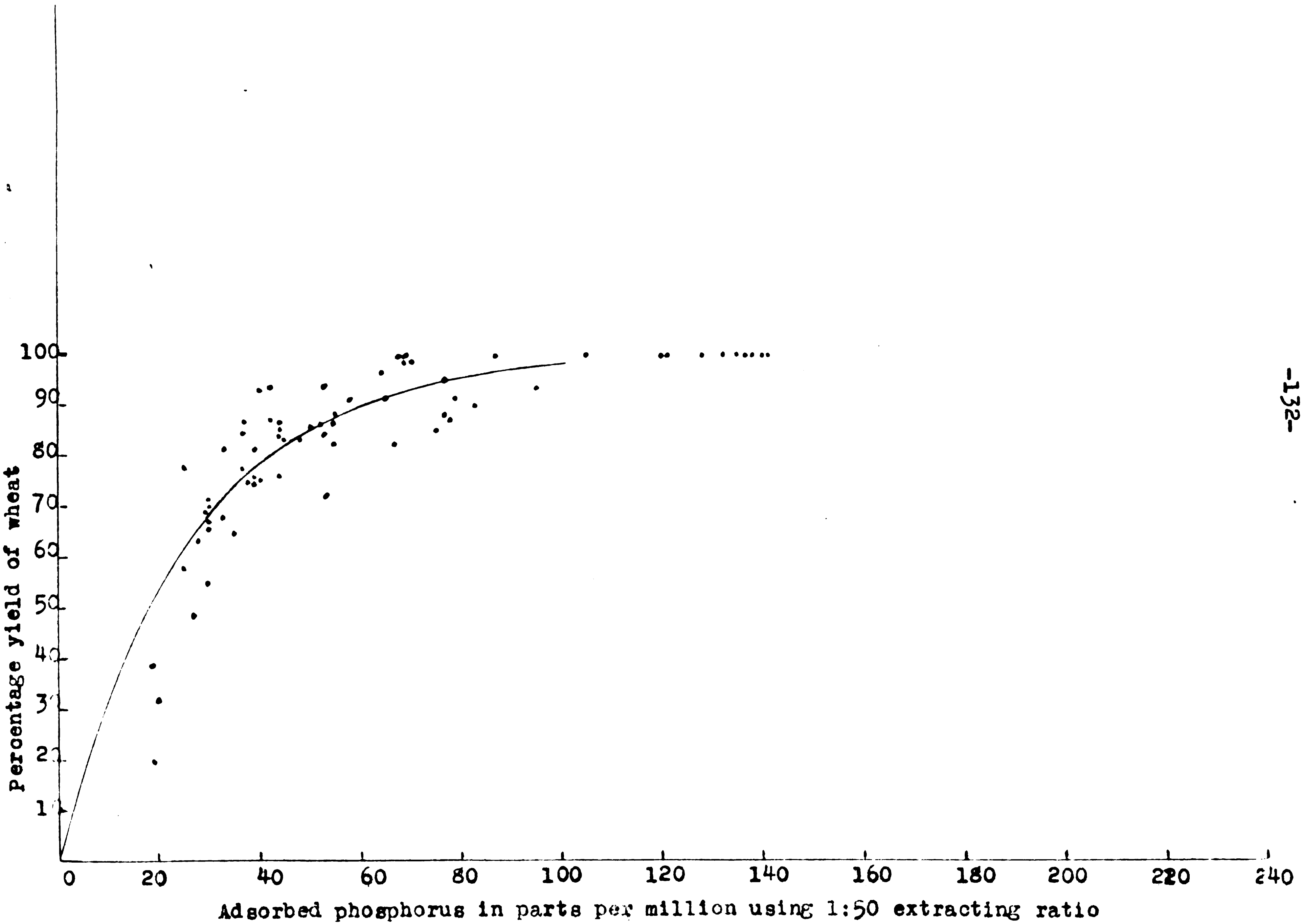

Figure 26. Relationship between adsorbed phosphorus and total yield of wheat.

of the relationship between total available phosphorus extracted at a ratio of 1:50 and plant growth response indicates a relatively wide scatter of points and, therefore, a somewhat inferior correlation. Apparently the best correlation is found in Figure 26 where the scatter of points is not large and where a large number of the points fall on or very near the calculated curve.

A better conception of the reliability of any given chemical method of measuring phosphorus availability is furnished by the statistical analyses provided in Table 21. The c_1 value of equation (III) relates the chemically measured available phosphorus value to the plant response by means of the equation. The more nearly this value remains constant over a large group of soils for a given method the more reliable this method may be considered in actual capability to predict yield response. Therefore it was decided to measure the variability of the sample for each system utilized in the mathematical evaluation. The standard deviation, coefficient of variability and standard error of estimate were calculated for each series of c_1 values. Also included in Table 21 is the mean c_1 value for each method of extraction. This value corresponds to the one used in calculating the curve presented for each of the graphs.

Table 21. Statistical analysis of c_1 values for the various chemical methods of measuring phosphorus availability.

Statistic	Chemical Method of Measuring Available Phosphorus					
	(1) Spurway's Active	(2) Spurway's Reserve	(5) Bray's Total Available (1:10)	(6) Bray's Adsorbed (1:10)	(7) Bray's Total Available (1:50)	(8) Bray's Adsorbed (1:50)
$\bar{X}$	.1311	.0214	.0129	.0284	.0102	.0169
σ	.0885	.0133	.0050	.0114	.0042	.0050
V	67.50	62.24	38.53	40.14	40.74	29.60
$\sigma_{\bar{x}}$ (actual)	±.01227	±.00185	±.00069	±.00158	±.00058	±.00069
$\sigma_{\bar{x}}$ (%)	± 9.15	± 8.65	± 5.35	± 5.56	± 5.68	± 4.11

The actual values for the standard deviation (σ) do not permit a comparison of variability of the c_1 values. However, the use of the coefficient of variation (V) which expresses the standard deviation as a per cent of the mean ($\bar{X}$) does provide a means whereby the various systems can be compared. Upon the basis of such a comparison it is seen that the variation in the c_1 values is considerably greater for the two Spurway systems than for any of the other methods.

Detailed examination of the individual c_1 values indicates that the Spurway active extraction failed, especially on the Isabella loam from Kent county and to a certain extent on such soils as the Clyde clay loam from Macomb county and

the Kent silt loam from Kent county. The Spurway reserve extraction varied the most from the mean on such soils as the two Brookston silt loams from Macomb county, the Brookston loam from Saginaw county and the Brookston loam from Kent county. However, the variability was also rather general throughout all of the Series of Samples.

The variation from the mean was greatest in the case of Bray's total availably phosphorus extraction (1:10) on such soils as the two Brookston silt loams from Macomb county and the Brookston loam from Saginaw county. The use of Bray's adsorbed phosphorus extracting solution apparently did not vary so greatly for any individual soil as some of the other techniques, except possibly for the Clyde clay loam.

In the case of the 1:50 extraction ratios, the measurement of total available phosphorus did not produce any spectacular changes from the use of the same solution at a ratio of only 1:10. However, with the use of the adsorbed extracting solution at a 1:50 ratio a considerable improvement in results was obtained and as a consequence the best single method for chemically measuring available phosphorus under the conditions of this investigation resulted. There was still some variation among the c_1 values as compared to the mean value, but as evidenced by the coefficient of variation (V) and standard error of estimate ($\sigma_{\bar{x}}$ (%)) this method was a notable improvement over the other Bray

techniques and especially an improvement over the methods of Spurway.

In explaining the advantages of any one system of measuring available phosphorus over another certain fundamental concepts must be considered. Seemingly the role of adsorption of phosphorus is extremely important in phosphorus fertility relationships of the Michigan soils included in this study and therefore any chemical method of measuring phosphorus availability should include this consideration.

In the case of the Isabella soil from Kent county, Spurway's active extraction failed especially to correlate with plant growth response due largely to the fact that very little phosphorus was soluble in this extracting solution even after the addition of as much as 160 ppm of comparatively soluble phosphorus. Similarly even with Spurway's reserve extraction the available phosphorus value was low. An explanation of this apparently lies in the fact that the adsorbed phosphorus content is comparatively high and plays a major role in the portion of this element readily available to plants. The measurement of the total available phosphorus or the adsorbed phosphorus by Bray's methods in this soil gave values which were somewhat low for the untreated soil but the values were very good for soils to which soluble phosphorus had been added. Therefore, the significance of the adsorbed portion of the phosphorus seemingly must be considered in attempting to correlate crop response to the chemically measured portion of available phosphorus.

Already it has been pointed out that a ratio of 1:50 was desirable in extracting the adsorbed form of phosphorus purely because such an extraction was capable of more nearly giving a true measure of this portion of the element. Further evidence to support this contention was provided in the studies of the correlation between plant growth and chemically measured available phosphorus. No doubt one of the main reasons why the adsorbed phosphorus extracted at a 1:50 ratio correlated better with growth response was the fact that a more accurate measurement of this portion of phosphorus was provided. Indirectly this improvement would, therefore, seem also to add support to the significance of the adsorbed portion of phosphorus as a factor in plant growth.

The standard error of estimate of the mean of the σ_1 values for the extraction of adsorbed phosphorus at a 1:50 ratio was ± 4.11%. Bray (6) reported a standard error of estimate in connection with his work on the relationship of exchangeable potassium to crop response of ± 5.0%. Therefore, upon the basis of a well established method for potassium measurement and its use in a practical way, it would seem as though, under the conditions of this investigation, a method of equal reliability has been provided for the measurement of available phosphorus in the soil.

Certain other investigations in regard to the measurement of chemically available phosphorus and correlation of the same to crop response have been attempted in Michigan but seemingly with less success than resulted in the case of this present study. Most notable among these has been the study of Bowers (2). This investigator found no better correlation between "total adsorbed phosphorus" and the response of alfalfa to added phosphorus than between "acid soluble phosphorus" and alfalfa response. However, the chemical methods used to separate the above two fractions are not similar to those utilized in this study which are the recommended methods of Bray (5). Therefore, it may be assumed that at least a part of the discrepancy noted in these two investigations of Michigan soils may be due to a basic difference in analytic techniques employed.

No attempt was made to correlate actual tomato plant growth response with chemically measured available phosphorus. The plants were harvested in a very immature state and no doubt for this reason failed to show the great graduations in yield that the wheat plants did. The greatest actual response in the case of the first crop of tomatoes usually occurred with the addition of the first increment of added phosphorus and here the increase was so very great that few percentage yield points occurred between low values of only a few percent and the point where approximately 80 per cent yield had been attained. In the case of the second crop of tomatoes, the variation in replicates of the same culture was so great that it did not appear logical to use these data in any correlation studies.

SUMMARY AND CONCLUSIONS

A study was made in which both the chemical availability of phosphorus and availability of this element as measured by plant growth response were investigated. Additionally the first crop of tomatoes and the wheat plants were analyzed for phosphorus content in an effort to explain certain fundamental facts relative to phosphorus availability.

Eight chemical methods of extracting the available phosphorus in twenty Michigan soils or soil materials were attempted. These soils had received added increments of $Ca(H_2PO_4)_2 \cdot H_2O$ up to the equivalent of 3600 pounds per acre of superphosphate (0-20-0). The different extracting procedures gave widely varying results.

In general the amount of chemically measured available phosphorus as extracted by Spurway's active extracting solution was quite low in comparison to that extracted by solutions containing hydrochloric acid. In the case of certain soils, the method was not particularly effective in indicating a higher level of available phosphorus even though very large amounts of $Ca(H_2PO_4)_2 \cdot H_2O$ had been added. Increasing the shaking time employed in extraction was essentially of no benefit on many of these soils and likewise an increase in ratio of extracting solution to the amount of soil was not always beneficial.

Spurway's reserve extracting solution was more effective in indicating the increased availability of added phosphorus in each of the soils than was the active extraction solution. The results obtained by this method, however, did fluctuate considerably more from one soil to another. Consequently there seems to be some question as to its reliability. Additionally the method as used according to the accepted procedure proved very inconvenient to use due to the frequently very large amounts of phosphorus contained in the extracts and the resulting difficulty in reading the intensity of color.

The use of any of the methods of Bray provided a considerably clearer picture of phosphorus availability in the soil because of the inclusion of at least a portion of adsorbed or replaceable phosphorus in the extract which tends to be overlooked in an extraction involving only an acid solution. It became apparent that an extraction of the adsorbed phosphorus at a ratio of 1 part of soil to 50 parts os solution was especially desirable since a more complete removal of the adsorbed phosphorus was brought about. Additionally these methods are more easily adopted to colorometric measurement of the phosphorus due to a lesser concentration of the element in the extract and also a reduction in the variability of the extract in its content of the element.

Various plant characteristics such as number of wheat heads produced, the amount of plant material produced in both the straw and head portions of the wheat plant and the phosphorus content of the plant material were investigated. Similar studies were made on tomato plants of a first crop on certain of these soil.

In general the addition of phosphorus had a tendency to increase the number of heads formed although this was by no means a reliable method of measuring the phosphorus stimulating effects.

The yield of plant material in the case of wheat generally indicated an increase as a result of each addition of phosphorus. The greatest response in plant growth resulted on those soils which were noted to be especially low in chemically available phosphorus. The total yield of wheat plants apparently was a better measure of response to added phosphorus than either the head or straw portion alone and this was used in detail in an attempt to correlate growth response to chemically measured phosphorus.

Tomato yield data indicated a very great response to the addition of phosphorus, especially to the addition of only 40 ppm of this element, for all of the soils included in the study. Additional evidence as to the lack of native phosphorus fertility was provided on such soils as those obtained from Kent county, Michigan and pronounced indications of the lack of growth producing capabilities of the Oshtemo sand were provided.

In general the chemical analyses of plant material provided information much like that obtained from plant growth response. The actual phosphorus percentage of the straw portion of the wheat plants did not always reflect the addition of phosphorus to a soil and occasionally the total amount contained in the straw likewise did not indicate the true picture. However, this apparent discrepancy was accounted for by increased stimulation of head production. The variation of phosphorus content in the head portion of the plant was not great from one soil to another or within a given soil series depending upon the level of added phosphorus. However, the variation in percentage content of the straw was great depending upon either of the above factors.

The phosphorus content of tomato plants was considerably more variable than that of the wheat plants depending upon the level of added phosphorus. An indication was made that approximately a percentage composition of 0.40 - 0.45 was sufficient to provide maximum or near maximum growth to the point at which these plants were harvested.

The yield data for a second crop of tomatoes following the initial crop or likewise a crop of tomatoes following wheat did not provide as much information as either of the initial crops. However, there was some indication of a general depletion of fertility by the first crop of tomatoes and in the case of the wheat soils additional information was provided as to the suitability of the various soils for plant growth media.

An attempt was made to correlate growth response with chemically measured available phosphorus. The principles of Mitscherlish as modified by Bray were employed. A general applicability of such principles was indicated by graphic interpretation. The two methods of Spurway were apparently of about the same suitability and as such were distinctly poorer than any of the methods advocated by Bray and his associates.

The use of either the customary method of Bray for measuring total available phosphorus or adsorbed phosphorus at an extraction ratio of 1:10 gave comparable results. Increasing the extraction ratio to 1:50 did not improve the method for measuring total available phosphorus as evidenced by correlation with plant yield response. However, the increasing of the ratio to 1:50 for the adsorbed phosphorus extraction did result in a notable improvement and also resulted in the best single method employed under the conditions of this experiment.

Certain apparent discrepancies in this investigation in comparison to that of a similar investigation on Michigan soils were recognized. However, a study of the analytical method employed in the two studies indicates that the studies are not entirely comparable and therefore the results cannot necessarily be considered in disagreement.

LITERATURE CITED

(1) Arnold, C.Y. and Kurtz, T. 1946 Photometer method for determining available phosphorus in soils. Ill. Agr. Exp. Sta. Agron. Dept. Pamphlet AG 1306.

(2) 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.

(3) Bray, R. H. and Dickman, S. R. 1941 Adsorbed phosphates in soils and their relation to crop responses. Soil Sci. Soc. of Amer. Proc. 6: 312-320.

(4) Bray, R. H. and Dickman, S. R. 1942 Tenative fluoride extraction methods for soil phosphorus. Ill. Agr. Exp. Sta. Agron. Dept. Pamphlet AG 1006.

(5) Bray, R. H. 1942 Rapid tests for measuring and differentiating between the adsorbed and acid-soluble forms of phosphate in soils. Ill. Agr. Exp. Sta. Agron. Dept. Pamphlet AG 1028.

(6) Bray, R. H. 1944 Soil-plant relations : I. The quantitative relation of exchangeable potassium to crop yields and to crop response to potash additions. Soil Sci. 58: 305-324.

(7) Bray, R. H. 1945 Photometer method for determining available potassium in soils. Ill. Agr. Exp. Sta. Agron. Dept. Pamphlet AG 1275.

(8) Bray, R. H. and Kurtz, L. T. 1945 Determination of total, organic, and available forms of phosphate in soils. Soil Sci. 59: 39-45.

(9) Bray, R. H. 1946 Soil-plant relations : II. Balanced fertilizer use through soil tests for potassium and phosphorus. Soil Sci. 60: 463-473.

(10) Bray, R. H. 1949 Correlation of soil tests with crop response to added fertilizers and with fertilizer requirement. Diagnostic Techniques for Soils and Crops. Published by The American Potash Institute.

(11) Dickman, S. R. and Bray, R. H. 1941 Replacement of adsorbed phosphate from kaolinite by fluoride. Soil Sci. 52: 263-273.

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

(13) Peech, M. and English, L. 1944 Rapid microchemical soil tests. Soil Sci. 57: 167-195.

(14) Spurway, C. H. 1944 Soil testing. Mich. Agr. Exp. Sta. Tech. Bul. 132 (3rd rev.).

(15) Ulrich, A. 1945 Critical phosphorus and potassium levels in ladino clover. Soil Sci. Soc. of Amer. Proc. 10: 150-161.

(16) Ulrich, A. 1949 Plant analysis - methods and interpretation of results. Diagnostic Techniques for soils and crops. Published by American Potash Institute.

(17) Veatch, J. O. 1933 Agricultural land classification and land types of Michigan. Mich. Agr. Exp. Sta. Spec. Bul. 231.

(18) Watson, A. J. 1949 The effect of varied levels of nitrogen, phosphorus, potassium and boron in soil on the yield and chemical composition of greenhouse tomatoes. Ph.D. Thesis, Michigan State College.

ROOM USE ONLY
ROOM USE ONLY