THE EFFECTS OF WATER-SOLUBLE PHOSPHORUS CONTENT AND GRANULE SIZE OF MIXED FERTILIZERS ON PHOSPHORUS AVAILABILITY TO PLANTS

Thesis for the Degree of M. S.

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Lowell D. Owens

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THESIS

This is to certify that the

thesis entitled

The Effects of Water Soluble Phosphorus Content and Granule Size of Mixed Fertilizers on Phosphorus Availability to Plants

presented by

Lowell Owens

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R L Cook
Major professor

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THE EFFECTS OF WATER-SOLUBLE PHOSPHORUS CONTENT AND GRANULE SIZE OF MIXED FERTILIZERS ON PHORPHORUS AVAILABILITY TO PLANTS

By

Lowell D. Owens

AN ABSTRACT

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

MASTER OF SCIENCE
1955

Approved R. L. Cook

THESIS

Lowell Owens

ABSTRACT

The Effects of Water-soluble Phosphorus Content and Granule Size of Mixed Fertilizers on Phosphorus Availability to Plants

Greenhouse and field experiments were undertaken to investigate the effects of water-soluble phosphorus content and granule size of mixed fertilizers on the availability of phosphorus to plants.

Wheat plants grown in the greenhouse showed no significant differences in dry weight yields resulting from varying the water-soluble phosphorus content of mixed fertilizers having similar N-P_2O_5-K_2O ratios. Plant absorption of phosphorus from granular fertilizers was directly proportional to the water-soluble phosphorus content of the fertilizer. The percent of plant phosphorus derived from pulverant fertilizers was not markedly influenced by the water-soluble phosphorus content. There was a definite relationship between total phosphorus uptake by 3 week old plants and the water-soluble phosphorus content of the fertilizer applied, but the relationship was not observed in plants in a later stage of growth. Percent plant absorption of fertilizer phosphorus decreased as soil pH was increased from 5.5 to 7.5.

The phosphorus content of field grown sugar beet plants one month old was directly proportional to the water-soluble phosphorus content of the fertilizer used. During later stages of growth, phosphorus absorption by the leaves

and petioles of beets from plots treated with fertilizers widely varying in their water-soluble phosphorus contents were not significantly different. Phosphorus uptake by sugar beet plants was not affected by variations in the mesh size of the materials tested. There were no significant differences in sugar beet yields resulting from fertilizer treatments.

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TABLE OF CONTENTS

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. . . .

. . .

. . . .

. .

. . . .

. . . .

. . . .

. . . .

. . . .

. . . .

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. . . .

. . . .

LIST OF TABLES

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

INTRODUCTION

The availability of phosphorus from fertilizers is influenced by certain factors that are inherent in the fertilizer, the plant and the soil. Recent investigations have indicated that if only the fertilizer is considered, the water-soluble phosphorus content, the size of the fertilizer particles and the nature of the admixed salts influence the phosphorus absorption and dry matter yield. However, investigations of the interactive effect of solubility and particle size of phosphate fertilizers on the availability of phosphorus to plants has been largely confined to materials insoluble in water.

Due to current processing trends in the fertilizer industry, considerable proportion of the phosphorus in many mixed fertilizers is or will be dicalcium phosphate, a relatively water-insoluble compound. Also, at present, increasing amounts of fertilizers are being produced in granular forms. Recent investigations have indicated that there is some correlation between fertilizer granule size and the availability of fertilizer phosphorus to plants.

This investigation was undertaken to study the interaction of particle size and water-soluble phosphorus content of mixed fertilizers on the availability of fertilizer phosphorus to plants grown in the greenhouse and in the field.

REVIEW OF LITERATURE

Effect of Phosphate Form on Plant Phosphorus Uptake

In 1949 Dion et al. (4) found by means of a greenhouse and field experiment that there was a significantly greater utilization of fertilizer phosphorus by wheat plants from mono-ammonium phosphate than from monocalcium phosphate and tricalcium phosphate fertilizers. Their experiments were conducted on a neutral soil free of excess carbonates or alkali.

Somewhat similar results were obtained from experiments performed on Texas soils by Speer et al. (22) which disclosed that bean plants utilized a greater amount of phosphorus applied in the form of monoammonium phosphate than in the form of dicalcium or tricalcium phosphate.

Martin et al.(9) observed that the degree of ammonification of superphosphate had no effect on the availability of phosphorus to lettuce plants grown on an acid soil. However, when applied to a calcareous soil the growth response of the lettuce was related to the amount of water-soluble phosphorus in the fertilizer.

Rogers (18) compared the relative effects of ammoniated superphosphate and concentrated superphosphate on several crops grown both in the greenhouse and in the field. He concluded that there is no evidence that a high water-solubility (over 10%) is required for small grains, corn and cotton grown on acid soils in the southeastern states. However, limited tests in Iowa and Nebraska suggest that nitraphosphates of low water-solubility may on alkaline soils be less effective than the more soluble superphosphate.

In 1953 Mitchell et al. (12) observed that 25 percent of the phosphorus in barley, wheat and oat plants grown on a slightly responsive soil was derived from ammonium phosphate fertilizers, but at the same time there was a corresponding decrease in the uptake of soil phosphorus. On highly responsive soils the utilization of fertilizer phosphorus was as high as 33 percent, while the uptake of soil phosphorus was about the same as that on an untreated soil.

Experimentation by Hall et al. (5) has shown that the phosphorus uptake by corn plants was greater from superphosphate and metacalcium phosphate than from dicalcium phosphate fertilizers. However, the uptake from superphosphate and calcium metaphosphate, which have widely different water-soluble phosphorus contents, was virtually the same. Using the absorption of fertilizer phosphorus by cotton plants as a measure of phosphorus availability, they observed that on both high and low phosphorus soils, phosphorus uptake from dicalcium phosphate was less than that from four other phosphate fertilizers, alpha tricalcium phosphate, superphosphate, ammoniated superphosphate and calcium metaphosphate.

Similar observations were made by Stanford and Nelson (23) who found that phosphorus absorption by oats was greater from superphosphate than from dicalcium phosphate.

Greenhouse studies conducted by Moschler (13) have shown that ammoniation of superphosphate lowers its availability to wheat in early stages of growth.

Field data suggest that this reduction in availability may be masked by unfavorable growing conditions such as the lack of sufficient moisture.

Experiments conducted on irrigated calcareous soils by Olsen et al. (15, 16) have shown that the total uptake of phosphate from the soil and applied phosphates was about the same from treatments involving fertilizers of widely varying water-soluble phosphorus contents. Calcium metaphosphate furnished less phosphorus to the plants in the early stages of growth than did superphosphate, but the plants obtained about equal amounts of phosphorus from these fertilizers in later stages of growth. Dicalcium phosphate was not as effective as superphosphate in supplying phosphorus to wheat, barley and sugar beets.

Effect of Fertilizer Granule Size on Plant Phosphorus Uptake

The effect of granule size of radioactive superphosphate and dicalcium phosphate fertilizers on crop yield, total plant phosphorus uptake and percent fertilizer phosphorus uptake was studied by Starostka et al. (24). Using these results as a criterion for evaluation these workers observed that 14 to 20 mesh size granules of superphosphate were most effective while 28 to 35 size granules were the best for dicalcium phosphate fertilizers.

Rogers (18), using crop response as a criterion of fertilizer effectiveness, indicated that granules of phosphatic fertilizer coarser than 12 mesh were less effective than finer materials. On the other hand there was some evidence that particles finer than 40 mesh were also inferior.

Mitchell et al (11) observed that the utilization of fertilizer phosphorus from a granular state was significantly greater than from a pulverized state.

Similar results were reported by Sayre (19) who observed that granulated fertilizers gave superior yields in all field tests on tomatoes where the fertilizer was applied broadcast. The same occurred with three of four fertilizers applied in bands.

Using cotton yields as a criterion for evaluating the efficiency of various sized superphosphate granules, Mehring (10) stated that for the average circumstances encountered in their experiments the 80 to 150 mesh fertilizers were the most efficient.

Lawton and Vomicil (7) showed that rapid dissolution of phosphorus from the fertilizer granule occurred shortly after it was placed in the soil. Between 50 and 80 percent dissolution of the phosphorus occurred within the first 24 hours in moist soils. However, high concentrations of water-soluble phosphorus around the fertilizer pellet decreased the rate of dissolution. The phosphorus in larger granules was found to migrate the greatest distance.

On the other hand Killinger (6) observed from an experiment with cotton that fertilizer particle size did not significantly affect the stand or yield.

Van der Bauw, as quoted by Sherman and Hardesty (20), has stated that granulation reduces the assimilability of $CaHPO_4$. However, this is not true in the case of water-soluble phosphates (superphosphates).

Experimentation by Torstensson and Eriksson (25) and also by Franck (21) has disclosed that in pot tests with oats and barley, granulated superphosphate

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phate was superior to the powdered product. The use of granulated material favored a good root development which partially encircled the fertilizer granules.

Franck, as quoted by Sherman and Hardesty (21), has concluded after nearly a decade of phosphate experimentations that "Superphosphate is more suitable in the granular form---The large particles are able to saturate soil zones in such a way as to enable the roots easily to take in the phosphoric acid. The phosphoric acid which has been taken in can be replaced from the supply which has not yet completely reacted with the soil, that is, from the superphosphate particles themselves. The granulated superphosphate is a more stable phosphate and provides a more constant supply of phosphoric acid in the soil."

Effect of Soil Reaction on Fertilizer Phosphorus Uptake

Studies by Cole et al. (2) indicate that the addition of soluble phosphorus fertilizers to calcareous soils results in monolayer sorption of phosphorus on the surface of calcium carbonate particles. If the phosphorus concentration is amply high, dicalcium phosphate or a compound with similar properties will form a precipitate. The initial products of these reactions, however, are more soluble in regard to phosphorus than more stable phosphorus compounds, such as hydroxyapatite and fluorapatite, found in calcareous soils.

Greenhouse studies on the effect of lime on the availability of applied

phosphorus were conducted by Robertson et al. (17). It was found that liming soils of a high sesquioxide content and low phosphorus level resulted in an increase in applied phosphorus availability up to a pH of 6.5. Liming the soil beyond pH 6.5 caused a leveling off or drop in the utilization of fertilizer derived phosphorus. This was due to the formation of an insoluble calcium-phosphorus complex.

In 1953 Neller (14) found that liming an acid soil to raise the pH to 6.76 had no effect on the percent uptake of fertilizer phosphorus, however, it decreased the total phosphorus content of oats and millet grown in the greenhouse. Field studies, though, revealed that liming had no effect on the plant absorption of either the applied or soil phosphorus.

Speer et al. (22) observed that the absorption of phosphorus from mono-ammonium phosphate fertilizer was greater on acid soils than on alkaline calcareous soils.

Phosphate fixation studies by Lewis et al. (8) indicate that on calcareous soils, a reduction in plant availability of applied phosphorus took place in the first 24 hours, after which it leveled off and tended to maintain a constant level.

PROCEDURE

Greenhouse Experiment

The soil used in this experiment was a Hillsdale sandy loam taken from the SW 1/4 of Sec. 20, T 3N, R 1W, Meridian township, Ingham county, Michigan. The pH of the soil was 5.1 and the quantity of available phosphorus extractable in 0.13N HCl was low. Three soil pH levels, 5.5, 6.5, and 7.5 were obtained by liming with precipitated $CaCO_3$, followed by three weeks moist incubation prior to fertilizer application. Six 12-12-12 fertilizers[1] having variable percentages of their phosphorus water-soluble were used. These percentages were 2 to 3, 8 to 10, 18 to 20, 28 to 30, 40 to 45 and 85 to 90. The fertilizers were synthesized from $CaHPO_4$, $NH_4H_2PO_4$, NH_4NO_3 and KCl in slurry mixtures. Phosphorus water-solubility was varied by changing the proportion of ammonium to dicalcium phosphate with adjustments in ammonium nitrate to keep the N to P_2O_5 ratio the same. All of the fertilizers were labelled with P^{32} and prepared in the mesh sizes 4 to 6, 14 to 20 and minus 60 per inch.

Except in a fertilizer application rate study all fertilizers were uniformly mixed with the soil at the rate of 500 pounds per acre. For the application rate study 14 to 20 mesh sized fertilizers having 28 to 30 percent of their phosphorus water-soluble were applied at the rates of 0, 30, 120 and

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[1]The 12-12-12 fertilizers labelled with P^{32} were prepared by W. L. Hill and associates, Fertilizer and Agricultural Lime Division, Agr. Research Service, Beltsville, Md.

180 pounds of P_2O_5 per acre. Three replicates of each treatment were employed. The soils were placed in four gallon glazed pots, and Henry variety of spring wheat was planted on March 9th at the rate of 30 seeds per pot. Optimum moisture conditions were maintained by bringing the soil up to an estimated value of moisture equivalent at periodic intervals. Two thinning samples and a final harvest were taken on April 2nd, April 21st, and May 8th, respectively. The plant samples were dried at 65°C., weighed, ground and a one gram portion pressed into a pellet at 14,000 pounds per square inch. After obtaining measurements of their specific activity the pellets were wet ashed with nitric, sulfuric and perchloric acids. Residue of the ash was taken up with 0.2N HCl and phosphorus determined as molybdenum blue by the Dickman and Bray method (3).

Field Experiment

Four non-radioactive fertilizers[1], including 7-14-14, 6-12-12, 10-20-20 and 11-22-22 analyses with water-soluble phosphorus contents of 0, 25, 50 and 100 percent, respectively, were used in this experiment. Two particle sizes, 6 to 14 and finer than 35 mesh, of each formulation were tested.

This experiment was conducted on Kawkawlin loam soil in Bay County, Michigan. The variation in soil pH from six replications was 6.8 to 7.5. Phosphorus and potassium extractable in 0.13N HCl averaged 41 and 115 pounds

[1]Fertilizers having a 1-2-2 ratio were supplied by the Soil and Fertilizer Research Branch, Agr. Relations Division, T.V.A., Knoxville, Tennessee.

per acre,respectively. A total of 140 pounds of P_2O_5 was applied broadcast, one half before plowing on April 22nd and the remainder topdressed after plowing on May 18th. The experimental design was a randomized block with six replications, each 14 by 31 feet. Beet seed was planted on May 20th in 28-inch rows. Plant samples for total phosphorus analyses were taken from each plot 4 and 8 weeks after planting. On October 8th the beets were harvested.

EXPERIMENTAL RESULTS AND DISCUSSION

Greenhouse Experiment

A greenhouse experiment was designed to measure the plant availability of phosphorus from mixed fertilizers. Variables under investigation included water-soluble phosphorus content and mesh size of fertilizers and soil reaction.

The data given in Tables I, II, and III (see Appendix for data by replicates) and Figures 1 through 9 show that the plant absorption of phosphorus from the 4 to 6 and 14 to 20 mesh 12-12-12 fertilizers was markedly increased as the water-soluble phosphorus content was increased. Wheat plants obtained less than 12 and 17 percent of their phosphorus, respectively, from 4 to 6 and 14 to 20 mesh granules of fertilizers containing less than 3 percent of their phosphorus water-soluble. This condition was true for all pH levels. In contrast, the percent of plant phosphorus derived from 4 to 6 mesh particles having over 85 percent of their phosphorus water-soluble rose at the final harvest to over 75 at pH 5.5 and 6.5, and over 50 at pH 7.5. Large granules with a low content of water-soluble phosphorus did not afford sufficient surface for extensive dissolution and root contact. However, when the same size granules had a high percentage of their phosphorus water-soluble considerable dissolution resulted. Fixation was not sufficient to prevent movement of the phosphorus to a considerable distance from the granule, thus a high concentration of plant available phosphorus existed near the fertilizer source.

A comparison of fertilizer and total phosphorus absorption by wheat

Table I. The relative uptake of fertilizer phosphorus by wheat plants from mixed fertilizers varying in water-soluble phosphorus content and mesh size (soil pH 5.5).

Portion of fert. P H_2O-sol.	Sampling date: 3 weeks Plant P from fert.*	3 weeks Total plant P*	3 weeks Plant P from fert.	6 weeks Plant P from fert.	6 weeks Total plant P	6 weeks Plant P from fert.	8 weeks Plant P from fert.	8 weeks Total plant P	8 weeks Plant P from fert.
%	mg/gm plant tissue		%	mg/gm plant tissue		%	mg/gm plant tissue		%
	4 to 6 mesh			4 to 6 mesh			4 to 6 mesh		
2 to 3	0.17	2.3	7	0.21	1.9	11	0.17	2.2	8
8 to 10	0.56	2.7	21	0.95	2.4	40	0.48	2.0	24
18 to 20	1.61	3.0	54	1.45	2.3	63	0.60	1.6	38
28 to 30	1.82	3.2	57	1.56	2.4	65	0.74	1.8	41
40 to 45	2.21	3.8	58	1.81	2.7	67	0.83	1.3	64
85 to 90	3.04	4.3	71	2.18	2.7	81	1.19	1.5	79
	14 to 20 mesh			14 to 20 mesh			14 to 20 mesh		
2 to 3	0.24	1.9	13	0.40	2.6	15	0.36	2.1	17
8 to 10	0.40	2.3	17	0.61	2.2	28	0.48	2.0	24
18 to 20	0.72	2.6	18	0.81	2.2	37	0.68	2.1	32
28 to 30	0.86	2.2	39	0.95	2.2	43	0.65	1.9	34
40 to 45	1.51	2.7	56	1.33	2.2	60	0.77	1.7	45
85 to 90	1.87	3.3	57	2.00	2.2	91	1.04	1.4	74
	- 60 mesh			- 60 mesh			- 60 mesh		
2 to 3	0.46	2.5	18	0.67	2.3	29	0.75	1.9	39
8 to 10	0.61	2.6	23	0.87	2.8	31	0.78	1.9	41
18 to 20	0.68	2.4	28	0.96	2.5	38	0.73	1.8	41
28 to 30	0.50	2.5	20	0.67	2.1	32	0.67	2.0	34
40 to 45	0.63	2.4	26	0.79	2.2	36	0.75	2.0	38
85 to 90	0.54	2.7	20	0.60	2.5	24	0.50	1.8	28

*Average of three replications.

Table II. The relative uptake of fertilizer phosphorus by wheat plants from mixed fertilizers varying in water-soluble phosphorus content and mesh size (soil pH 6.5).

Portion of fert. P H_2O-sol.	Sampling date: 3 weeks Plant P from fert.*	3 weeks Total plant P*	3 weeks Plant P from fert.	6 weeks Plant P from fert.	6 weeks Total plant P	6 weeks Plant P from fert.	8 weeks Plant P from fert.	8 weeks Total plant P	8 weeks Plant P from fert.
%	mg/gm plant tissue		%	mg/gm plant tissue		%	mg/gm plant tissue		%
	4 to 6 mesh			4 to 6 mesh			4 to 6 mesh		
2 to 3	0.10	2.5	4	0.10	2.2	5	0.14	1.8	7
8 to 10	0.30	2.5	12	0.61	2.3	27	0.39	1.7	23
18 to 20	1.06	2.8	38	1.06	2.2	48	0.68	2.1	32
28 to 30	1.39	3.2	44	1.13	2.2	51	0.65	1.5	43
40 to 45	1.65	3.4	49	1.38	2.2	63	0.75	1.4	54
85 to 90	2.51	4.3	58	1.81	2.7	67	1.07	1.3	78
	14 to 20 mesh			14 to 20 mesh			14 to 20 mesh		
2 to 3	0.08	2.5	3	0.16	2.2	7	0.24	1.6	15
8 to 10	0.28	2.5	11	0.28	1.9	15	0.28	1.8	16
18 to 20	0.55	3.0	18	0.60	2.5	24	0.51	1.9	27
28 to 30	0.60	2.9	24	0.65	2.2	30	0.52	2.0	26
40 to 45	1.03	3.1	33	1.03	2.0	52	1.03	1.9	53
85 to 90	1.83	3.7	49	1.79	2.7	66	0.96	1.4	69
	-60 mesh			-60 mesh			-60 mesh		
2 to 3	0.29	2.4	12	0.46	2.4	19	0.54	2.1	26
8 to 10	0.31	2.6	12	0.57	2.6	22	0.61	2.3	27
18 to 20	0.36	2.5	14	0.68	2.4	28	0.68	2.2	31
28 to 30	0.33	2.5	13	0.54	2.3	23	0.67	2.2	30
40 to 45	0.46	2.8	16	0.54	2.0	27	0.54	1.8	30
85 to 90	0.50	3.0	17	0.57	2.5	23	0.47	1.9	25

*Average of three replications.

Table III. The relative uptake of fertilizer phosphorus by wheat plants from mixed fertilizers varying in water-soluble phosphorus content and mesh size (soil pH 7.5).

Portion of fert. P H_2O-sol.	Sampling date: 3 weeks, Plant P from fert.*	3 weeks, Total plant P*	3 weeks, Plant P from fert.	6 weeks, Plant P from fert.	6 weeks, Total plant P	6 weeks, Plant P from fert.	8 weeks, Plant P from fert.	8 weeks, Total plant P	8 weeks, Plant P from fert.
%	mg/gm plant tissue		%	mg/gm plant tissue		%	mg/gm plant tissue		%
	4 to 6 mesh			4 to 6 mesh			4 to 6 mesh		
2 to 3	0.07	2.4	3	0.07	2.0	4	0.07	1.4	5
8 to 10	0.35	2.7	13	0.56	2.2	25	0.26	1.2	22
18 to 20	0.94	3.0	31	0.72	2.2	33	0.34	1.2	28
28 to 30	0.87	3.1	28	0.82	2.3	36	0.35	1.6	22
40 to 45	1.30	3.3	39	1.10	2.6	42	0.51	1.4	36
85 to 90	1.97	3.8	52	1.69	2.8	60	0.78	1.5	52
	14 to 20 mesh			14 to 20 mesh			14 to 20 mesh		
2 to 3	0.08	2.5	3	0.08	2.3	3	0.12	1.7	7
8 to 10	0.24	2.5	10	0.24	2.3	10	0.20	2.1	10
18 to 20	0.47	2.7	17	0.60	2.3	26	0.34	1.9	18
28 to 30	0.52	2.8	19	0.69	2.2	31	0.52	2.0	26
40 to 45	0.77	2.9	27	0.95	2.6	37	0.56	1.6	35
85 to 90	1.33	3.2	42	1.58	2.8	56	0.92	1.6	58
	-60 mesh			-60 mesh			-60 mesh		
2 to 3	0.17	2.7	6	0.25	2.3	11	0.29	1.8	16
8 to 10	0.22	2.7	8	0.26	2.2	12	0.35	1.9	18
18 to 20	0.36	2.6	14	0.50	2.5	20	0.46	2.2	21
28 to 30	0.25	2.8	9	0.33	2.7	12	0.33	1.9	17
40 to 45	0.42	2.9	14	0.42	2.0	21	0.33	1.4	24
85 to 90	0.44	2.9	15	0.50	2.4	21	0.34	1.3	26

*Average of three replications.

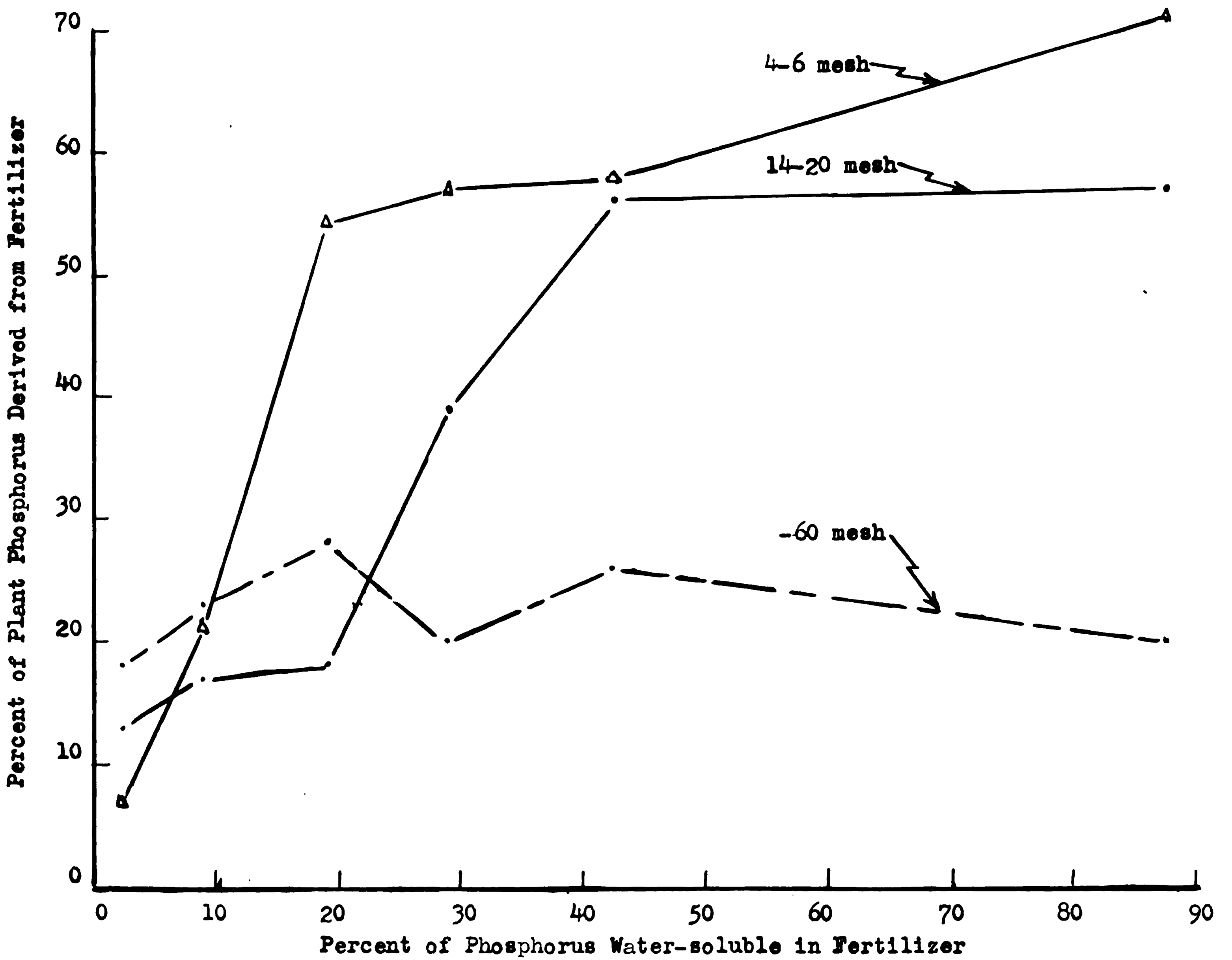

Figure 1. The Relative Uptake of Fertilizer Phosphorus by Three Week Old Wheat Plants from Mixed Fertilizers Varying in Water-soluble Phosphorus Content and Mesh Size (soil pH 5.5).

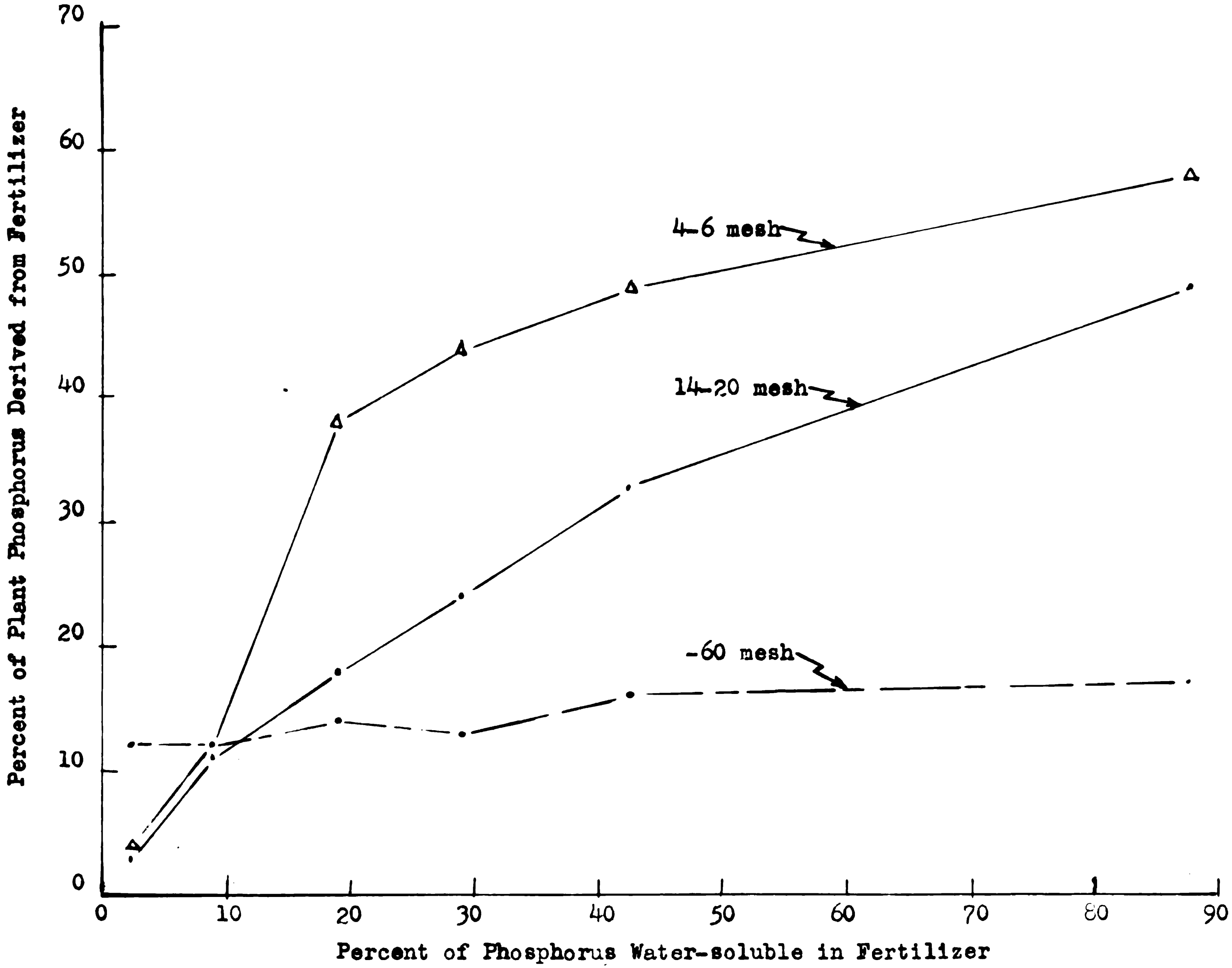

Figure 2. The **Relative** Uptake of **Fertilizer Phosphorus** by **Three Week** Old Wheat **Plants** from **Mixed Fertilizers** Varying in **Water-soluble** Phosphorus Content **and Mesh** Size **(soil** pH 6.5).

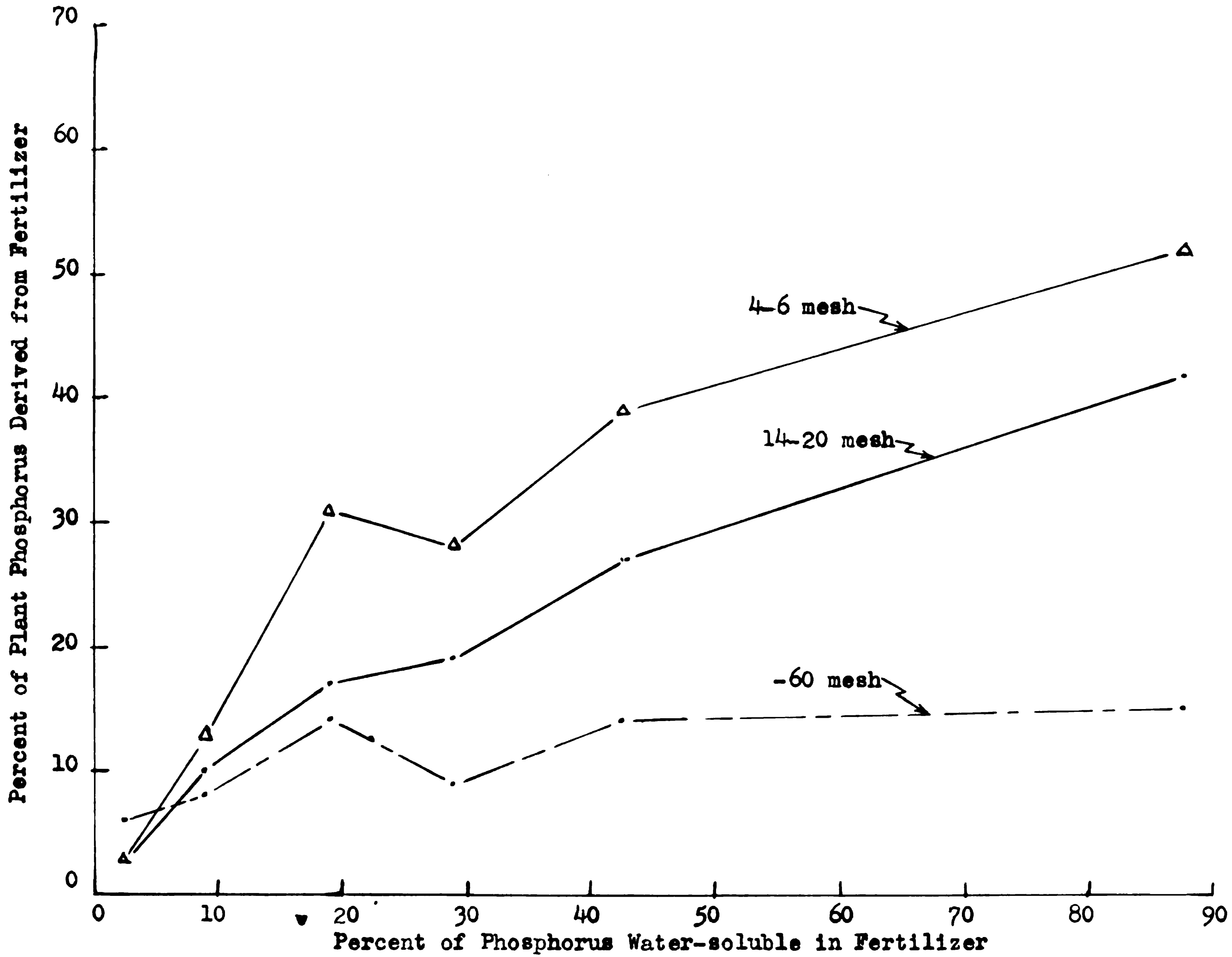

Figure 3. The Relative Uptake of Fertilizer Phosphorus by Three Week Old Wheat Plants from Mixed Fertilizers Varying in Water-soluble Phosphorus Content and Mesh Size (soil pH 7.5).

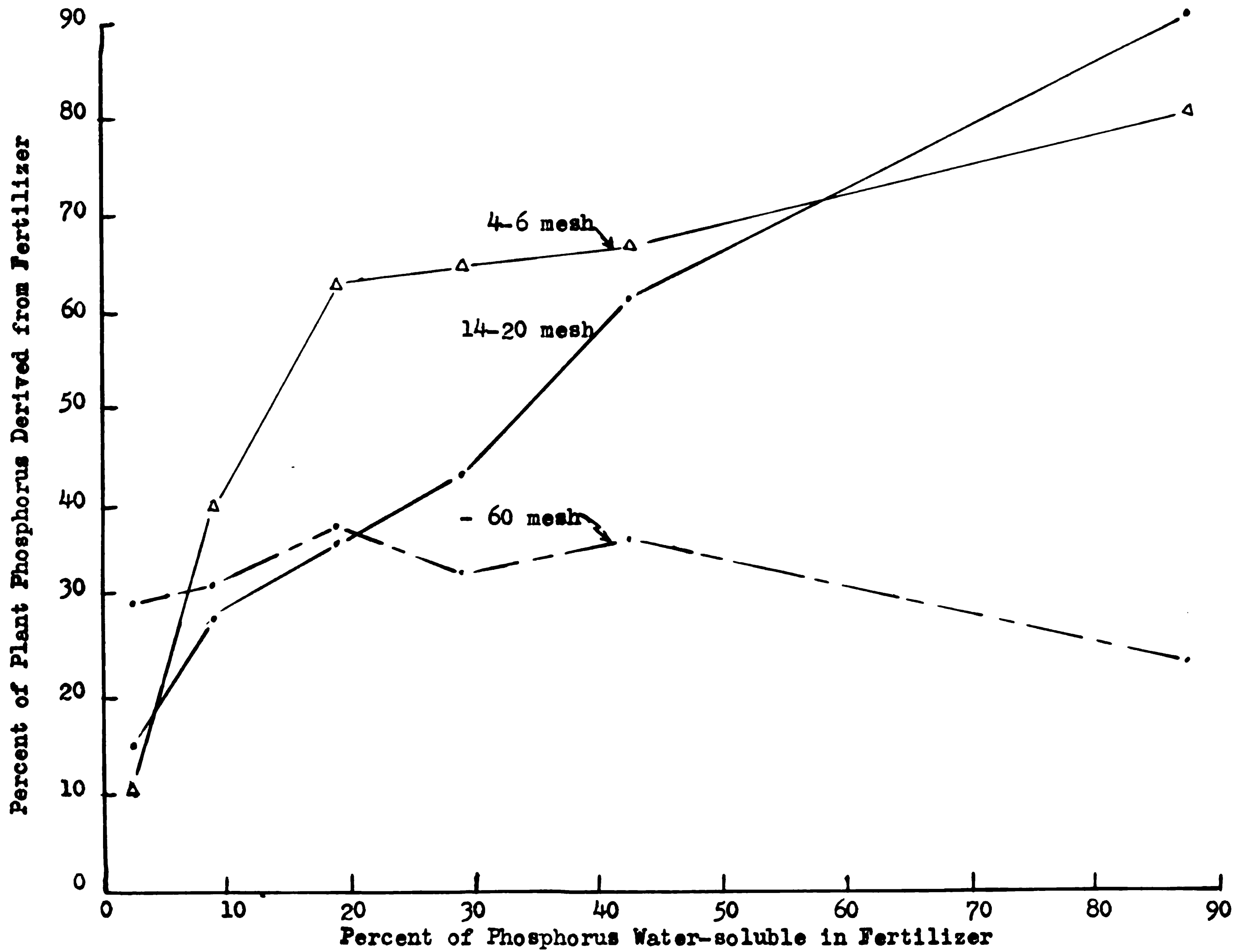

Figure 4. The Relative Uptake of Fertilizer Phosphorus by Six Week Old Wheat Plants from Mixed Fertilizers Varying in Water-soluble Phosphorus Content and Mesh Size (soil pH 5.5).

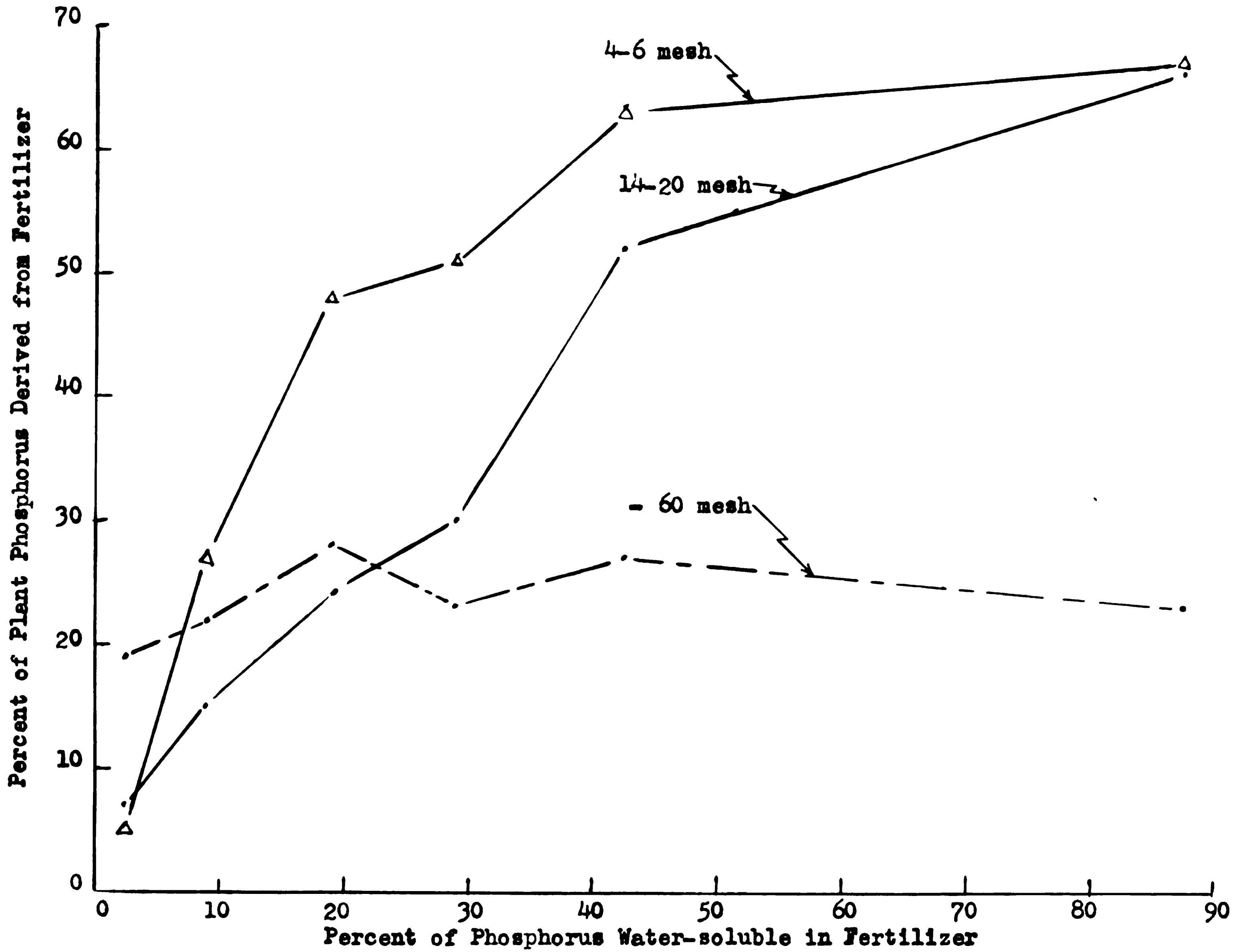

Figure 5. The Relative Uptake of Fertilizer Phosphorus by Six Week Old Wheat Plants from Mixed Fertilizers Varying in Water-soluble Phosphorus Content and Mesh Size (soil pH 6.5).

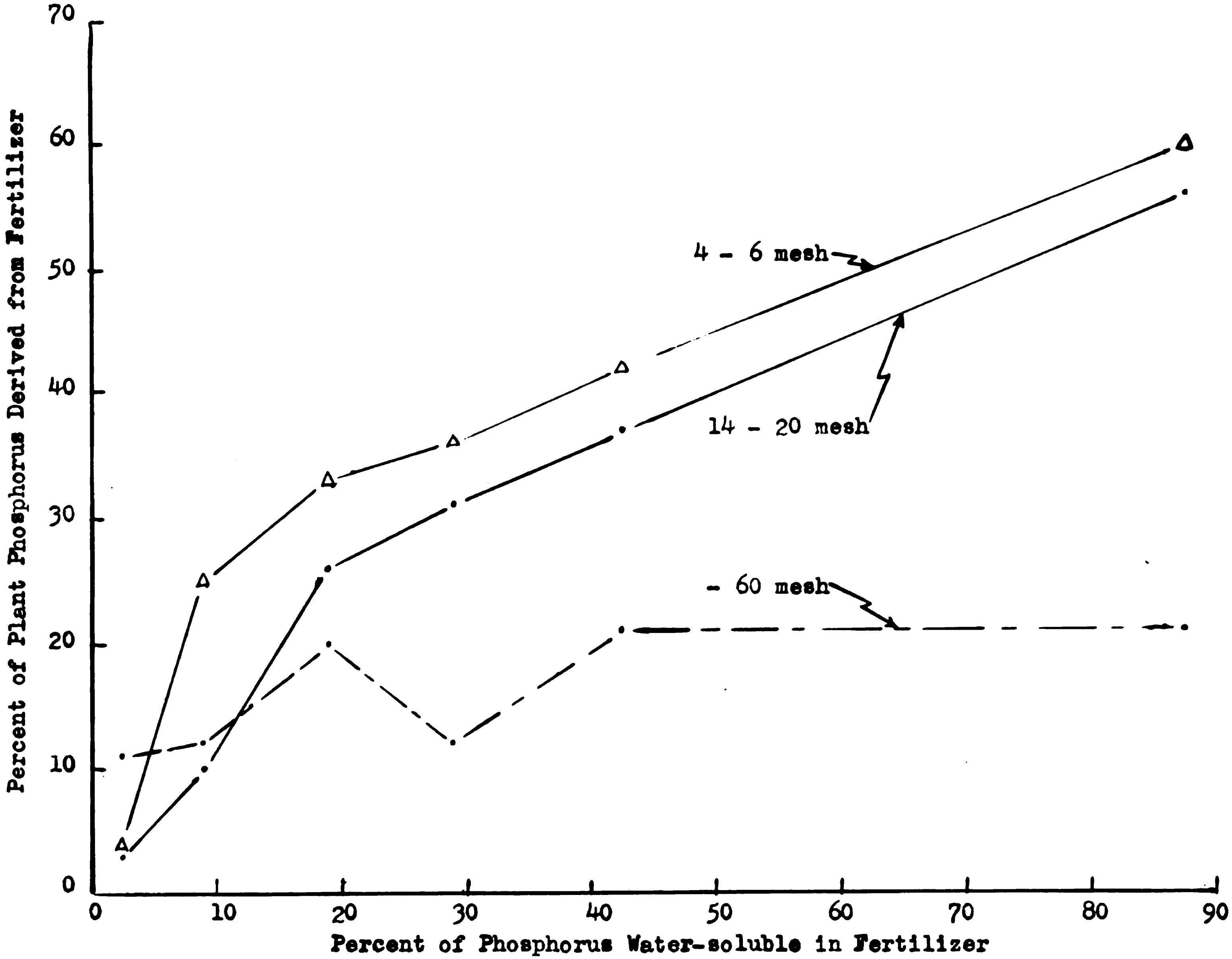

Figure 6. The Relative Uptake of Fertilizer Phosphorus by Six Week Old Wheat Plants from Mixed Fertilizers Varying in Water-soluble Phosphorus Content and Mesh Size (soil pH 7.5).

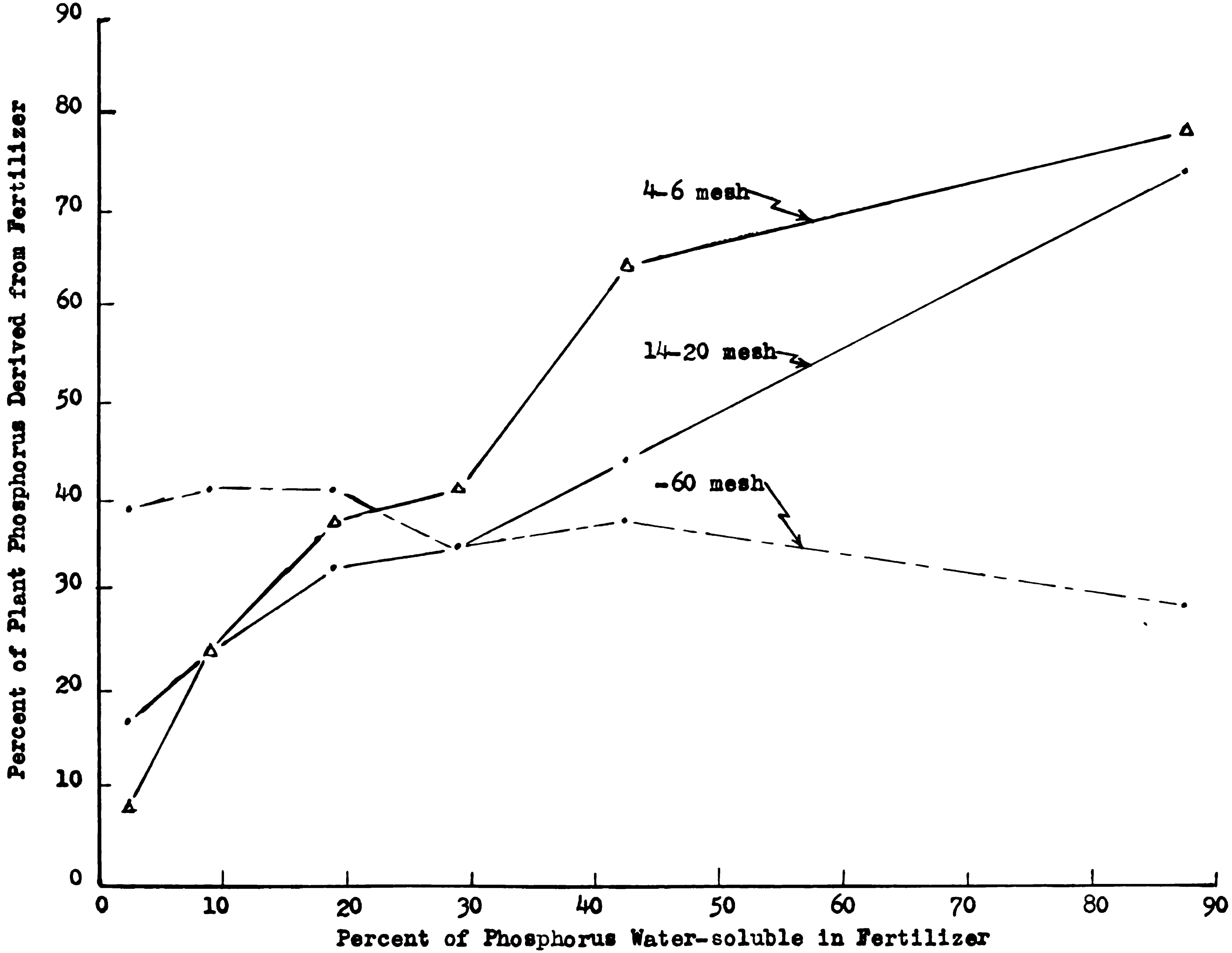

Figure 7. The Relative Uptake of Fertilizer Phosphorus by Eight Week Old Wheat Plants from Mixed Fertilizers Varying in Water-soluble Phosphorus Content and Mesh Size (soil pH 5.5).

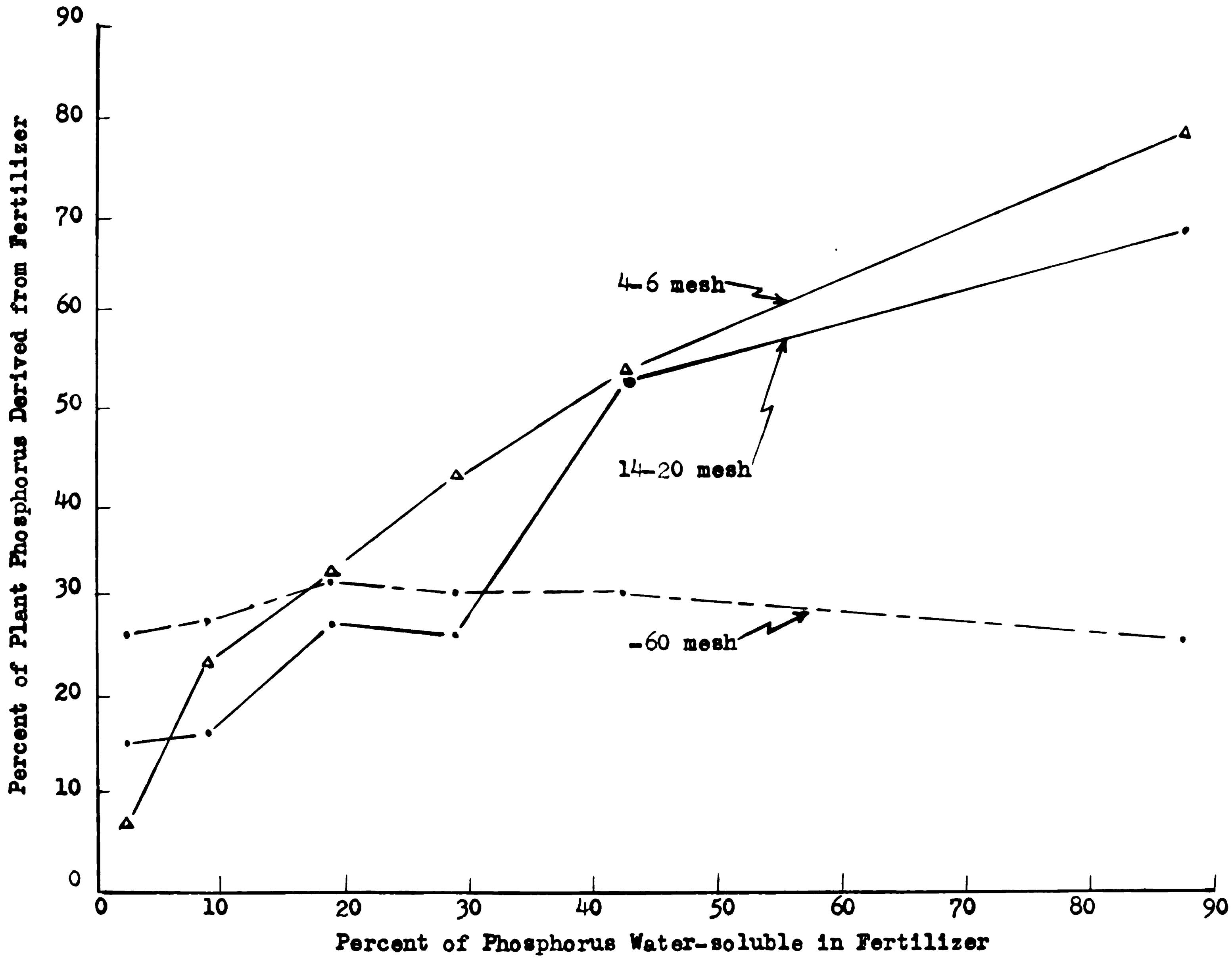

Figure 8. The Relative Uptake of Fertilizer Phosphorus by Eight Week Old Wheat Plants from Mixed Fertilizers Varying in Water-soluble Phosphorus Content and Mesh Size (pH 6.5).

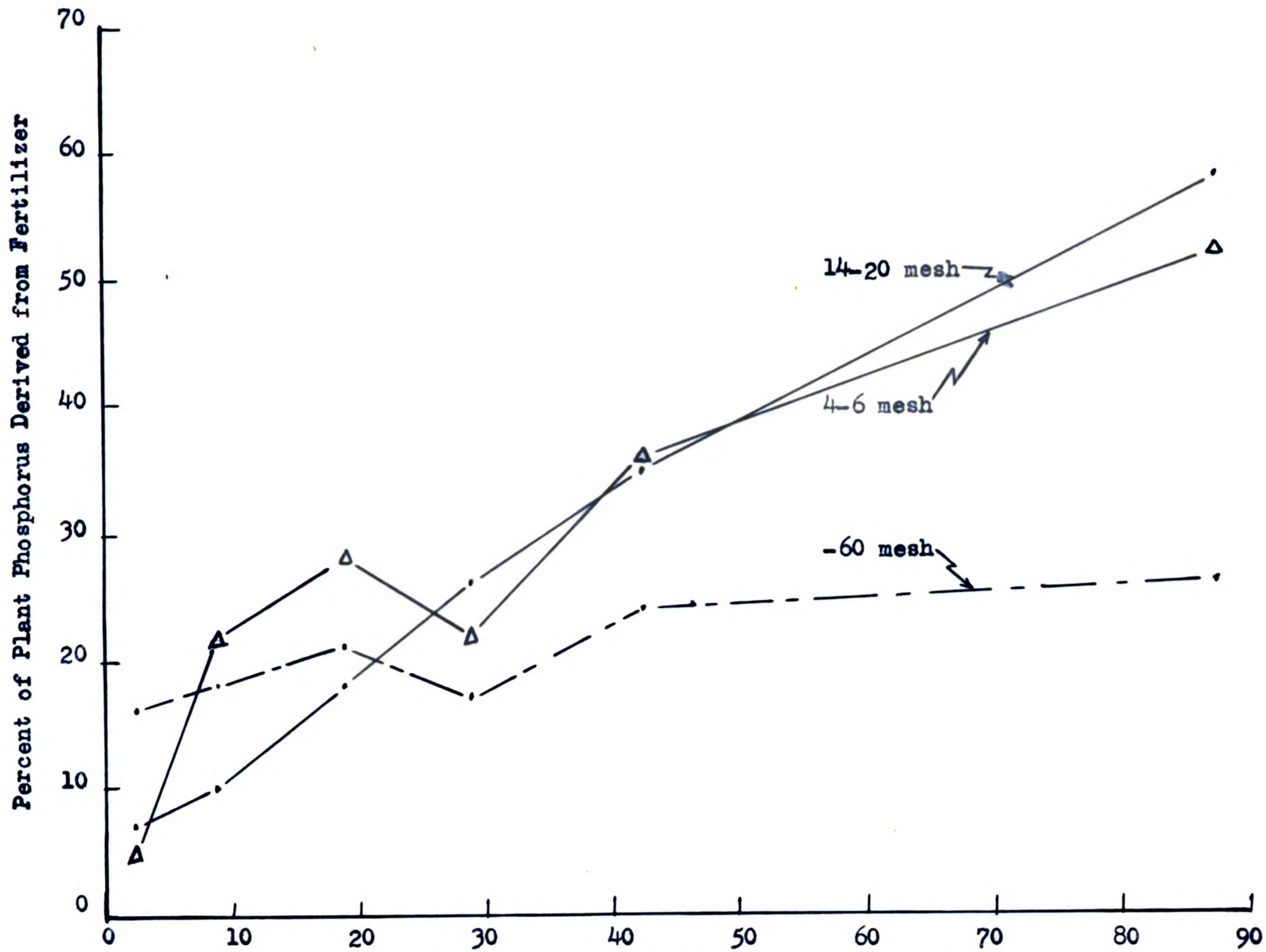

Figure 9. The Relative Uptake of Fertilizer Phosphorus by Eight Week Old Wheat Plants from Mixed Fertilizers Varying in Water-soluble Phosphorus Content and Mesh Size (soil pH 7.5).

plants can be made from data presented in Tables I, II, and III. It was observed that as the percentage of water-soluble phosphorus in the 4 to 6 and 14 to 20 mesh sized fertilizers increased from 2 to 85 the variation in uptake of fertilizer phosphorus by wheat plants was more than 0.65 mg/gm plant material at the 8 weeks old and more than 1.50 mg/gm at the 6 weeks old stage. These relatively wide differences indicate that a direct relationship existed between fertilizer phosphorus uptake and the water-soluble phosphorus content of the fertilizer.

In contrast, the variations in uptake of total phosphorus by wheat plants receiving these same treatments were less than 0.90 mg/gm plant material at both the 6 and 8 weeks sampling time, and were generally considerably less when compared to corresponding variations in fertilizer phosphorus uptake. Also, no definite relationship could be established between total plant phosphorus uptake and the water-soluble phosphorus content of fertilizer.

These data seem to indicate that at later stages of growth the water-soluble fraction of fertilizer phosphorus is the more readily available source of phosphorus to wheat plants. After depletion of this source, phosphorus from the soil is then absorbed by the plant until a relatively near optimum level is reached. This reasoning is further substantiated by data presented in Table IV (see appendix for data by replicates) where soil pH and fertilizer application rates were the only variables considered. As phosphorus application was increased from 30 to 180 pounds of P_2O_5 per acre the uptake of fertil-

Table IV. The effect of rate of application of mixed fertilizers* on the uptake of total and fertilizer phosphorus** by wheat plants*** grown on a Hillsdale sandy loam soil limed to three pH levels.

Pounds P_2O_5 per acre	Sampling date: 3 weeks Plant P from fert.	3 weeks Total plant P	3 weeks Plant P from fert.	6 weeks Plant P from fert.	6 weeks Total plant P	6 weeks Plant P from fert.	8 weeks Plant P from fert.	8 weeks Total plant P	8 weeks Plant P from fert.
	mg/gm plant material		%	mg/gm plant material		%	mg/gm plant material		%
					pH 5.5				
0		1.6			3.0			1.6	
30	0.56	2.4	23	0.73	2.8	26	0.52	2.2	24
120	1.34	2.6	52	1.68	2.4	70	1.17	1.8	65
180	1.64	3.3	50	1.77	2.8	63	1.25	1.8	69
					pH 6.5				
0		2.1			2.5			1.9	
30	0.39	2.6	15	0.48	2.0	24	0.43	1.9	23
120	1.08	3.0	36	1.21	2.4	50	0.95	2.1	45
180	1.30	3.0	43	1.56	2.4	65	1.04	1.7	61
					pH 7.5				
0		2.4			2.4			1.8	
30	0.30	2.8	11	0.39	2.5	16	0.30	2.0	15
120	0.82	2.8	29	1.08	2.6	42	0.82	1.7	48
180	1.04	2.9	36	1.25	2.5	50	0.73	1.3	56

*14 to 20 mesh size and 28 to 30 percent of phosphorus water-soluble.

**Average of three replications.

***Six plants per pot harvested at each sampling date.

izer phosphorus by 6 and 8 week old plants increased over two-fold in all instances, while the total phosphorus absorption showed no definite variation trend as related to the application rate.

These interactions do not hold, however, for the 3 week old wheat plants, in which the uptake of both total and fertilizer phosphorus from 4 to 6 and 14 to 20 mesh fertilizer treatments was directly proportional to the water-soluble phosphorus content of the fertilizer. However, as the amount of phosphorus water-soluble in the fertilizer was increased, the increase in absorption of fertilizer phosphorus was considerably greater than that of total phosphorus. Therefore, the plant absorption of soil phosphorus decreased as the portion of phosphorus water-soluble in the fertilizer was increased. This relationship suggests that limited plant root extension and dissolution of phosphorus out of the granules resulted in total phosphorus absorption that was somewhat below the optimum level of the plant. These limitations wereovercome by increasing root extension and phosphorus dissolution during later stages of growth. Plant uptake data from 6 and 8 week old plants show that wheat plants were eventually able to absorb a near optimum amount of phosphorus regardless of the fertilizer water-soluble phosphorus content.

The relationships between plant uptake of total phosphorus from minus 60 mesh sized fertilizers and the water-soluble phosphorus content of the fertilizer were somewhat similar to those obtained using granular fertilizers. The variations in uptake of total phosphorus at the 3 week sampling, however, were much smaller than corresponding variations from granular fertilizers. Less than 15 percent difference in percentage of plant phosphorus from pulverant fertilizers was recorded for the entire range of water-solubility, regardless of soil pH or stage of plant growth. The relatively uniform plant absorption of fertilizer phosphorus from pulverant materials of low and high water-soluble phosphorus content can be explained on the basis of fixation and dissolution of phosphorus from its compounds. Although essentially insoluble in water, dicalcium phosphate (2 to 3% H_2O-soluble) in the finely divided state presented considerable surface area for dissolution and root contact, resulting in a fairly high availability. Phosphorus in pulverized mono-ammonium phosphate (85 to 90% H_2O-soluble) moved quickly out of very fine particles into the soil, where a considerable portion became fixed in the soil into forms not readily available to wheat plants. This reaction left but slightly greater amounts of readily available phosphorus in the soil than did dicalcium phosphate. These two different reactions resulted in soil-fertilizer systems having rather similar amounts of phosphorus available to plants, regardless of the water-soluble phosphorus content of the fertilizer applied.

Plant absorption of phosphorus from 14 to 20 mesh materials of varying water-soluble phosphorus content was intermediate to that from 4 to 6 and minus 60 mesh particles at each pH level. However, the values for plant uptake of phosphorus from these medium sized particles more closely resembled those obtained from the large particles than those obtained from the use of material finer than 60 mesh.

From the data in Tables I, II, III, and IV it can be observed that the relative phosphorus contents of the wheat plants at the 8 weeks sampling time were generally somewhat lower for all treatments than those from 3 and 6 week old plants.

Liming an acid soil is believed to have resulted in the formation of relatively insoluble calcium phosphates or reduced the proportion of $H_2PO_4^-$ ions in the soil solution. As shown by data presented in Tables I, II, III, and IV and Figures 9 through 18, percent plant absorption of fertilizer phosphorus was highest from soils at pH 5.5, intermediate at pH 6.5 and lowest at pH 7.5.

Tests for available soil phosphorus and field observation indicated a need of phosphate fertilization for optimum crop growth. However, the data presented in Tables V and VI show that the dry weight yields of wheat plants at the full heading stage were not significantly affected by the variables under investigation. Somewhat similar results were reported by Martin et al. (9) who observed that the degree of ammoniation of superphosphate did not affect the yield of lettuce grown on four acid Californian soils deficient in phosphate. However, when phosphate was applied to a calcareous soil the growth response of the lettuce was related to the amount of water-soluble phosphorus in the fertilizer. Starostka et al. (24) also re-

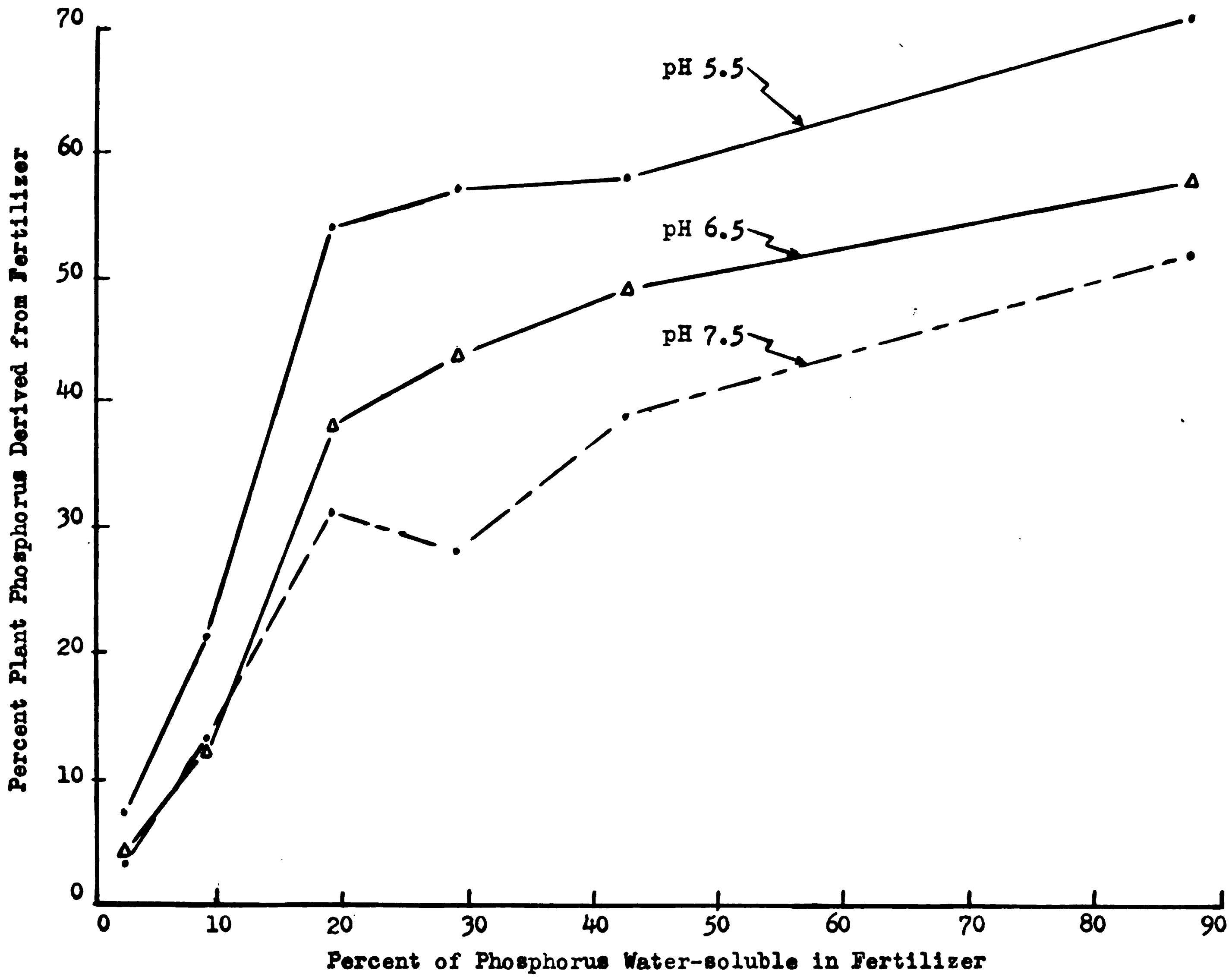

Figure 10. Effect of Soil pH on the Relative Uptake of Phosphorus by Three Week Old Wheat Plants from Fertilizers of Varying Water-soluble Phosphorus Contents (mesh size 4 to 6).

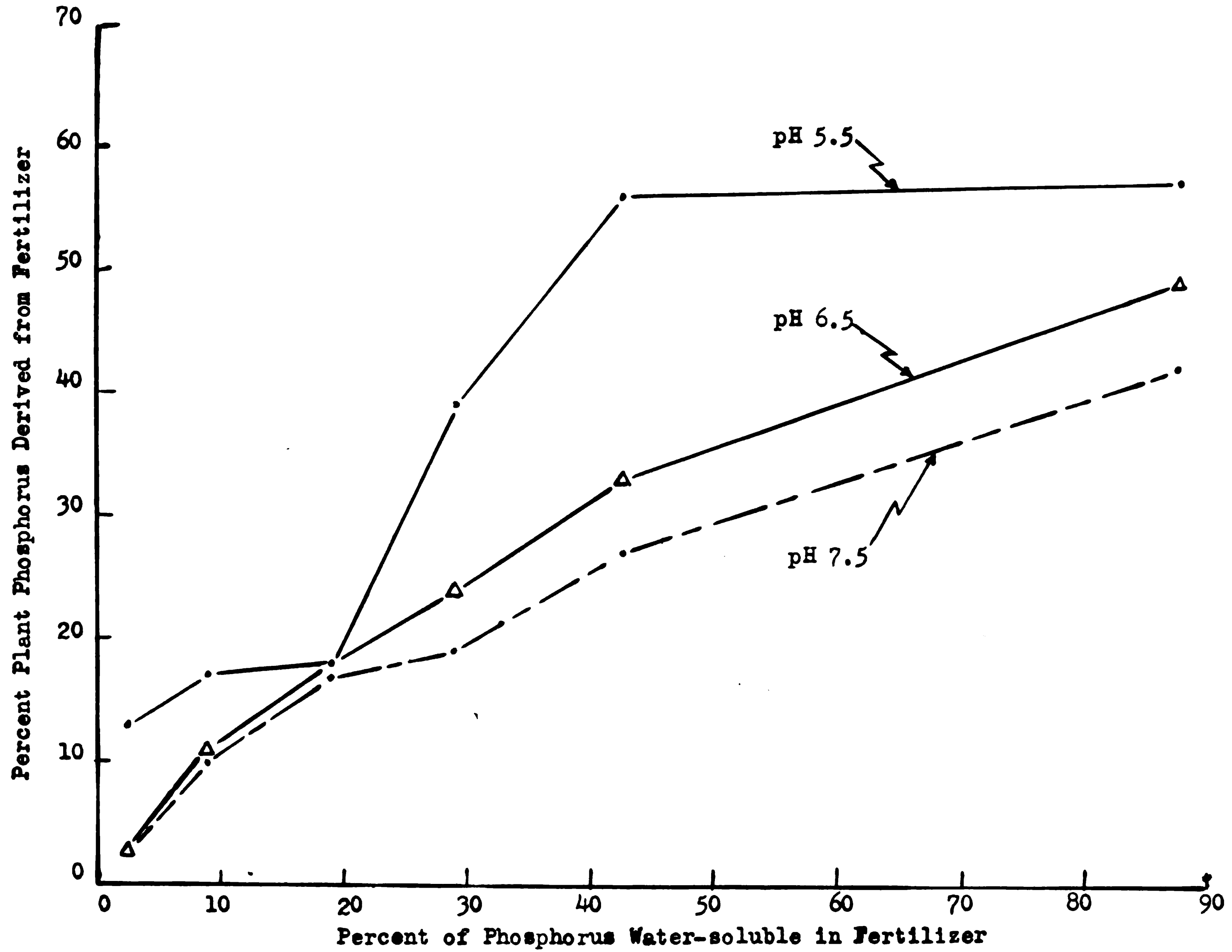

Figure 11. Effect of Soil pH on the Relative Uptake of Phosphorus by Three Week Old Wheat Plants from Fertilizers of Varying Water-soluble Phosphorus Contents (mesh size 14 to 20).

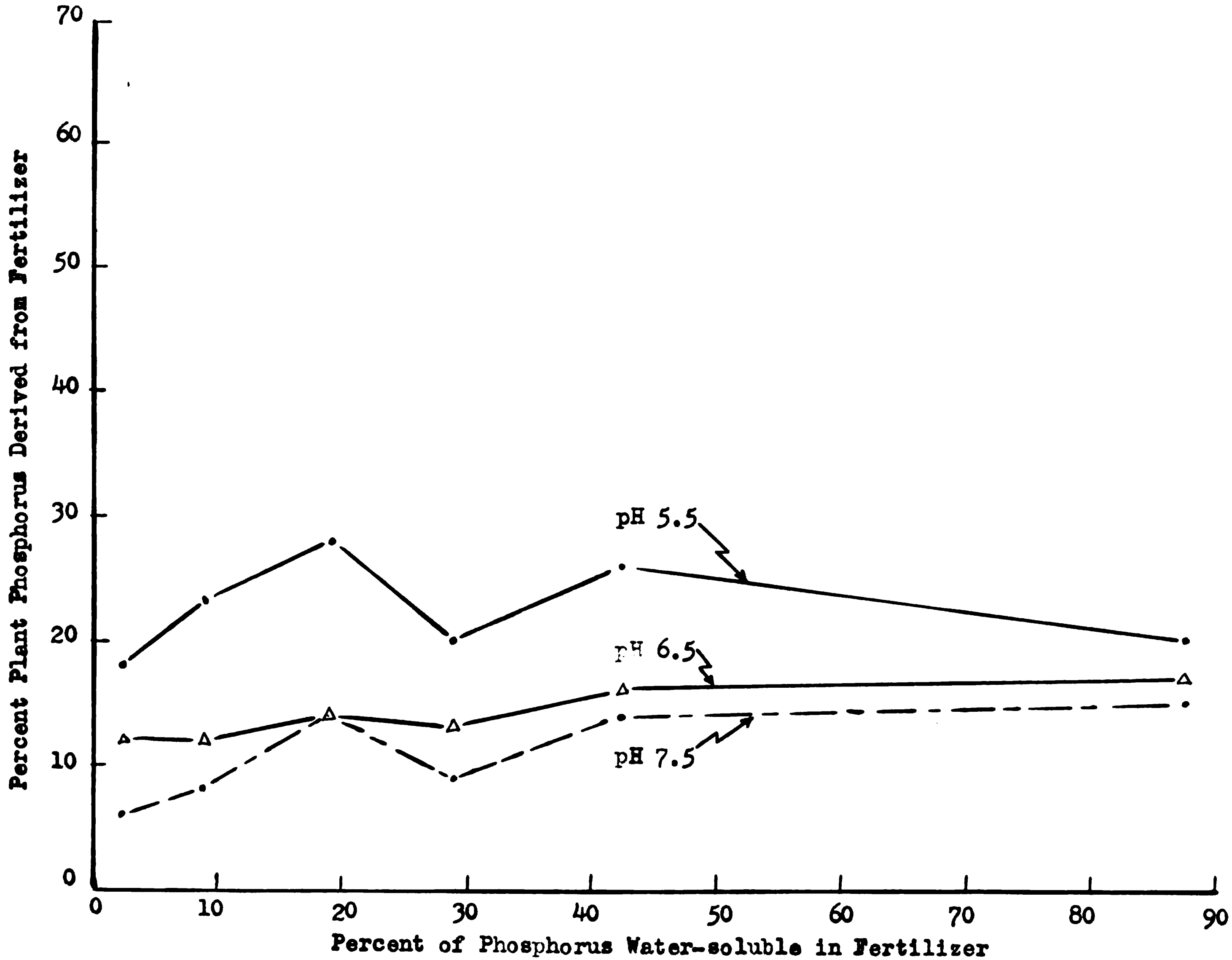

Figure 12. Effect of Soil pH on the Relative Uptake of Phosphorus by Three Week Old Wheat Plants from Fertilizers of Varying Water-soluble Phosphorus Contents (mesh size -60).

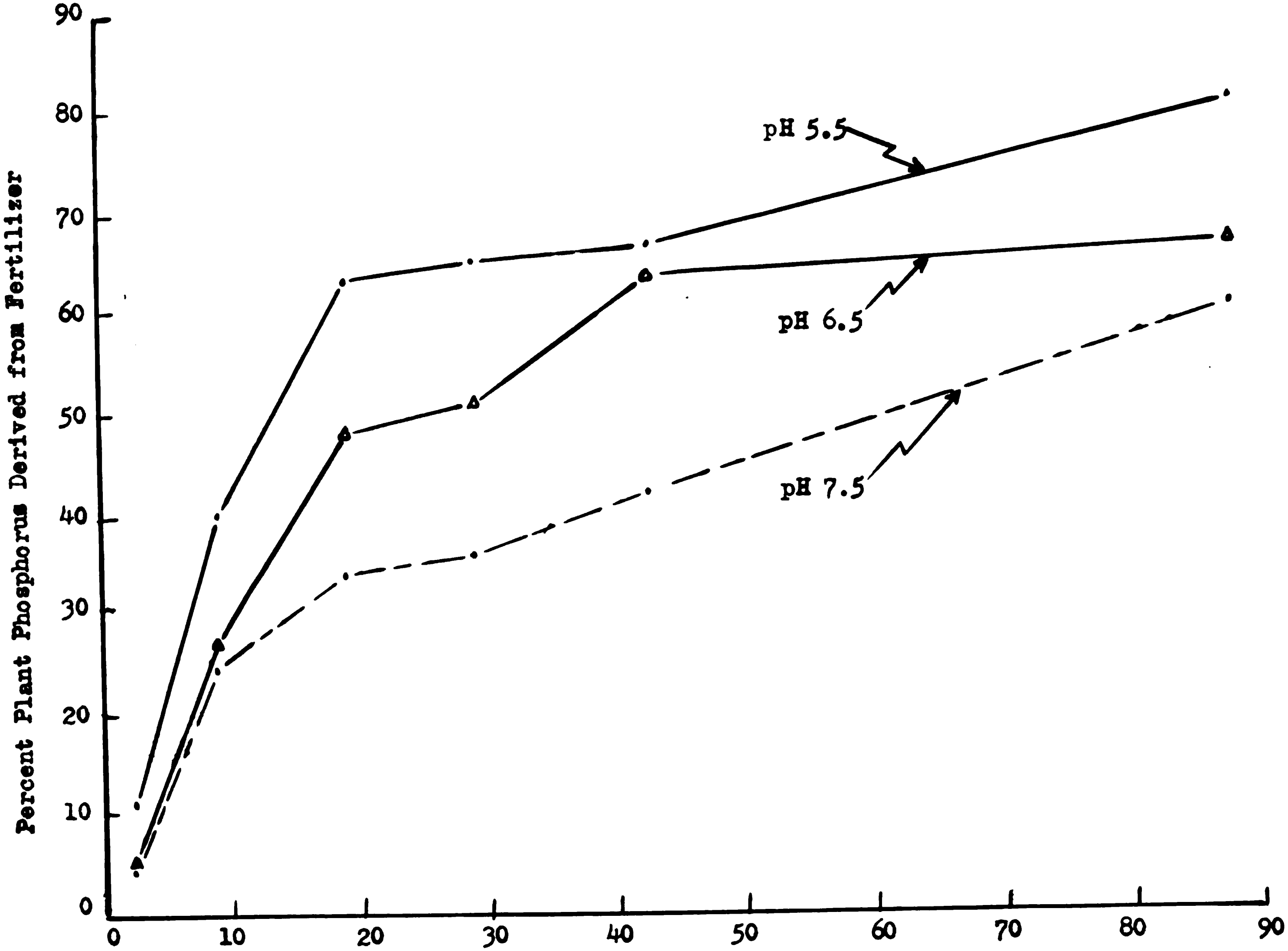

Figure 13. Effect of Soil pH on the Relative Uptake of Phosphorus by Six Week Old Wheat Plants from Fertilizers of Varying Water-soluble Phosphorus Contents (mesh size 4 to 6).

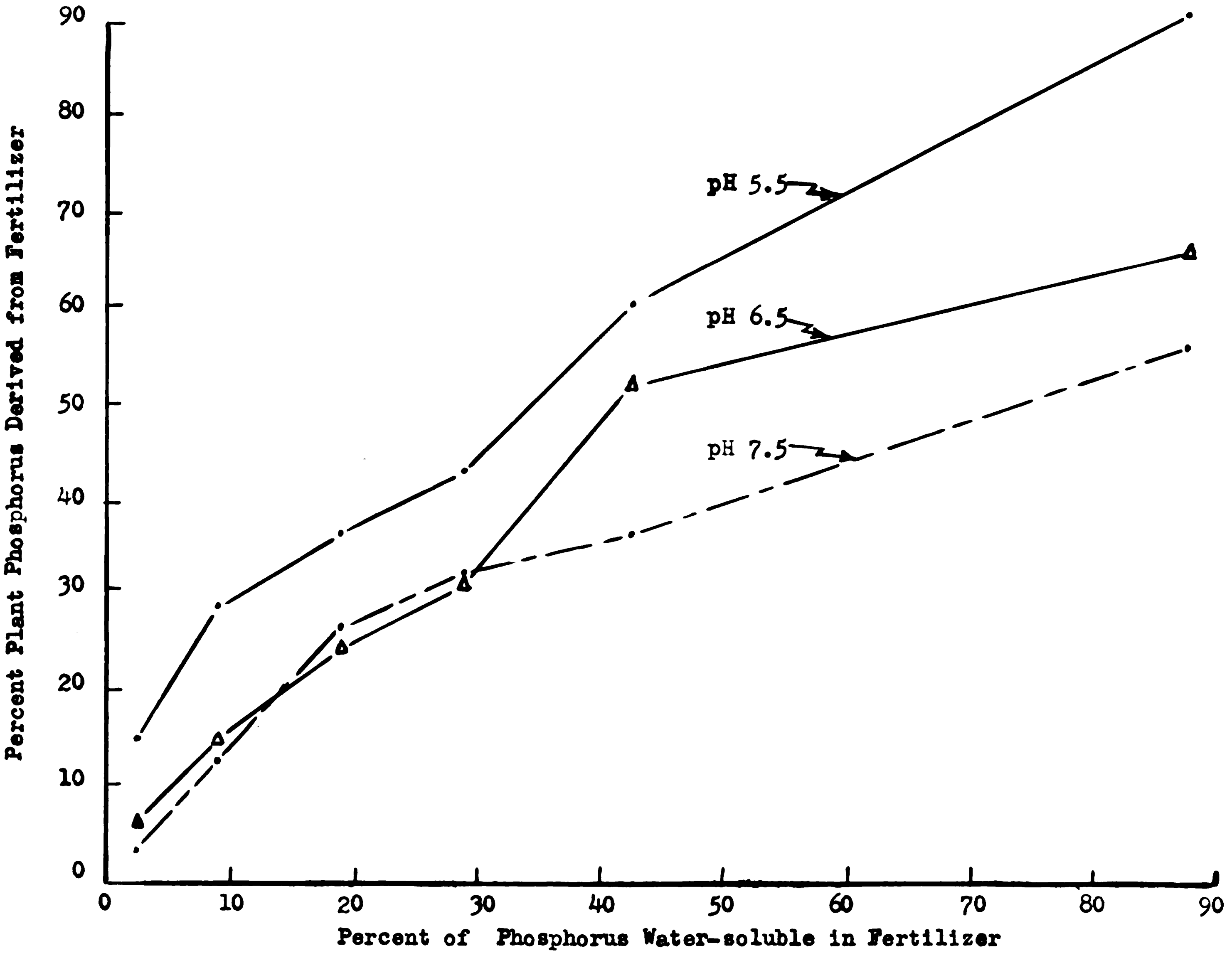

Figure 14. Effect of Soil pH on the Relative Uptake of Phosphorus by Six Week Old Wheat Plants from Fertilizers of Varying Water-soluble Phosphorus Contents (mesh size 14 to 20).

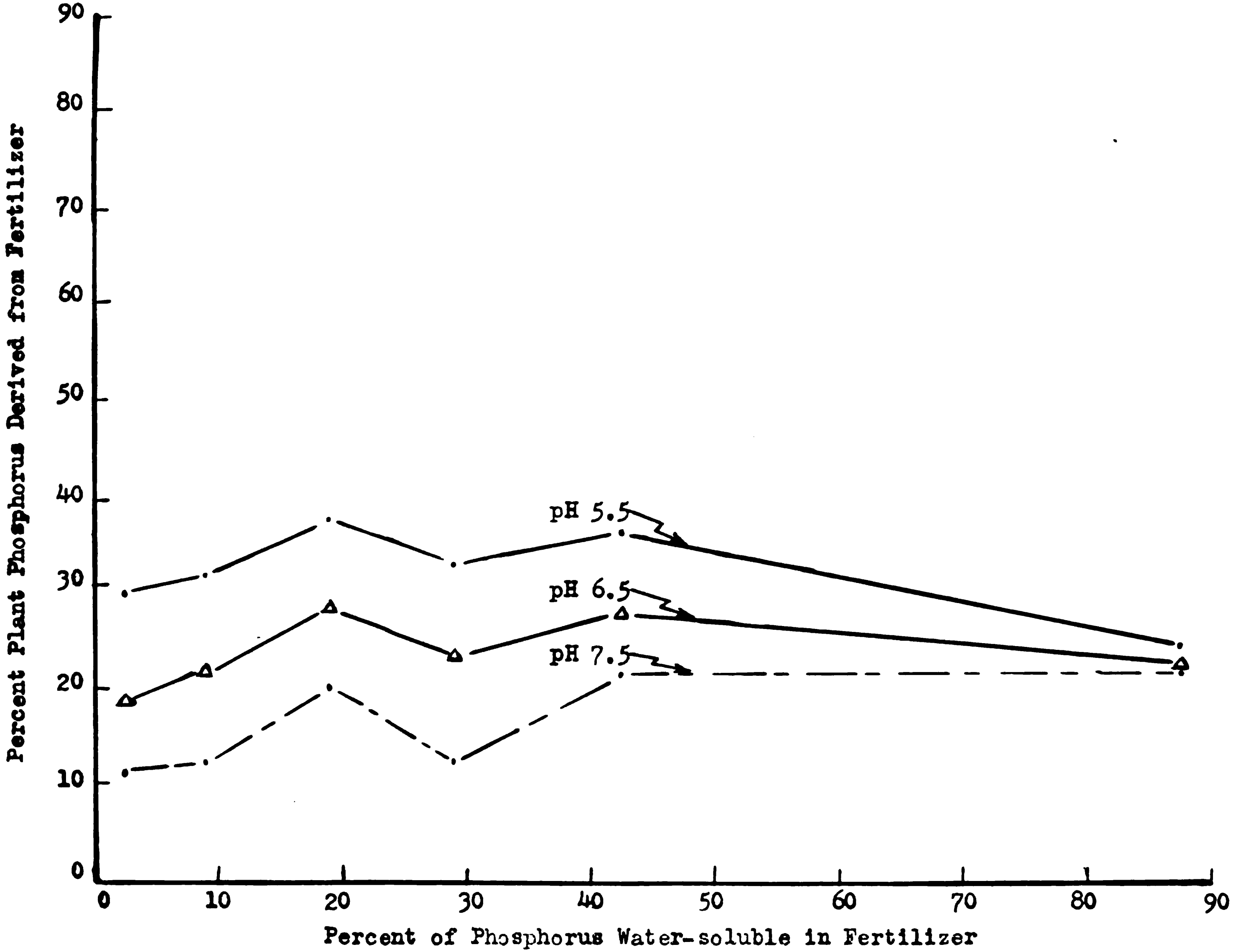

Figure 15. Effect of Soil pH on the Relative Uptake of Phosphorus by Six Week Old Wheat Plants from Fertilizers of Varying Water-soluble Phosphorus Contents (mesh size -60).

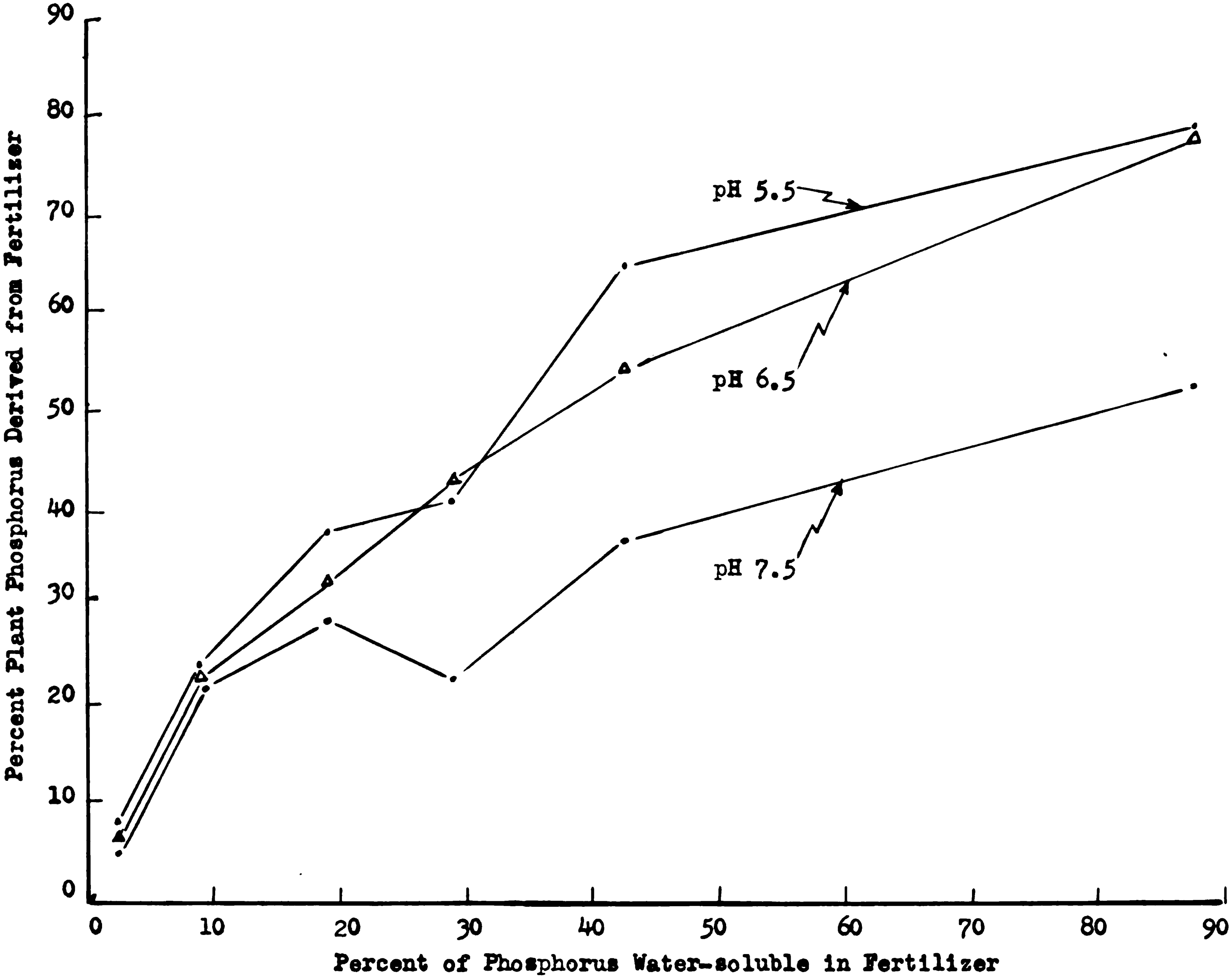

Figure 16. Effect of Soil pH on the Relative Uptake of Phosphorus by Eight Week Old Wheat Plants from Fertilizers of Varying Water-soluble Phosphorus Contents (mesh size 4 to 6).

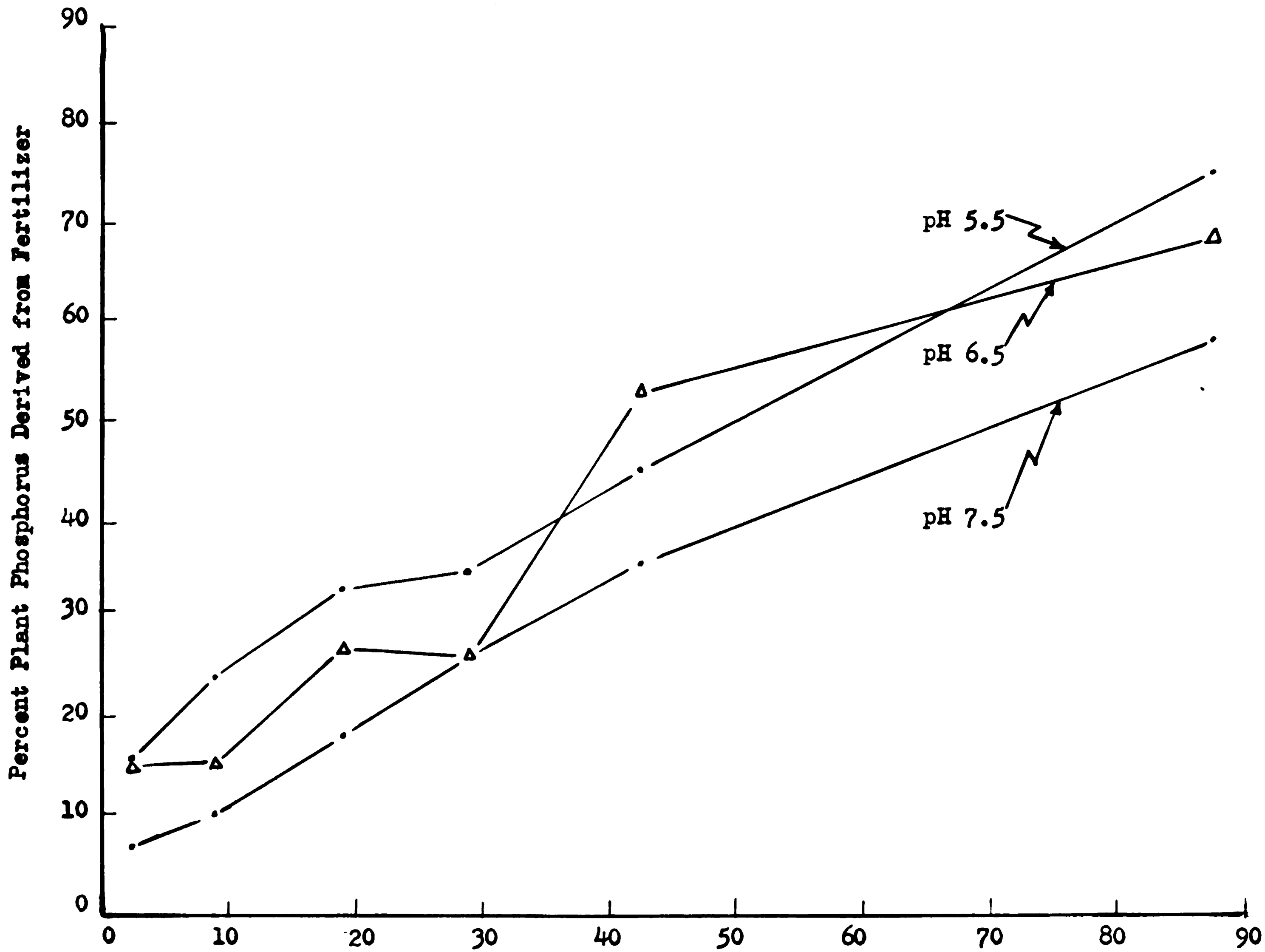

Figure 17. Effect of Soil pH on the Relative Uptake of Phosphorus by Eight Week Old Wheat Plants from Fertilizers of Varying Water-soluble Phosphorus Contents (mesh size 14 to 20).

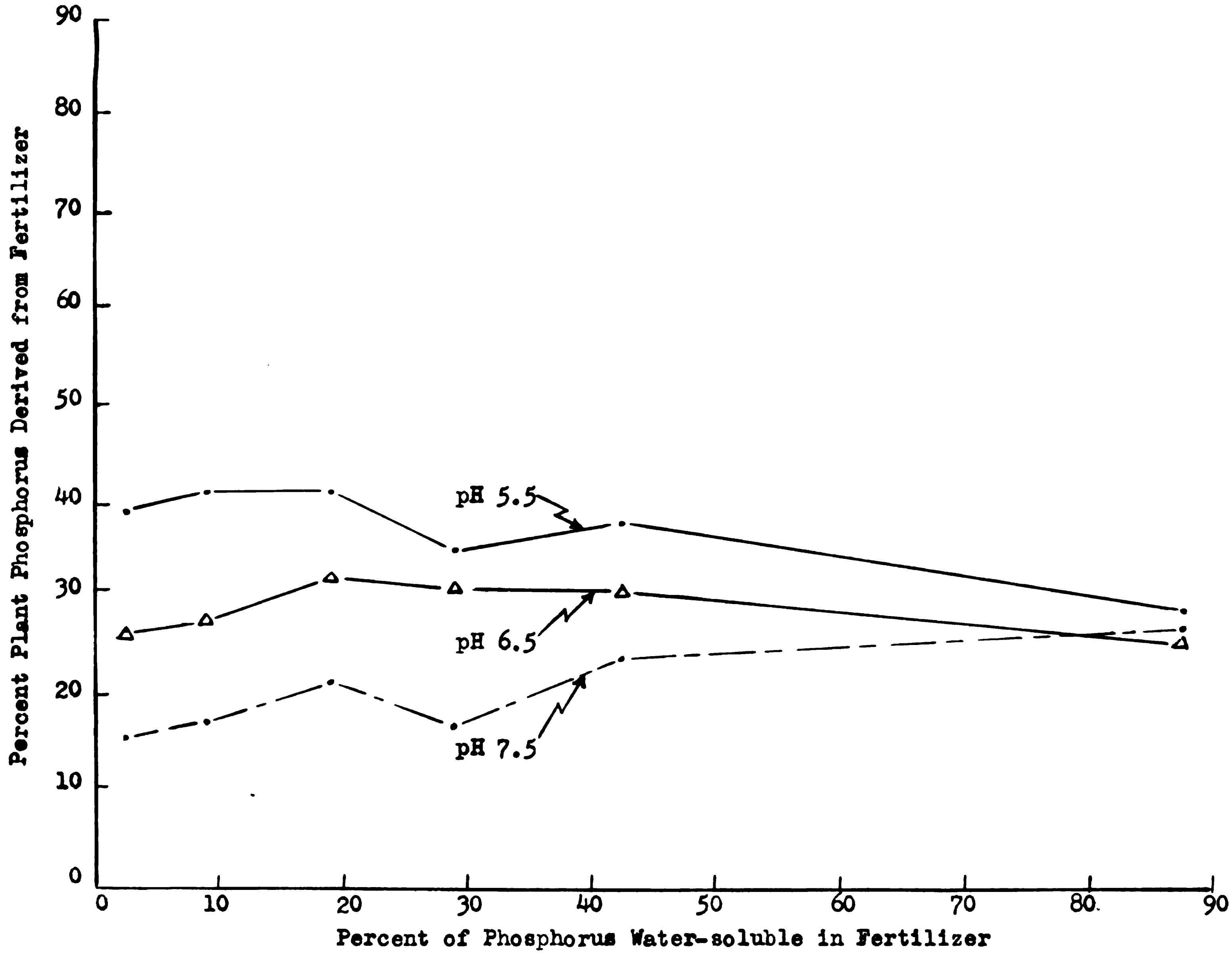

Figure 18. Effect of Soil pH on the Relative Uptake of Phosphorus by Eight Week Old Wheat Plants from Fertilizers of Varying Water-soluble Phosphorus Contents (mesh size -60).

Table V. The effect of rate of application of mixed fertilizers* on the dry weight of wheat plants** grown on a Hillsdale sandy loam limed to three pH levels.

Pounds P_2O_5 per acre	Dry weight yield of wheat plants***		
	pH 5.5	pH 6.5	pH 7.5
pounds	gms/pot	gms/pot	gms/pot
0	13.0	13.3	13.4
30	13.4	13.4	13.7
120	12.9	12.9	13.3
180	13.3	13.9	13.6
L. S. D. at 5% level	N.S.	N.S.	N.S.

*14 to 20 mesh size and 28 to 30 percent of phosphorus water-soluble.
**Six plants per pot harvested 8 weeks after seeding.
***Average of three replications.

ported no yield response from varying the mesh sizes of either superphosphate and dicalcium phosphate fertilizers applied to a sandy clay loam soil.

Field Experiment

A field experiment was conducted to evaluate the effects of water-soluble phosphorus content and mesh size of four 1-2-2 ratio fertilizers on the phosphorus content of sugar beet plants and yield of beets. Values given in Table VII show that with one exception the two mesh size materials tested, 6 to 14 and minus 35, had no significant effect on total phosphorus uptake by sugar beet plants.

Table VI. The effect of water-soluble phosphorus content and particle size of a mixed fertilizer on the dry weight of wheat plants* grown on a Hillsdale sandy loam soil limed to three pH levels.

Water soluble fraction of fertilizer phosphorus	Dry weight of yield of wheat plants**								
	pH 5.5 Mesh per inch			pH 6.5 Mesh per inch			pH 7.5 Mesh per inch		
	4 to 6	14 to 20	-60	4 to 6	14 to 20	-60	4 to 6	14 to 20	-60
percent		gms/pot			gms/pot			gms/pot	
2 to 3	12.6	13.3	13.8	12.7	14.0	13.0	14.1	13.0	13.4
8 to 10	12.9	13.2	13.4	12.6	13.2	12.5	13.7	13.0	13.8
18 to 20	13.2	14.0	14.3	12.8	13.0	13.3	14.6	12.7	12.8
28 to 30	13.8	14.1	14.5	13.5	13.5	13.3	14.2	12.7	13.8
40 to 45	13.6	15.1	13.3	13.1	13.5	13.1	13.5	13.1	14.2
85 to 90	14.0	14.3	13.7	14.7	14.1	13.6	13.8	13.8	13.9
No phosphate		13.0			13.3			13.4	
L.S.D. at 5% level	N.S.	N.S.	N.S.	1.02	N.S.	N.S.	N.S.	N.S.	N.S.

*Six plants per pot harvested 8 weeks after seeding.

**Average of three replications.

Table VII. The effect of water-soluble phosphorus content and particle size of fertilizer on the phosphorus content of sugar beet plants and yield of beets.

Fertilizer analysis	Portion of phosphorus water-soluble	Mesh size	Sampling date after planting*	P content of dry plant tissue**	Yield of beets
	percent	Per inch	Weeks	percent	tons/acre
7-14-14	0	6 to 14	4	0.15	
			8	0.26	10.7
7-14-14	0	35	4	0.17	
			8	0.26	11.3
6-12-12	25	6 to 14	4	0.19	
			8	0.24	11.0
6-12-12	25	35	4	0.15	
			8	0.25	10.2
10-20-20	50	6 to 14	4	0.24	
			8	0.26	9.7
10-20-20	50	35	4	0.22	
			8	0.26	9.0
11-22-22	100	6 to 14	4	0.25	
			8	0.29	11.7
	100	35	4	0.26	
			8	0.27	11.5
L.S.D. at 5% level				0.03	N.S.

*Four week sampling represents 20 plants minus roots; eight week sampling represents 20 recently matured leaves and petioles from individual plants.

**Average of 6 replications.

It was observed however, that as the percentage of water-soluble phosphorus in the fertilizer was increased from 0 to 100 the plant tissue phosphorus content increased from 0.15 to 0.25 percent at the time of the 4 weeks sampling date. This trend indicates that fertilizers with low water-soluble phosphorus contents do not provide enough phosphorus to the plant for optimum growth, when available soil phosphorus is low. This conclusion was further substantiated by the fact that there was a greater prevalence of black root disease in plants on plots receiving the 7-14-14 and 6-12-12 fertilizers. Vigorous young seedlings are not highly susceptible to this disease. However, continued dissolution and plant root extension resulted in similar phosphorus absorption from plots treated with fertilizers of widely varying water-soluble phosphorus contents. Yield data indicate that there were no significant differences resulting from fertilizer treatments.

The relatively low yields obtained from all of the plots were due to an unfavorable planting season. Approximately five inches of rain fell in the last week of May, and a poor stand of beets resulted.

SUMMARY

Greenhouse and field experiments were undertaken to determine the effect of water-soluble phosphorus content and granule size of mixed fertilizers on the availability of phosphorus to plants.

In the greenhouse experiment wheat plants were grown on Hillsdale sandy loam soil limed to three pH levels. Field observations and laboratory tests indicated the soil to be low in available phosphorus. Six 12-12-12 fertilizers having from 2-3 to 85-90 percent of their phosphorus water-soluble were used. All the phosphorus in these materials was citrate-soluble. Each fertilizer was labelled with P^{32} and prepared in mesh sizes of 4 to 6, 14 to 20, and minus 60 per inch. Fertilizers were applied at the rate of 500 pounds per acre and the soil placed in four-gallon jars.

The following results were obtained:

1. Plant absorption of phosphorus from granular fertilizers was directly proportional to the water-soluble phosphorus content of the fertilizer, regardless of growth stage.

2. Soil-fertilizer systems resulting from pulverant fertilizer application had similar amounts of phosphorus available to plants regardless of the water-soluble phosphorus content of the fertilizer.

3. Absorption of total phosphorus by 3 week old wheat plants was directly proportional to the water-soluble phosphorus content of all mesh sized fertilizers tested.

4. At later stages of growth no relationship existed between the uptake of total phosphorus by the plant and the water-soluble phosphorus content of the fertilizer.

5. Percent plant absorption of fertilizer phosphorus was highest from soils at pH 5.5, intermediate at pH 6.5 and lowest at pH 7.5.

6. Phosphorus content of wheat plants was generally less at the full heading stage than at earlier stages of growth.

7. Dry weight yields of wheat plants at the full heading stage were not significantly affected by the variables under investigation.

In a field experiment sugar beet plants were grown on Kawkawlin loam soil of pH varying from 6.8 to 7.5. The soil tested medium for available phosphorus. Four 1-2-2 ratio fertilizers having from 0 to 100 percent of their phosphorus water-soluble were used. All the phosphorus in these materials was citrate-soluble. Mesh sizes 6 to 14 and minus 35 per inch of each formulation were tested. A total of 140 pounds of P_2O_5 was applied broadcast, one-half before plowing and the remainder after plowing.

The results may be summarized as follows:

1. Plant absorption of total phosphorus at the 4 weeks sampling was directly proportional to the water-soluble phosphorus content of the fertilizer. Four week old sugar beet plants grown on plots treated with fertilizers low in water-soluble phosphorus showed phosphorus deficiency symptoms.

2. During later stages of growth sugar beet plants absorbed similar amounts of phosphorus from plots treated with fertilizers of widely varying water-soluble phosphorus contents.

3. The two mesh sized materials tested, 6 to 14 and minus 35, had no significant effect on phosphorus uptake by sugar beet plants.

4. Sugar beet yields failed to show any significant differences resulting between fertilizer treatments.

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APPENDIX

Table 1. The relative uptake of total and fertilizer phosphorus by wheat plants from mixed fertilizers varying in water-soluble phosphorus content and mesh size (soil pH 5.5).

Mesh size	Portion of P H_2O-sol.	Plant P from fertilizer sampling date 3 weeks	6 weeks	8 weeks	Total plant phosphorus Sampling date 3 weeks	6 weeks	8 weeks
	%	mg/gm plant material			mg/gm plant material		
4 to 6	2 to 3	0.21	0.21	0.21	2.3	1.5	2.3
		0.14	0.21	0.14	2.3	2.2	2.2
		0.14	0.24	0.14	2.2	2.1	2.1
	8 to 10	0.26	0.74	0.48	2.4	2.4	2.2
		0.78	1.22	0.48	2.6	---	1.9
		0.61	0.91	0.48	3.0	2.4	1.8
	18 to 20	----	1.40	0.64	2.7	2.3	1.6
		1.66	1.57	0.60	3.2	2.1	1.2
		1.53	1.40	0.55	3.2	2.6	2.1
	28 to 30	----	1.43	0.61	3.2	2.5	1.5
		1.91	1.61	0.91	3.3	2.4	1.8
		1.74	1.52	0.69	3.2	2.3	2.1
	40 to 45	1.69	1.97	1.14	3.2	3.0	1.7
		2.44	1.81	0.67	4.1	2.5	1.1
		2.48	1.62	0.67	4.2	2.6	1.1
	85 to 90	3.08	2.22	1.11	4.4	2.5	1.6
		3.04	2.18	1.27	4.4	2.7	1.5
		2.96	2.18	1.19	4.1	2.9	1.4
14 to 20	2 to 3	0.20	0.40	0.32	1.6	2.4	1.8
		0.16	0.44	0.44	2.2	2.7	2.4
		0.32	0.40	0.36	2.1	---	2.1
	8 to 10	0.36	0.57	0.40	2.4	---	2.0
		0.44	0.65	0.48	2.2	2.4	2.1
		0.44	0.61	0.53	2.2	2.1	2.0

Table 1 (cont.).

	18 to 20	0.72	0.81	0.68	3.0	2.1	2.1
		0.72	0.89	0.68	2.5	2.2	2.0
		0.72	0.77	0.68	2.4	---	2.2
	28 to 30	0.91	0.82	0.60	2.4	2.1	2.0
		0.82	0.99	0.65	2.2	2.3	2.0
		0.82	0.99	0.60	2.0	2.4	1.6
	40 to 45	1.46	1.25	0.69	2.3	2.2	1.3
		1.89	1.33	0.77	2.9	2.1	1.9
		1.89	1.42	0.86	2.8	2.5	1.8
	85 to 90	2.04	1.87	0.87	3.3	2.5	1.0
		2.16	----	1.12	3.5	---	1.7
		1.87	2.08	1.16	3.2	1.9	1.5
minus 60	2 to 3	0.46	0.62	0.96	2.6	2.4	2.1
		0.54	0.79	0.71	2.7	2.2	1.7
		0.37	0.62	0.62	2.3	2.2	1.8
	8 to 10	0.65	----	0.78	2.5	2.8	2.0
		0.61	0.92	0.78	2.7	2.8	1.8
		0.57	0.78	0.78	2.7	---	---
	18 to 20	0.68	1.05	0.82	1.9	2.5	1.9
		0.64	0.82	----	2.4	2.4	1.8
		0.67	0.96	0.64	2.8	2.6	1.8
	28 to 30	0.62	0.62	0.62	2.7	2.2	1.8
		0.50	0.75	0.67	2.4	2.0	2.1
		0.42	0.67	0.67	2.4	2.0	2.0
	40 to 45	0.63	0.75	0.67	2.4	2.3	2.0
		0.63	0.88	0.71	2.6	2.4	1.9
		0.58	0.79	0.83	2.2	2.0	2.0
	85 to 90	0.57	0.57	0.50	2.7	2.5	1.8
		0.54	0.67	0.54	2.6	2.5	---
		0.47	0.57	0.47	2.7	---	1.8

Table 2. The relative uptake of total and fertilizer phosphorus by wheat plants from mixed fertilizers varying in water-soluble phosphorus content and mesh size (soil pH 6.5).

Mesh size	Portion of P H_2O-sol.	Plant P from fertilizer Sampling date 3 weeks	6 weeks	8 weeks	Total plant phosphorus Sampling date 3 weeks	6 weeks	8 weeks
	%	mg/gm plant material			mg/gm plant material		
4 to 6	2 to 3	0.10	---	0.10	2.7	2.3	2.0
		0.10	0.10	0.21	2.5	2.3	1.6
		0.14	0.10	0.14	2.4	1.9	2.0
	8 to 10	0.48	0.56	0.35	2.5	2.3	1.5
		0.13	0.61	0.39	2.6	2.3	2.1
		0.35	0.65	0.39	2.4	---	1.7
	18 to 20	----	1.32	0.77	2.4	2.1	2.1
		0.85	0.72	0.60	2.0	2.2	2.3
		1.23	1.11	0.64	3.1	2.3	1.9
	28 to 30	1.65	1.09	0.74	3.4	2.0	1.4
		1.48	1.09	0.69	3.2	2.0	1.8
		1.09	1.17	0.56	2.9	2.5	1.5
	40 to 45	1.26	1.89	0.83	3.0	2.5	1.2
		1.93	1.06	0.75	3.8	2.0	1.4
		1.73	1.14	0.75	3.4	2.1	1.6
	85 to 90	2.30	1.81	1.19	4.2	2.9	1.3
		2.63	1.73	0.86	4.6	2.6	1.3
		2.59	2.06	1.19	4.0	2.6	1.3
14 to 20	2 to 3	0.08	0.20	0.28	2.4	2.0	1.8
		0.08	0.16	0.24	2.5	2.4	1.3
		0.08	0.12	0.24	2.6	2.1	1.8
	8 to 10	0.28	0.32	0.32	2.4	2.0	1.8
		0.32	0.32	0.28	2.6	2.0	2.1
		0.28	0.20	0.36	2.5	1.8	1.7

Table 2 (cont.).

	18 to 20	0.51	0.51	0.47	---	2.6	2.1
		0.60	0.68	0.47	2.9	2.1	1.7
		0.60	0.64	0.55	3.1	2.7	2.2
	28 to 30	0.60	0.69	0.56	2.9	2.4	2.1
		0.60	0.65	0.52	2.9	2.3	1.4
		0.65	0.65	0.52	2.8	2.0	2.3
	40 to 45	0.99	0.99	0.95	3.2	1.7	1.9
		1.08	1.08	0.69	3.1	2.3	1.9
		1.03	0.99	0.60	2.9	2.0	2.1
	85 to 90	1.83	1.91	0.71	3.7	3.0	1.3
		1.87	1.79	1.04	3.6	2.9	1.5
		1.83	1.71	1.08	3.8	2.2	1.5
minus 60	2 to 3	----	----	----	2.6	2.5	2.2
		0.25	0.46	0.58	2.3	2.3	2.2
		0.29	0.46	0.50	2.3	2.5	2.0
	8 to 10	0.31	0.70	0.78	2.5	2.5	1.8
		0.35	0.52	0.57	2.7	2.7	2.5
		0.26	0.52	0.52	2.5	---	2.5
	18 to 20	0.37	0.68	0.59	2.8	2.7	2.2
		0.37	0.68	0.64	2.5	2.8	2.0
		0.37	2.64	0.77	2.3	1.8	2.3
	28 to 30	0.33	0.50	0.67	2.6	2.2	2.1
		0.33	0.50	0.62	2.6	2.5	2.3
		0.33	0.58	0.75	2.4	---	2.2
	40 to 45	0.38	0.54	0.58	2.8	1.5	2.2
		0.46	0.54	0.50	2.6	2.3	1.5
		0.50	0.54	0.54	3.0	2.3	1.8
	85 to 90	0.47	0.57	0.44	3.0	2.6	1.9
		0.54	0.57	0.44	3.2	2.3	1.7
		0.47	0.54	0.50	2.9	---	2.0

Table 3. The relative uptake of total and fertilizer phosphorus by wheat plants from mixed fertilizers varying in water-soluble phosphorus content and mesh size (soil pH 7.5).

Mesh size	Portion of P H_2O-sol.	Plant P from fertilizer Sampling date 3 weeks	6 weeks	8 weeks	Total plant phosphorus Sampling date 3 weeks	6 weeks	8 weeks
	%	mg/gm plant material			mg/gm plant material		
4 to 6	2 to 3	0.10	0.10	0.10	2.4	---	1.1
		0.10	0.10	0.10	2.4	2.0	1.8
		0.10	0.10	0.10	2.5	2.1	1.3
	8 to 10	----	0.52	0.26	2.9	2.4	1.5
		0.39	0.61	0.26	2.6	2.4	1.0
		0.30	0.56	0.22	2.6	1.9	1.0
	18 to 20	0.77	0.77	0.38	2.9	1.9	0.9
		1.06	0.81	0.34	3.2	2.4	1.5
		0.94	0.64	0.34	3.0	2.3	1.4
	28 to 30	0.87	0.69	0.39	3.0	2.5	1.5
		0.78	0.87	0.35	3.1	2.3	1.9
		0.95	0.95	0.35	---	2.1	1.5
	40 to 45	1.34	1.18	0.39	3.2	2.7	1.1
		1.38	1.10	0.59	3.6	2.8	1.4
		1.18	1.02	0.59	3.1	2.4	1.7
	85 to 90	1.73	1.69	0.86	3.5	2.9	1.7
		2.34	1.64	0.83	3.9	2.8	1.4
		1.81	1.77	0.70	3.9	2.9	1.4
14 to 20	2 to 3	0.08	0.08	0.16	2.6	2.4	1.8
		0.08	0.08	0.12	2.5	2.8	1.7
		0.08	0.08	0.12	2.5	1.7	1.7
	8 to 10	0.20	0.28	0.16	2.3	2.3	1.8
		0.24	0.24	0.20	2.5	2.2	2.2
		0.24	0.24	0.24	2.8	2.4	2.3

Table 3 (cont.)

	18 to 20	0.55	0.60	0.26	2.8	2.3	2.1
		0.38	0.60	0.38	2.7	2.2	1.7
		0.43	0.60	0.34	2.7	---	---
	28 to 30	0.43	0.69	0.43	2.5	---	2.1
		0.56	0.69	0.52	3.0	2.3	2.0
		0.60	0.65	0.56	3.1	2.1	2.0
	40 to 45	0.73	1.08	0.56	3.0	2.9	1.7
		0.77	0.95	0.52	2.9	2.4	1.4
		0.82	0.86	0.56	2.9	2.5	1.8
	85 to 90	1.37	1.71	0.92	3.2	2.8	1.8
		1.33	1.33	0.87	3.1	2.5	1.4
		1.33	1.66	----	3.3	3.0	1.7
minus	2 to 3	0.21	0.29	0.47	2.9	2.4	---
60		0.12	0.21	0.25	2.4	2.3	1.7
		0.21	0.25	0.25	2.9	2.2	1.9
	8 to 10	0.22	0.26	0.31	2.6	2.3	1.7
		0.22	0.26	0.39	2.6	2.5	2.0
		0.26	0.26	0.39	2.8	2.2	2.1
	18 to 20	0.27	0.32	0.36	2.9	2.4	2.0
		----	0.73	0.55	2.2	2.8	2.2
		0.46	0.46	0.46	2.9	2.2	2.3
	28 to 30	0.21	0.29	0.33	2.9	2.5	1.9
		0.21	0.37	0.37	2.7	2.8	2.1
		0.21	0.37	0.37	2.8	2.8	1.8
	40 to 45	0.46	0.42	0.33	2.9	2.0	1.6
		0.42	0.42	0.29	2.9	1.7	1.2
		0.33	0.42	0.33	---	2.2	1.5
	85 to 90	0.47	0.50	0.37	2.9	2.4	1.2
		0.47	0.50	0.34	2.9	2.4	1.3
		0.37	0.47	0.30	2.9	2.5	1.4

Table 4. The effect of rate of application of mixed fertilizers* on the relative uptake of total and fertilizer phosphorus by wheat plants grown on a Hillsdale sandy loam soil limed to three pH levels.

Pounds P_2O_5 per acre	Plant P from fertilizer Sampling date 3 weeks	6 weeks	8 weeks	Total plant phosphorus Sampling date 3 weeks	6 weeks	8 weeks
pounds	mg/gm plant material			mg/gm plant material		
			pH 5.5			
0				1.8	2.8	2.0
				1.5	3.3	1.5
				1.6	3.1	2.0
30	0.60	0.73	0.48	2.5	2.9	2.1
	0.60	0.78	0.48	2.4	---	2.4
	0.48	0.73	0.60	2.2	2.6	2.1
120	1.25	1.77	1.25	2.6	2.7	1.8
	1.34	1.77	1.08	2.7	---	1.9
	1.38	1.56	1.12	2.5	2.2	1.6
180	1.64	1.64	1.25	3.3	2.8	2.0
	1.68	1.99	1.25	3.3	2.7	2.0
	1.56	1.68	1.30	3.2	---	1.5
			pH 6.5			
0				1.9	2.8	1.9
				2.3	2.3	2.0
				2.1	2.5	1.8
30	0.43	0.48	0.43	2.7	2.0	2.1
	0.39	0.56	----	2.4	---	1.9
	0.39	0.43	0.39	2.7	---	1.8
120	1.12	1.25	----	3.2	2.2	2.1
	1.08	1.21	0.91	2.9	2.5	1.9
	1.04	1.12	0.99	2.9	2.4	2.3
180	1.30	1.68	1.21	3.1	2.5	2.5
	1.34	1.56	0.86	2.9	2.2	1.1
	1.21	1.47	0.99	2.9	2.4	1.6

Table 4 (cont.)

			pH 7.5			
0				2.3	2.5	1.8
				2.5	2.8	1.7
				2.5	2.1	1.7
30	0.30	0.35	0.30	3.0	2.6	1.5
	0.30	0.39	0.35	2.7	2.2	2.3
	0.26	0.39	0.30	2.7	2.7	2.1
120	0.82	1.08	0.78	2.7	2.8	1.5
	0.73	1.17	0.86	2.7	3.0	2.1
	0.91	0.99	0.82	2.9	2.1	1.6
180	1.12	1.43	0.86	3.0	2.5	1.2
	1.04	1.12	0.65	2.8	2.2	1.5
	0.99	1.21	0.73	3.0	2.7	1.2

*14 to 20 mesh size and 28 to 30 percent of phosphorus water-soluble.