AVAILABILITY OF APPLIED PHOSPHORUS TO

WHEAT GROWN ON FOURTEEN OKLAHOMA

SOILS IN GREENHOUSE POTS

By

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I INTRODUCTION

Soil Plant Relations in Phosphorus Uptake

Plant growth requires a net removal of phosphorus from the soil system into the plant. There is a continuous release of phosphorus from the solid phase into the soil solution, a continuous metabolic removal of phosphorus from the soil solution by the plant, and a subsequent incorporation of phosphorus into the plant system. For any short time interval in a given environment, the amount of phosphorus released by the soil equals the amount removed by the plant. Thus, the soil-plant system is in a steady state with regard to phosphorus uptake and removed by the plant. One of the objectives of the field of soil chemistry and fertility has been to determine the fertilizer needs of a soil by means of chemical methods. Bray (5)[1] reviewed the historical development of this subject, and noted that, in general, three methods have been followed in establishing the fertilizer needs of a given soil: (1) the experiment field method, (2) the pot culture method, and (3) chemical studies of the soil and elemental uptake by plants growing on the soil. Early studies involved total analysis of the soil, but no practical recommendations for the needs of the soil were given. Later more promising procedures were developed and rather broad correlations between chemical tests and field responses were obtained. At this stage, the basic concept involved not only the idea of measuring the availability of the element in question, but also the procedure to be

[1]Figures in parentheses refer to Literature Cited.

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followed. For example, it was thought that the chemical method of extraction should imitate closely the absorption of elements by plant roots. However, advances in this branch of knowledge made these concepts appear inadequate. The latest concept of an extracting solution is one that can extract all of that form or forms of the element being tested for and which have, therefore, "a purely chemical basis". The chemical methods must be correlated with fertility studies using the plants and soils on which the tests are to be applied.

The objectives of the research reported in this work were: (1) to review the background of research on soil testing and soil phosphorus and (2) to determine the relationship between phosphorus uptake and growth of plants grown on soils of widely divergent characteristics and with various amounts phosphorus fertilizer.

II LITERATURE REVIEW

Soil-plant relations in phosphorus uptake and soil testing procedures have been studied for many years by soil scientists. Williams (44) stated that in determining the so-called "available phosphorus," many methods have been developed in an attempt to assess the fertility requirement of the soil or its ability to supply phosphorus to growing plants. Most of these methods are empirical and must be correlated with field experiments before they can be used as a source of information. The chemical methods usually extract the soil with a solution which, it is hoped, will dissolve that fraction of the soil phosphorus which would be utilized by the plant.

Olsen et al. (31) discussed the characteristics of a useful chemical extractant for available soil phosphorus. They identified these characteristics as: (a) measure all of a definite proportion of the various forms of phosphorus in the same relative amounts as they are absorbed by plants during the growing season; (b) correlate to a high degree with plant uptake of phosphorus and yield response to added phosphorus over a wide range of soil types; (c) minimize the secondary precipitation and adsorption reactions that may occur during extraction; and (d) be adaptable to routine-test procedures.

Freid and Shapiro (18) divided phosphorus uptake by plants from a soil system into four stages: (1) release of the phosphate ion from the solid phase into the soil solution; (2) movement of the phosphate ion from any point in the soil solution to the vicinity of the root;

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(3) movement of the ion from the vicinity of the root into the root; and
(4) movement of the phosphate ion from the root to the shoot. They show
the soil-plant relations in phosphate absorption by the plant as the follow-
ing equilibrium equation where $\underline{P}$ is a phosphate ion.

P(minerals)

diffusion

P(soil solution)   P(vicinity of root)

bulk movement

P(adsorbed)

phloem   P(in roots)

P(in plant)
top

xylem
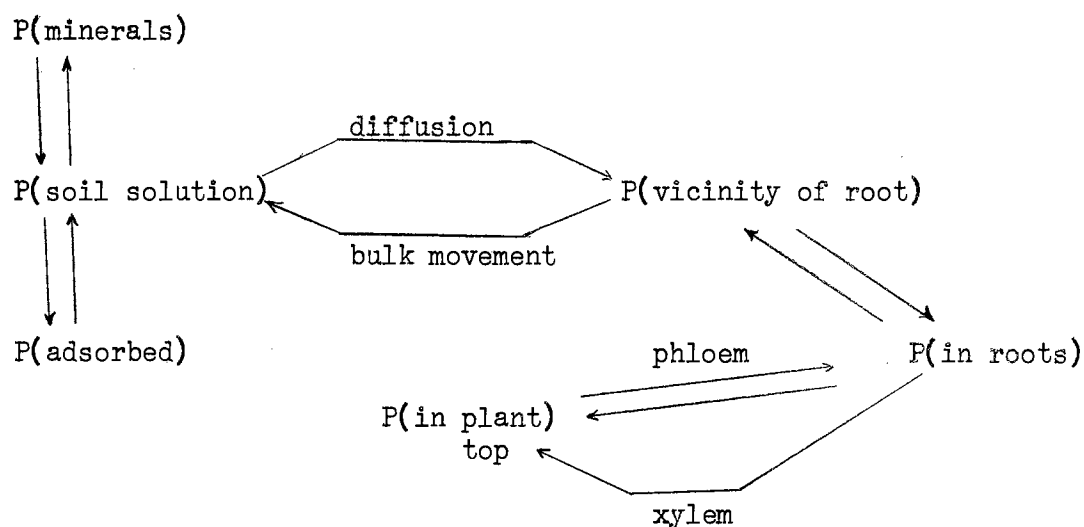
The concentration of phosphate in the soil solution is determined
by the nature of the solid phase and is best described by adsorption
equations, insofar as seasonal growth of crop plants is concerned.
The phosphate ion moves toward the root by diffusion along with the
bulk of the water movement. The ion is either stored in the soil in the
vicinity of the root, or moves into the root either by an active or
passive process. The probable process is the active one, involving a
carrier mechanism and described by such biological constants as an
apparent dissociation constant. The ions that reach the transpiration
stream move along a pathway of living cells. The ions are then used for
metabolism and growth.

The Phosphorus Compounds

According to Russell (34) four groups of phosphorus compounds have been shown to exist in the soil: (1) Inorganic minerals containing phosphates as a part of their structure. Hydroxy apatites ($Ca(OH)2.3Ca(PO4)2$), and fluorapatites ($CaF_2.3Ca3(PO4)2$) are the most widespread, but iron and aluminum phosphates also occur under some conditions; (2) Insoluble calcium phosphates produced when soluble phosphates are added to the soil, however it is still uncertain what these compounds are. Dicalcium phosphate $CaH(PO4)2$ almost certainly occurs, and the tricalcium phosphate ($Ca3(PO4)2$) probably does not occur as a compound of this composition, but $Ca4H(PO4)3$ may be present as intermediate compounds of tricalcium phosphate. Calcium phosphates probably become converted to hydroxyapatite with this compound (octaphosphate) as an intermediate; (3) Phosphates held on the surface of hydrated iron and possibly aluminum oxides are found in this group. There is no sharp distinction between this group and the iron and aluminum phosphate minerals, for under some conditions these compounds crystallize to form new minerals of iron and aluminum phosphate; (4) The fourth and last group is the organic phosphates, such as phytin and other inositol phosphates, and nucleic acid and its derivatives in the humic materials. These organic compounds are formed in the partially decomposed plant tissues, and the tissues of the living plant roots.

Dean (10) proposed fractionation of total soil phosphorus by means of an alkali extract followed by an acid extraction. He identified four groups of compounds in soils: (1) Inorganic alkali-soluble iron and aluminum phosphates and small amounts of mono and dicalcium phosphates if they were present in the soil, (2) Acid soluble, but alkali-insoluble

apatites and tricalcium phosphates, (3) Organic phosphates, definite organic combinations of phosphorus, and (4) Insoluble phosphorus of unknown chemical composition.

Haseman et al. (22) classified all iron and aluminum phosphates into nine groups with respect to their crystal phases, and on a basis of X-ray diffraction spacing, crystallographic properties, and chemical composition of the phosphates.

Calcium Phosphates

Knowledge of the chemistry of the calcium phosphates is still very limited, although such knowledge is fundamental for any meaningful discussion of soil phosphates and soil testing. According to Leher (27), monocalcium phosphate ($Ca(H2PO4)_2$), the phosphatic component in super phosphate is water soluble, but when added to soils containing exchangeable calcium ions it becomes converted to the insoluble dicalcium phosphate ($CaHPO4$), and may be deposited on the surface of soil particles as microcrystals. Although dicalcium phosphate is water insoluble for most practical purposes, it is soluble enough to maintain an adequate supply of (H_2PO4) ions, particularly as dissolved by acid solutions. However, dicalcium phosphate becomes converted to still more insoluble phosphates, with the weakly dissociated ions of $HPO4$ or $PO4$ as the only source of water soluble phosphorus. Under acid conditions, however, the H_2PO4 concentration in the soil solution is high enough to support an adequate phosphorus concentration for good plant growth. According to Moreno et al. (29), more soluble fertilizers, such as concentrated superphosphate and monocalcium phosphate are applied to soils, dicalcium phosphate dihydrate (DCPD) is one of the major products formed.

He states that: "Results of equilibrations of dicalcium phosphate, with the soil, strongly suggest that the solution in the fertilizer reaction zones where DCPD is present remains saturated with respect to this salt. A continuous removal of phosphorus from solution was interpreted as a reaction of phosphate in solution with hydrous oxides of iron and aluminum. The rise in pH resulting from this reaction caused DCPD to precipitate and the solution composition to change along the solubility isotherm for DCPD".

Iron and Aluminum Phosphates

Although the formation of Fe, Al phosphates is considered by many soil scientists to represent a path of phosphate fixation in soils the extent to which particular compounds retain phosphate is a point needing further clarification. Iron and aluminum phosphates in three of the nine groups described by Haseman et al. (22) are recognized as reaction products in the soil-fertilizer system, and have also been identified as naturally occurring soil minerals. Potassium tarankite $H6K3AL5(PO4)'$. $18H2O$ (Haseman group I) was shown by Lindsay and Stephenson (28) to be formed in soils by the action of solutions derived from monocalcium phosphate. The ammonium analogue $H6(NH4)3AL(PO4)8.H2O$ was obtained by Lindsay in a similar experiment with solutions of ammonium phosphate fertilizer. These compounds $KAL2(PO4)2OH.2H2O$ and $KFe2(PO4)2OH.2H_2O$ are classified as group 4 by Haseman et al. (22) and are identical with the naturally occurring Leucophosphites described by Axelrod et al. (2). Taylor et al. (40) concluded that calcium ferric phosphate $H4Ca\ Fe2(PO4)$ $4.5H2O$, potassium tarankite, colloidal aluminum phosphate, and colloidal iron phosphate, all of which are believed to be formed by the action of

acid solutions of fertilizers upon soil, were found to be relatively good sources of phosphorus and cannot be regarded as responsible for the "fixation" of phosphate from water soluble fertilizers. An acidic potassium phosphate H8KF23.(PO4)6.6H20 was found to be a very poor source of phosphate for the growth of plants.

Numerous investigators (5, 17, 24) have shown that the amount of phosphate precipitated by iron and aluminum solutions and the fixation of phosphate by soils increase as the pH value of the soil solution decreases.

Teakle (41) and Davis (9) found that iron phosphate was least soluble at pH 3. Swenson, Cole, and Sieling (39) found that the pH of maximum precipitation of basic iron phosphate was 2.5 to 3.5 whereas for basic aluminum phosphate it was from 3.5 to 4.5. This is the pH at which H2PO4 predominates and where there is relatively little HPO4 and virtually no PO4. This indicates that H2PO4 is the phosphate ion which reacts to form chemically combined insoluble iron and aluminum phosphates. The amount of phosphate which would combine chemically with one iron or aluminum ion increased as the phosphate increased, to values where one iron or one aluminum ion, and two hydroxyls were required to complete the precipitation. In no instance was the ratio of phosphate to iron or aluminum in the precipitated compound greater than unity even when the amount of phosphate present was nine times that of the iron or aluminum.

Soil Organic Phosphorus

According to Van Diest and Black (13) the evidence currently available suggests that the amount of phosphorus absorbed by plants from the

organic form in the soil is relatively small and perhaps negligible, and that the principle contribution of the organic phosphorus of soils to the phosphorus supply of plants is made after the phosphorus has been mineralized, that is, changed from the organic to the inorganic form. Semb and Uhlen (37) obtained a significant association of the phosphorus availability index and the total soil organic phosphorus in soils having pH values of 5.5 and above, but not in soils having lower pH values. Eid et al. (15) associated the "phosphorus availability index" with the fraction of soil organic phosphorus that was extracted by potassium carbonate and hydrolyzed by hypobromide. Van Diest and Black (13) also found that phosphorus present in organic form in soils at the beginning of a season may contribute substantially to the phosphorus nutrition of plants grown during that season.

Mechanism of Phosphate Fixation

Many concepts have been advanced to explain the process involved in the conversion of soluble phosphates to forms which are unavailable for plant use. Davis (9) groups these insoluble compounds as follows: (1) cations of soluble salts present in the soil, or cations replaced from the soil by those present in the solution, which form precipitates with the phosphate ions; (2) by double decomposition, relatively insoluble soil minerals react to form insoluble phosphates; (3) phosphates are absorbed at the extensive soil-solution interface; and (4) phosphates are absorbed by the soil minerals to form complex systems in one or more of the solid soil phases.

Microbiological consumption, precipitation, and physiochemical absorption, according to Bear and Toth (3) are responsible for phosphate

fixation. Davis (9) tentatively concluded that phosphates may penetrate the liquid-solid interface and form new compounds with the hydrated minerals. Davis named two conditions that may occur at the interface: (1) hydroxy groups originated outward in a negative surface are replaced by phosphate ions, and (2) metal ions oriented outward react with phosphate ions. The mechanism of phosphate fixation by iron or aluminum described by Swenson, Cole and Sieling (39) is represented by the following equilibrium equation:

$$Al(H_2O)3 \overset{OH}{\underset{OH}{-OH}} + H_2PO_4 \longrightarrow Al(H_2O)_3 \overset{OH}{\underset{H_2PO4}{=OH}} + OH^-$$
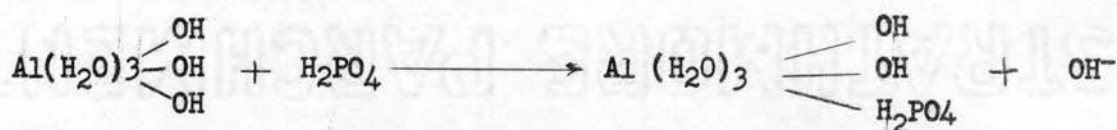
Hydrous oxides of aluminum and iron are effective in combining chemically with $H_2PO_4^-$ at low pH values because the stability of the basic metal phosphate is greater than the hydrous oxide at lower pH. When the pH of the soil is increased, the equilibrium is shifted toward a greater stability of hydrous oxides and the release of phosphate.

Extraction of Soil Phosphorus

For the extraction of readily soluble phosphorus in soils, it would appear desirable, if possible and practicable, to use solvents which are approximately the same strength as the ones operating in absorption by the plant. Some evidence indicates that the solvent operating at the points of contact between the root and the soil particle is a saturated solution of carbonic acid. This solution has a normality of slightly greater than one twenty fifth and a pH of 3.7. In an attempt to approximate this solvent in a practical and convenient way many different extracting solutions have been investigated by soil scientists. Many analytical procedures for determining replaceable phosphate in soils are based on

use of acid and salt solutions. Fluoride and arsenate will replace chemi-
cally combined phosphate, and the effectiveness of replacement depends upon
the relative stability of the compound formed and on the concentration of
the replacing anion. Dean and Rubins (10) have compared the effectiveness
of fluoride, citrate, tartrate, arsenate, and acetate for removing
adsorbed soil phosphorus. Kurtz et al. (25) found that various anions
replaced adsorbed phosphate ion in the following order; fluoride, oxalate,
citrate, bicarbonate, borate, acetate, thiocyanate, sulfate, and chloride.
The borate, acetate, thiocyanate, sulfate, and chloride ion removed
amounts similar to or smaller than the amounts removed by water. Demelon
and Bestisse observed that less phosphorus is absorbed from a mixture con-
taining another absorbable ion, such as tartrate, citrate, oxalate, and
silicate than from a mixture with a nonabsorbable anion such as chloride,
sulphate, and nitrate. They further established that phosphate fixed by
the soil could be removed more easily by a salt of an absorbable ion than
by one of a nonabsorbable ion. Truog (42) selected a 0.05 N sulfuric acid
solution buffered with ammonium sulfate to a pH of 3 as a phosphorus
extracting agent. On a quantitative basis, the saturated carbonic acid
solution (believed to be related to the solvent operating at the root
surface) is about 1/20 times as strong as the 0.05 N sulfuric acid solvent
on an intensity basis. According to Truog (42) the sulfuric acid solvent
is a little more than four times as strong as the carbonic acid solution.
The intensity of the above solution may appear too high, but quantity and
intensity components compensate for each other to some extent.

According to Truog (42) it is desirable for several reasons to use
a high ratio of solvent to soil in the extraction process. The extent of
the soil-solution ratio which is practicable to use is limited largely by

the analytical procedures available. The solution of readily soluble phosphates is especially rapid during the first few minutes of extraction, in which time the greater portion of the readily soluble phosphorus may be dissolved. According to Truog (42) at the end of 30 minutes the reaction rate usually slows up greatly and it may be assumed that practically all of the readily available phosphorus has been dissolved, with the exception of soils with high amounts of easily soluble phosphorus.

Acid Extraction of Soil for Phosphorus

The "available phosphorus" in soils has been extracted for many years with dilute solutions of organic or inorganic acids. Good correlations have been obtained between the phosphorus extracted and plant responses for soil of similar chemical properties, but poor correlations have been noted when soils of widely varying chemical properties were studied. Cook (8) pointed out two main causes of poor correlation between the amount of phosphorus extracted by acids and the amount of phosphorus taken up by plants. The first cause was that dilute acid extractions were based on the premise that plants dissolve chemical compounds in the soil through the activity of acids exuded by their roots. New evidence in plant nutrition has shown that plants may acquire nutrients by direct exchange between root and soil particles. Secondly, acid extracting solutions are more acid than most field soils. Thus, the acid extractants dissolve phosphorus compounds that are not normally available to plants. Elimination or diminution of phosphate "re-fixation" during dilute acid extraction is of great importance. Cook (8) cited three types of mechanisms of phosphate fixation that may occur when a soil is extracted with dilute acid: (1) chemical precipitation by soluble salts of iron, aluminum, titanium,

and manganese; (2) adsorption by the hydrous oxides of iron, aluminum, titanium, and manganese; and (3) adsorption by aluminosilicates.

Fraps (17) employed N/5 HNO_3 and concluded that this acid extractant dissolves calcium phosphates completely, but only dissolves aluminum phosphates or basic ferric phosphate to a slight extent. He recommended this extractant method for calcareous soils. Truog (42) used 0.002 N.H_2SO_4 on Wisconsin soils. He stated that it dissolves the readily available phosphate (calcium phosphate) and that this weak extractant does not bring into solution iron oxides or organic matter that may interfere in the colorimeteric determination of phosphorus. Harper (19) worked with 0.2 N. H2SO4 as an extractant in a study of soil samples from Oklahoma and other states. By using this method, he was able to establish response limits of phosphorus for alfalfa, cotton, oats, sweet clover, wheat, corn, soybeans, cowpeas and grain sorghums. Harper also used 0.1 N. acetic acid as a phosphate extractant with good results. He stated that this solution will dissolve considerable amounts of freshly precipitated iron, aluminum, and manganese phosphate. He also emphasized the fact that when there is some calcium phosphate in the soil, the strength of the solution will keep the dissolved phosphate from being adsorbed by the soil parti-cles. This method is not recommended for calcareous soils because con-siderable amounts of occluded and insoluble calcium phosphate is dissolved. Morgan (30) extracted soil for phosphorus with 0.5 N. acetic acid buffered at pH 4.8 with sodium acetate. Cook (8) also employed 0.5 N. acetic acid alone and with different reagents in a study of phosphate fixation during acid extraction. He concluded that in soils where fixation is caused largely by hydrous oxides, selenious acid mixtures will give more satisfactory values than acetic acid alone. It is possible that selenite ions replace

hydroxide groups on the surface of the hydrated oxides. He also pointed out that acids used to extract soils should not dissolve compounds which are not used by plants. Citric acid is thought to dissolve iron phosphate from some soils and give false high values for soluble phosphorus.

Fluoride Extraction

Bray and Kurtz (5) proposed two methods in which they included NH4F in addition to dilute hydrochloric acid. For method Number 1, they proposed for adsorbed forms of phosphorus a solution of 0.025 NHCl, and 0.03 N.NH4F. They noted that this extractant will remove proportional parts of each soil phosphate present and that the amount of phosphate extracted is largely influenced by the more readily soluble portion of each form.

The fluoride ion has been employed in several other studies. Turner and Ric (43) worked with neutral NH4F in studying the phosphate adsorption characteristics of $Al(OH)_3$ and $Fe(OH)_3$ gels. They found that the NH4F reacted with $Al(OH)_3$ gel to form $(NH4)_3Al F_6$ and the phosphate adsorbed by the gels was completely released by the fluoride ion through an exchange process. The $Fe(OH)_3$ gel was apparently not attacked by the fluoride and the phosphate adsorbed was not released. Seatz (36) obtained similar evidence in phosphate desorption studies. His results showed that the fluoride ion is more effective in desorbing P32 from aluminum phosphate than from iron phosphate.

Dickman and Bray (12) chose the fluoride ion as a more selective extractant of the adsorbable forms of phosphate. They stated that the fluoride ion is extremely reactive, is stable in neutral solutions, and offers no complications in the subsequent colorimetric determination of phosphate. The fluoride ion might be expected to replace OH groups from

the surface of kaolinite. Jackson (24) found that the inclusion of acid
in the Bray and Kurtz extractants causes the dissolution of the more
active calcium phosphate and prevents precipitation.

III MATERIALS AND METHODS

Fourteen soils were employed in this study. All of the samples were taken from locations where soil fertility experiments had been conducted. The soil types, locations where the samples were taken, farms, and kinds of experiments are shown in Table I. A bulk sample (0 to 6 inches deep) of about 200 pounds and a smaller sample of about two pounds from each genetic soil horizon below the cultivation layer were taken at each location. The 200 pound soil samples were crushed, screened through a 4-mesh sieve. A small portion of each soil was left aside for chemical and physical analysis and some of the rest was employed in the greenhouse experiment.

TABLE I

Soil Types	Location	Farm	Kind of Experiment
St. Paul silt loam	Buffalo	Felkel	Wheat fertility
Chouteau silt loam	Warner	Conners A & M	Sorghum fertility
Carey silt loam	Custer City	Schneider	Wheat fertility
Dalhart sandy loam	Fergan	Becker	Wheat fertility
Dill sandy loam	Burns Flat	Phillips	Sorghum fertility
Foard silty clay loam	Hobart	Cookley	Wheat fertility
Hollister silty clay loam	Altus	Irrigation Research Sta.	Wheat fertility
Brownfield sandy loam	Mangum	Sandy Land Research Sta.	Wheat fertility
Parsons	Welch	Welch FFA	Wheat fertility
Richfield	Goodwell	Panhandle A & M Research Sta.	Wheat fertility
Spur sandy loam	Slapout	Jett	Wheat fertility
Shella barger	Stratford	Peanut Research Farm	Sorghum fertility
Okema	Vinita	Vinita School	Wheat fertility
Dennis sandy loam	Liberty School	Ketchum	Wheat fertility

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Soil Analysis

The mechanical analysis was determined by the Day (4), (Hydrometer method). The pH was determined in a thick paste (35) made by moistening the soil with distilled water with a glass electrode pH meter. The percentage of organic matter was obtained by the wet combustion method (21). The percent nitrogen was determined by the Kjeldahl method (21). Available potassium was measured by analyzing the ammonium acetate leachate of the soil with the Beckman flame photometer (21). The cation exchange capacity was obtained by using ammonium acetate as the extractant and distilling the sorbed ammonia with magnesium oxide (1). Exchangeable calcium, magnesium, and sodium were analyzed in the leachate with the flame photometer. Some of the physical and chemical characteristics of the soils are shown in Table II.

Experimental Procedures and Results in Greenhouse

Small cylindrical cans of 5.5 inches high and 3.0 inches diameter were used in the greenhouse as the experimental pots. The cans were lined with a polyethylene layer to prevent loss of salts through drainage. A randomized complete block design with five fertilizer treatments, fourteen soil types and four replications was used.

Seven hundred grams of soil was placed in each can. Adequate amounts of $Ca(OH)_2$, $MgSO4$, and K_2SO_4 were applied to the soils to bring them to 80% calcium saturation, 6% potassium saturation, and 4% magnesium saturation. The prepared soils in the pots were then treated with treatments equivalent to 0, 17.5, 35, 70, 140 pounds per acre of phosphorus using $NH4H_2PO4$ as the source of phosphorus. The fertilizer treatments were supplied by supplementary amounts of $NH4NO_3$ to furnish 80 pounds per acre

TABLE II

PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE FOURTEEN SOILS USED IN THE GREENHOUSE AND LABORATORY EXPERIMENT

Soil Series	Texture	Depth	pH	% O.M	% N	Avail. #/A^K	C.E.C.* m.e	% Ca	% Mg	% Na
St. Paul	Silt loam	Surface	7.20	1.70	.0915	1020	12.92	67.72	17.4	0.61
Chouteau	Silt loam	Surface	4.95	2.53	.1288	100	12.32	36.52	34.49	1.05
Carey	Sandy loam	Surface	6.7	1.68	.074	929	8.66	51.97	56.58	1.50
Dalhart	Sandy loam	Surface	7.0	1.07	.0578	700	6.99	92.29	13.01	0.00
Dennis	Silt loam	Surface	5.3	1.16	.0653	80	5.12	48.82	32.40	0.00
Dill	Sandy loam	Surface	5.3	.692	.0552	200	6.57	31.96	22.83	0.60
Foard	Silty clay loam	Surface	7.0	1.01	.048	320	8.18	80.10	26.53	2.56
Hollister	Silty clay loam	Surface	7.5	1.84	.090	800	15.90	54.69	43.44	1.06
Brownfield	Sandy loam	Surface	5.9	.508	.024	115	3.49	28.65	33.23	1.71
Parsons	Silt loam	Surface	5.10	1.84	.1045	200	8.19	39.07	11.11	0.97
Richfield	Silt loam	Surface	7.70	1.44	.0802	1120	14.52	64.39	26.92	1.44
Spur	Sandy loam	Surface	8.1	0.91	.0635	600	7.46	187.6	24.53	2.81
Shella barger	Sandy loam	Surface	6.25	0.49	.0280	100	1.66	84.33	50.00	0.00
Okema	Silt loam	Surface	5.10	1.84	.1045	200	8.19	39.07	11.11	0.97

*C.E.C. = Cation Exchange Capacity in Milliequivalents/100 grms. of soil.

of nitrogen. Ten seeds of Early Triumph wheat were planted in each pot at
a 1-inch depth. The pots were watered and when germination was completed,
the plant population of each pot was thinned to eight plants or replanted
to bring the population to 8 per pot. The pots were watered throughout
the growing period to maintain adequate soil moisture. After 30 days of
growth, the forage was harvested by cutting off the plants about 1/3 of
an inch above the surface of the soil. The green samples were oven dried
at 80 degrees Centigrade for 48 hours and the weight of oven-dry tissues
was recorded. The oven-dry weights of the samples are shown in Table III.

Statistical Analysis

The analysis of variance of the greenhouse yields, and total phos-
phorus uptake obtained from the forage yield was made according to the
procedures described by Snedecor (38). In the linear regression studies
the procedures of Snedecor (38) were also used. The amount of phosphorus
applied on an acre equivalent was the independent or variable X, and
the forage yield was the dependent Y. These results are shown in Figures
1 through 3.

TABLE III

OVEN-DRY WHEAT FORAGE YIELDS OBTAINED
IN THE GREENHOUSE EXPERIMENT
(expressed in grams per pot)

Soil Series	Fertilizer Treatments				
	80-0-0	80-40-0	80-80-0	80-160-0	80-320-0
St. Paul	1.360*	1.516	1.446	1.561	1.465
Chouteau	0.699	.944	1.033	1.001	1.156
Carey	1.188	1.192	1.324	1.357	1.352
Dalhart	1.126	1.225	1.066	1.151	1.233
Dennis	0.449	0.805	0.811	0.868	0.915
Dill	0.678	0.816	0.897	0.873	0.928
Foard	1.075	1.512	1.184	1.533	1.421
Hollister (Altus)	1.103	1.216	1.021	1.198	1.199
Brownfield	1.146	0.986	0.951	0.899	1.222
Parsons	0.405	0.775	0.687	0.882	0.925
Richfield	1.072	1.207	1.204	1.207	1.493
Spur	1.328	1.614	1.431	1.520	1.480
Shella barger	1.061	1.300	1.235	1.177	1.247
Okema	0.397	0.750	0.676	0.781	0.834

*Each number is the average of four replications.

IV RESULTS AND DISCUSSION

Greenhouse Experiment

On six of the soils studied (Chouteau, Dennis, Dill, Okema, and
Richfield) the results were found to be significant in a test for the
slope of a line of yield vs. treatment. The yield results are indicated
in Table III and the graphs of yield vs. treatment for these soils are
on the figures 1, 2, and 3. The yield obtained from the non-treated or
check pots varied from 0.397 grams for Okema soil to 1.360 grams for the
St. Paul soil. With the Okema soil it seems that there is a considerable
increase in yield from 0 up to 17.5 pounds of phosphorus per acre, some
decrease from 17.5 to 35 pound per acre, and then an increase from 35 to
70 pound phosphorus per acre. However[1], the Parsons soil which had had
its percent calcium saturation brought up to 80% had considerably higher
yields at all phosphorus treatments. The decrease in yield from 17.5
to 35 pounds of phosphorus per acre was more pronounced on the limed
soil but yield increases were also more pronounced with liming from 35
to 70 pounds of phosphorus per acre than no lime. With the Chouteau
soil yields were high at 17.5 and 35 pounds phosphorus per acre. The
highest yield for this soil was 17.5 pounds of phosphorus per acre,
and decrease in yield was observed between the 17.5 to 35 pounds per
acre on the Dennis soil. The untreated pot had a very low yield for

[1]The two soils, Parsons and Okema, are very similar genetically. In this
experiment proper nutrients were applied only to Parsons soil to bring
the Ca% saturation to 80%, K% saturation to 6%, and Mg% on to 4%. Phos-
phorus treatments were exactly alike.

this soil. The differences in the forage yield were small for the Dill soil from 35 to 140 pounds of phosphorus per acre. There was a nonsignificant slight decrease in yield from 35 to 70 pounds per acre rate, however, yields at 35 pounds per acre were comparatively high.

The analysis of variance for the forage yield obtained from the pots are listed in Table IV. The treatments were found to be significantly different; at the 5% level for the Brownfield soil, and at the 1% level for Chouteau, Dennis, Okema, Parsons, and Richfield. The analysis of variance for yields on all soils are shown in Table I V.

Laboratory Investigations

The total amount of phosphorus extracted from the soil by the plants in the greenhouse experiment was found to be very highly related to the amount of phosphorus applied. The check pots had from 681.0 microgram/gram from Okema soil to 2217.0 microgram/gram for the St. Paul soil. In the test for the slope of the regression line--total phosphorus content vs. treatment--it was found that the slope of the line was highly significant on all soils. The graphs of these regression lines are shown in figures 4,5,6,and 7. The total phosphorus content of the forage yield is shown in Table IV. The amount of phosphorus taken up by the wheat plant was found to be correlated with the amount of phosphorus applied on all soils studied. In case of the Dalhart soil, an almost perfect correlation was found. A decrease in phosphorus uptake was found to occur between the 0 to 17.5 pound phosphorus rate for Dennis soil, however, the other rate showed an increase on the Dennis soil. Practically parallel regression lines were obtained for the two similar soils, Parsons and Okema. The wheat grown on the Parsons soil, which had been limed, had a

slightly higher phosphorus content at all points than the Okema soil, which was not limed.

TABLE IV

ANALYSIS OF VARIANCE OF WHEAT FORAGE YIELDS OBTAINED FROM A PHOSPHATE FERTILIZER STUDY IN THE GREENHOUSE

St. Paul Silt Loam

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Treatments	4	0.023227475	
Replications	3	0.052662867	1.16465 N.S.
Error	12	0.019943592	

Chouteau Silt Loam

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.014245833	
Treatments	4	.113534600	20.7386**
Error	12	.005474533	

Carey Silt Loam

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.014684833	
Treatments	4	.029121675	0.95052 N.S.
Error	12	.030637342	

Tabulated F:

    (1) 3.26 at the 5% level; significance*

    (2) 5.41 at the 1% level; significance**

TABLE IV (CONTINUED)

<u>Dalhart Sandy Loam</u>

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.089423767	
Treatments	4	.019775400	0.82613 N.S.
Error	12	.023937250	

<u>Dennis Sandy Loam</u>

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.034410967	
Treatments	4	.136442200	6.8187**
Error	12	.020009983	

<u>Dill Sandy Loam</u>

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.019977900	
Treatments	4	.038779475	2.5496 N.S.
Error	12	.015209725	

<u>Foard Silty Clay Loam</u>

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.06803133	
Treatments	4	.16759175	2.69016 N.S.
Error	12	.06229792	

TABLE IV (CONTINUED)

Hollister Silty Clay Loam

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.07164500	
Treatments	4	.02811850	.3495 N.S.
Error	12	.08045208	

Brownfield Sandy Loam

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.053606500	
Treatments	4	.075181725	4.4293*
Error	12	.016973675	

Parsons

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.022457867	
Treatments	4	.170944525	22.1278**
Error	12	.007725300	

Richfield

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.005545200	
Treatments	4	.106613750	5.8297**
Error	12	.018287817	

TABLE IV (CONTINUED)

Spur Sandy Loam

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.003012700	
Treatments	4	.044857050	2.7911 N.S.
Error	12	.016071425	

Shella barger

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.056678067	
Treatments	4	.033413625	1.6517 N.S.
Error	12	.020229742	

Okema

Analysis of Variance

Source	d.f.	M.S.	Calc. F
Replications	3	.008987067	
Treatments	4	.118577150	16.0321**
Error	12	.007396233	

TABLE V

TOTAL PHOSPHORUS FOUND IN THE OVEN-DRY WHEAT FORAGE
YIELDS OBTAINED IN THE GREENHOUSE EXPERIMENTS
(expressed in microgram/gram)

| Soil Series | Fertilizer Treatments | | | | |
	80-0-0	80-40-0	80-80-0	80-160-0	80-320-0
St. Paul	2217.00*	3081.75	4241.50	6350.75	8290.75
Chouteau	944.25	1222.50	1990.75	2513.75	4286.50
Carey	1044.50	2167.75	3374.75	4592.50	6941.25
Dalhart	1780.00	2577.25	3312.00	5156.75	8422.50
Dennis	2024.00	1052.00	2179.00	3114.25	4640.25
Dill	1125.25	1855.25	3196.25	5015.00	6977.25
Foard	1629.25	2102.25	2509.50	3406.25	4868.00
Hollister (Altus)	1268.75	1929.75	2651.00	3474.50	5076.25
Brownfield	2099.00	2861.00	5467.25	6302.00	8518.50
Parsons	879.50	1324.75	2257.50	2747.50	4161.75
Richfield	1614.00	2454.00	3016.50	4088.50	5366.50
Spur	771.25	1561.25	2318.00	2786.25	3396.00
Shella barger	1763.50	2975.00	3335.50	5166.00	6248.00
Okema	681.00	1176.25	1808.00	2628.75	4124.75

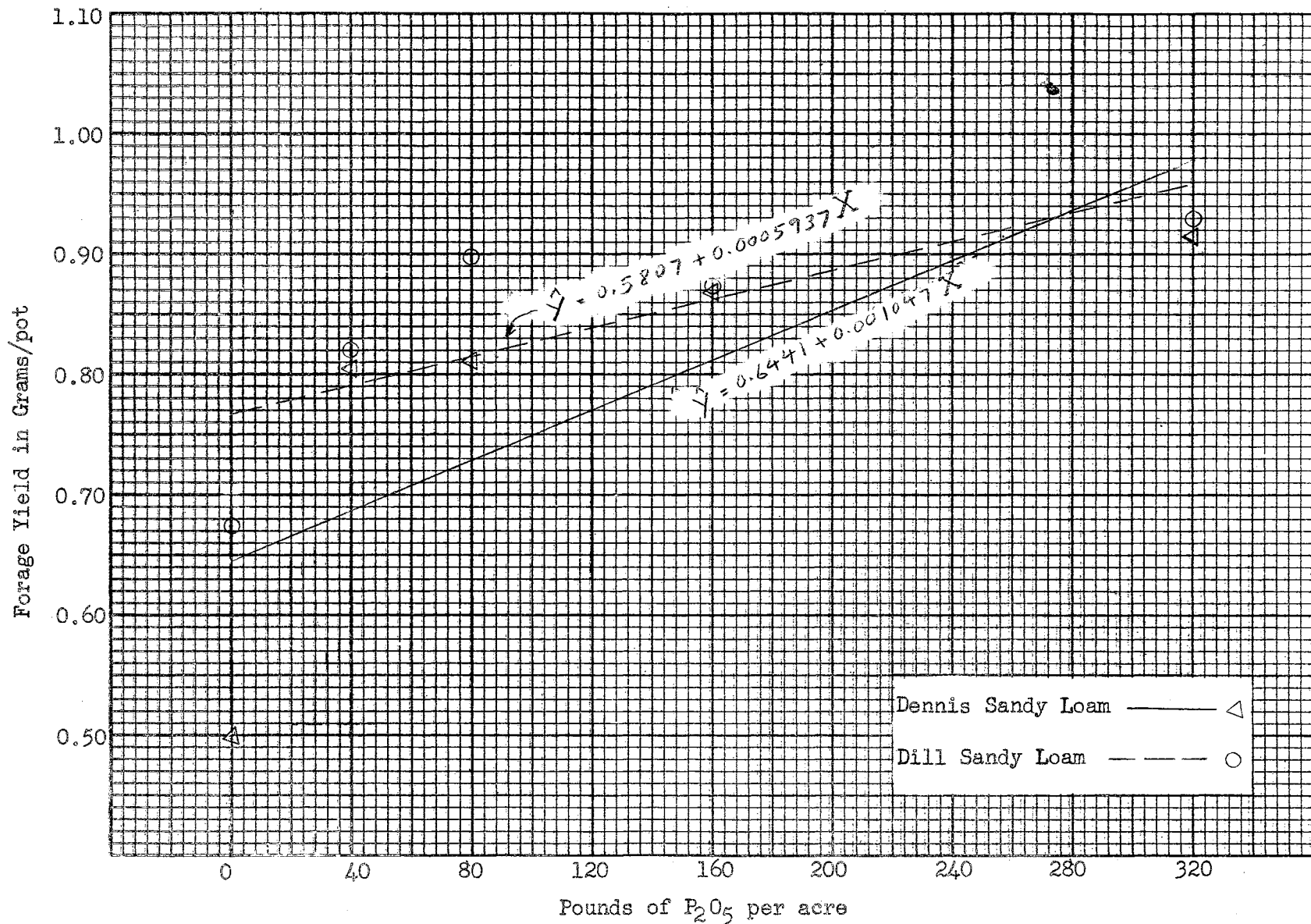*Each number is the average of four replications.

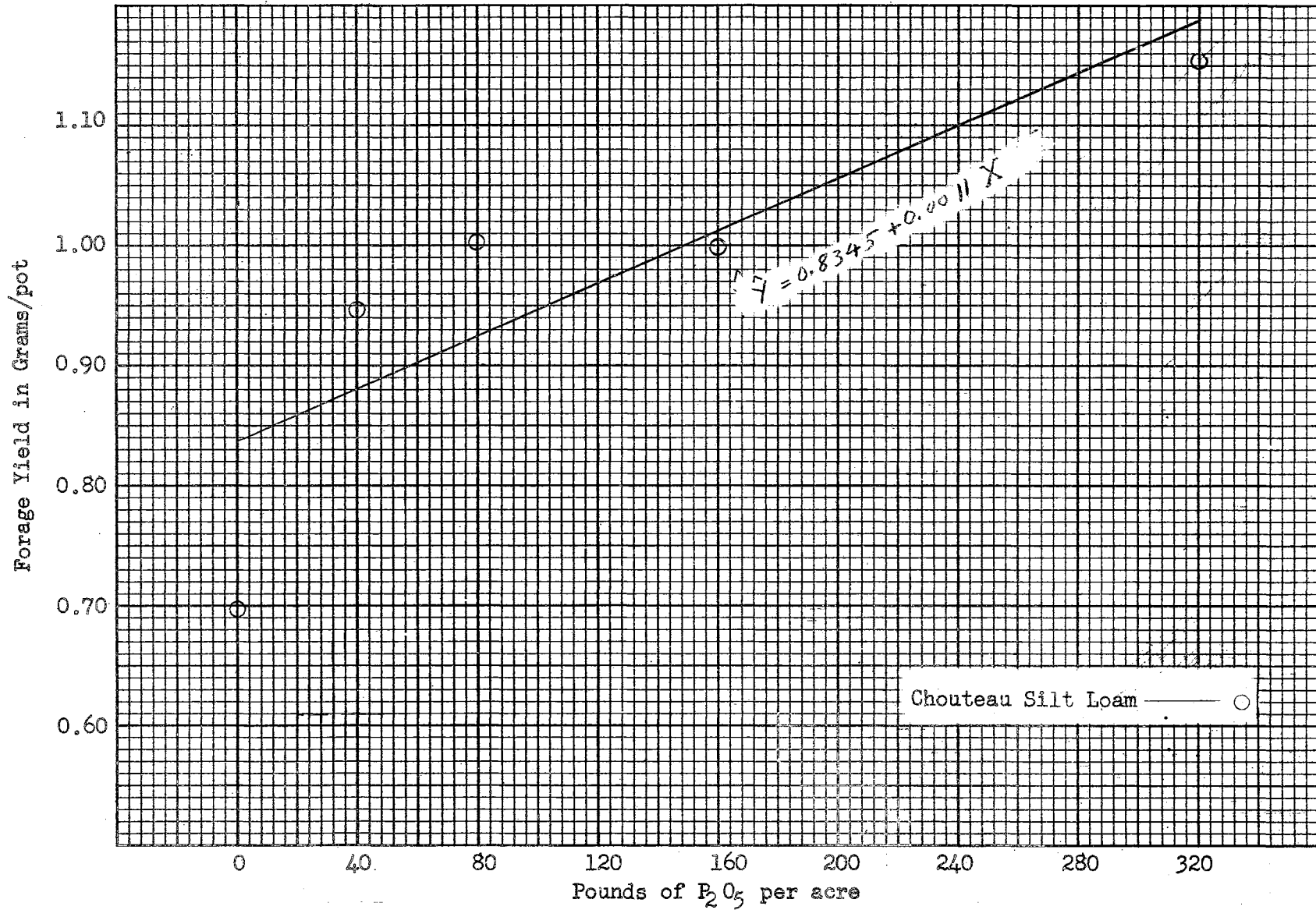Figure 1. Greenhouse forage yield obtained from Dennis sandy loam and Dill sandy loam.

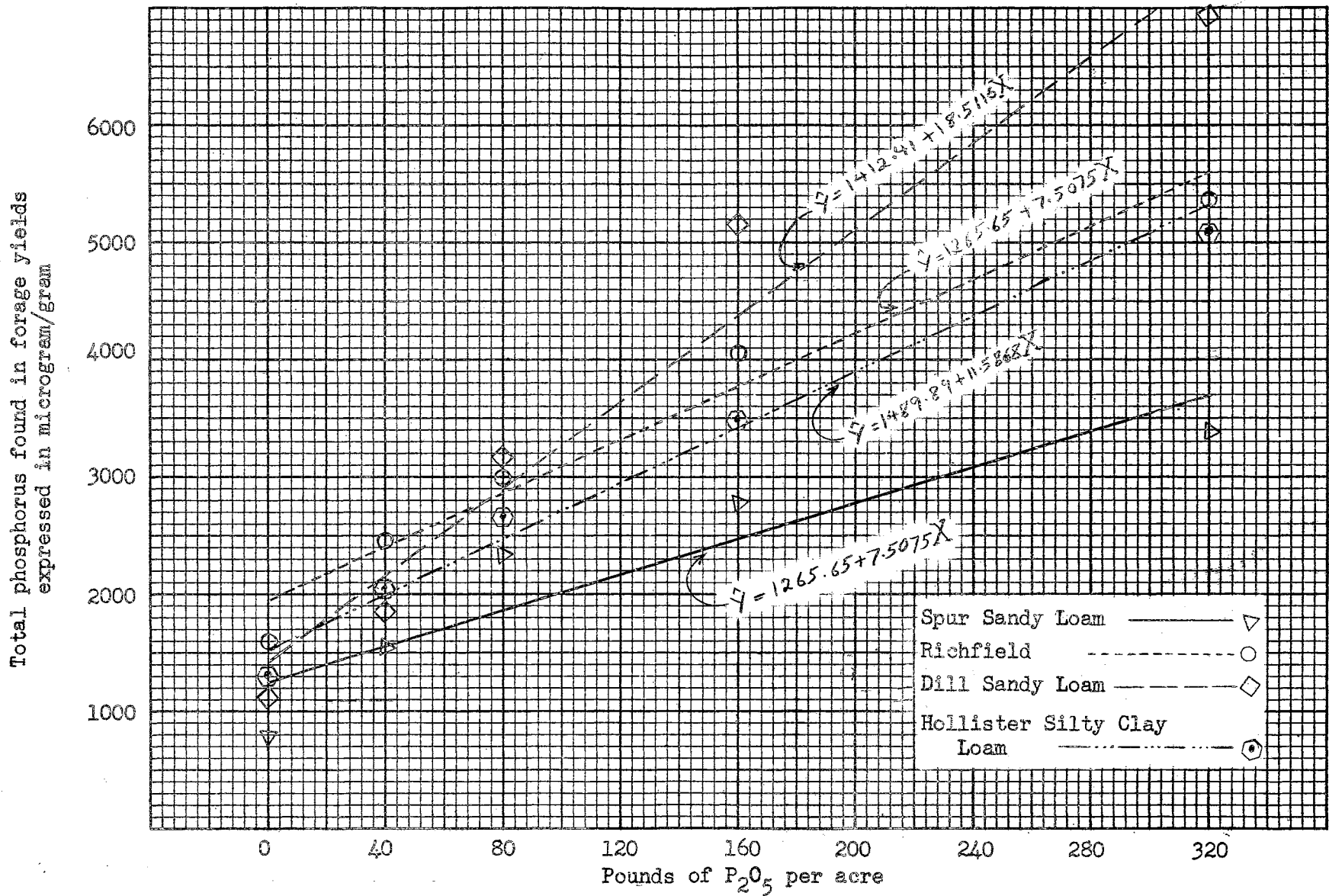Figure 2. Greenhouse forage yield obtained from Chouteau silt loam.

The chart shows "Forage Yield in Grams/pot" on the y-axis (ranging from 0.60 to 1.10) and "Pounds of P_2O_5 per acre" on the x-axis (ranging from 0 to 320). The legend reads "Chouteau Silt Loam ———— O". The equation on the line reads $Y = 0.8345 + 0.0011\ X$.

Figure 4. Total phosphorus from the forage yield obtained in greenhouse experiment.
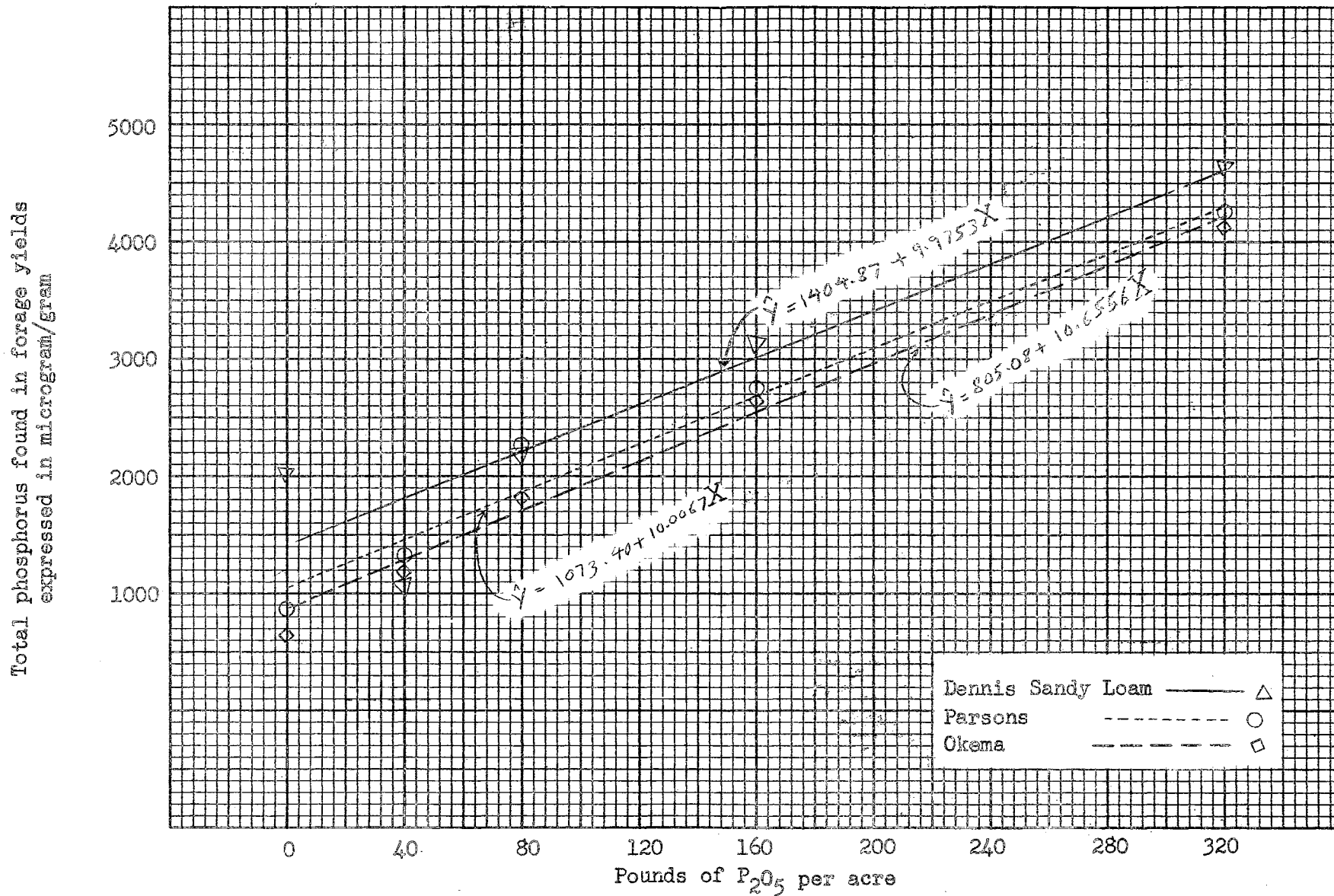
Figure 5. Total phosphorus from the forage yield obtained in greenhouse experiment.
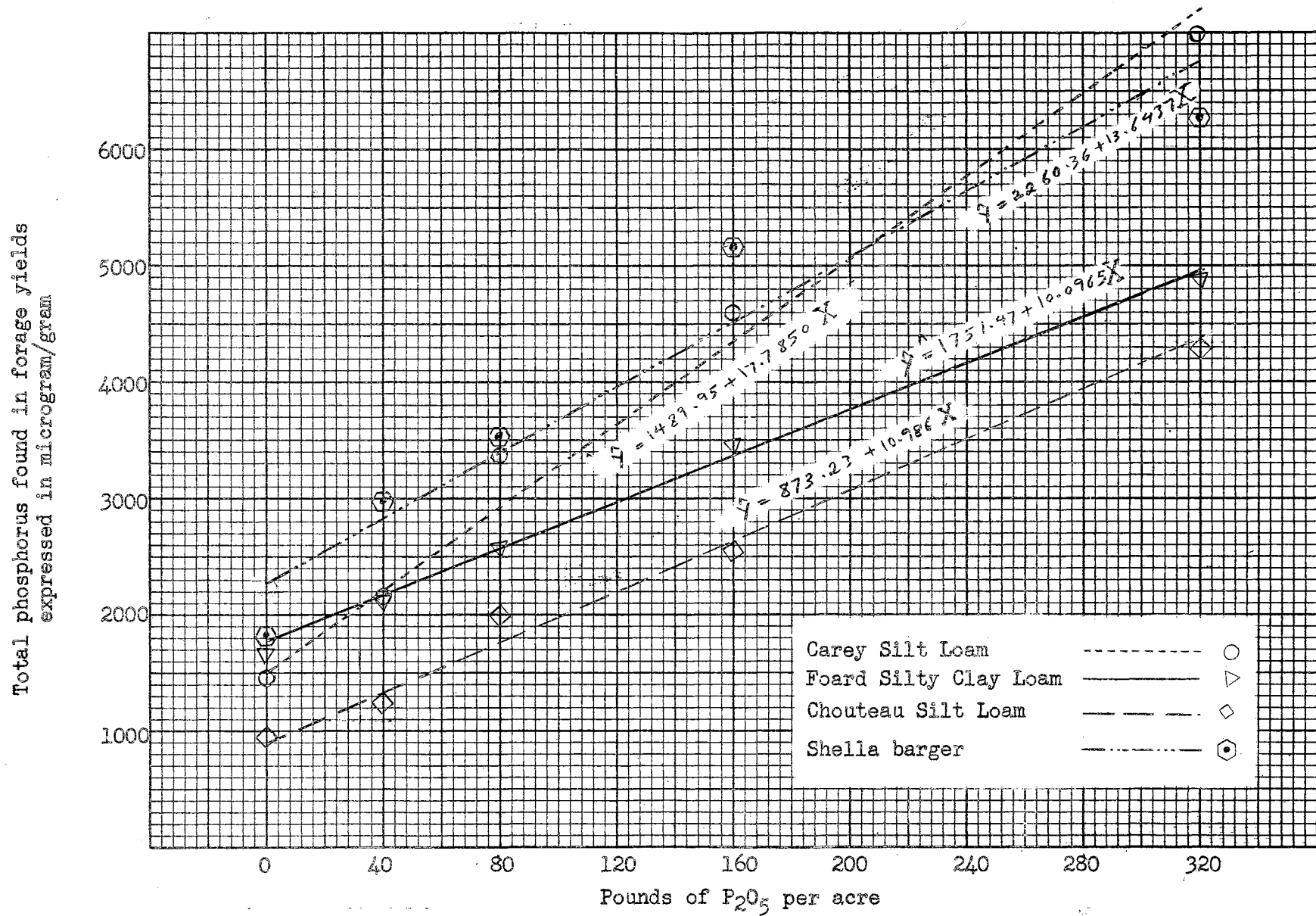
Figure 6. Total phosphorus from the forage yield obtained in greenhouse experiment.
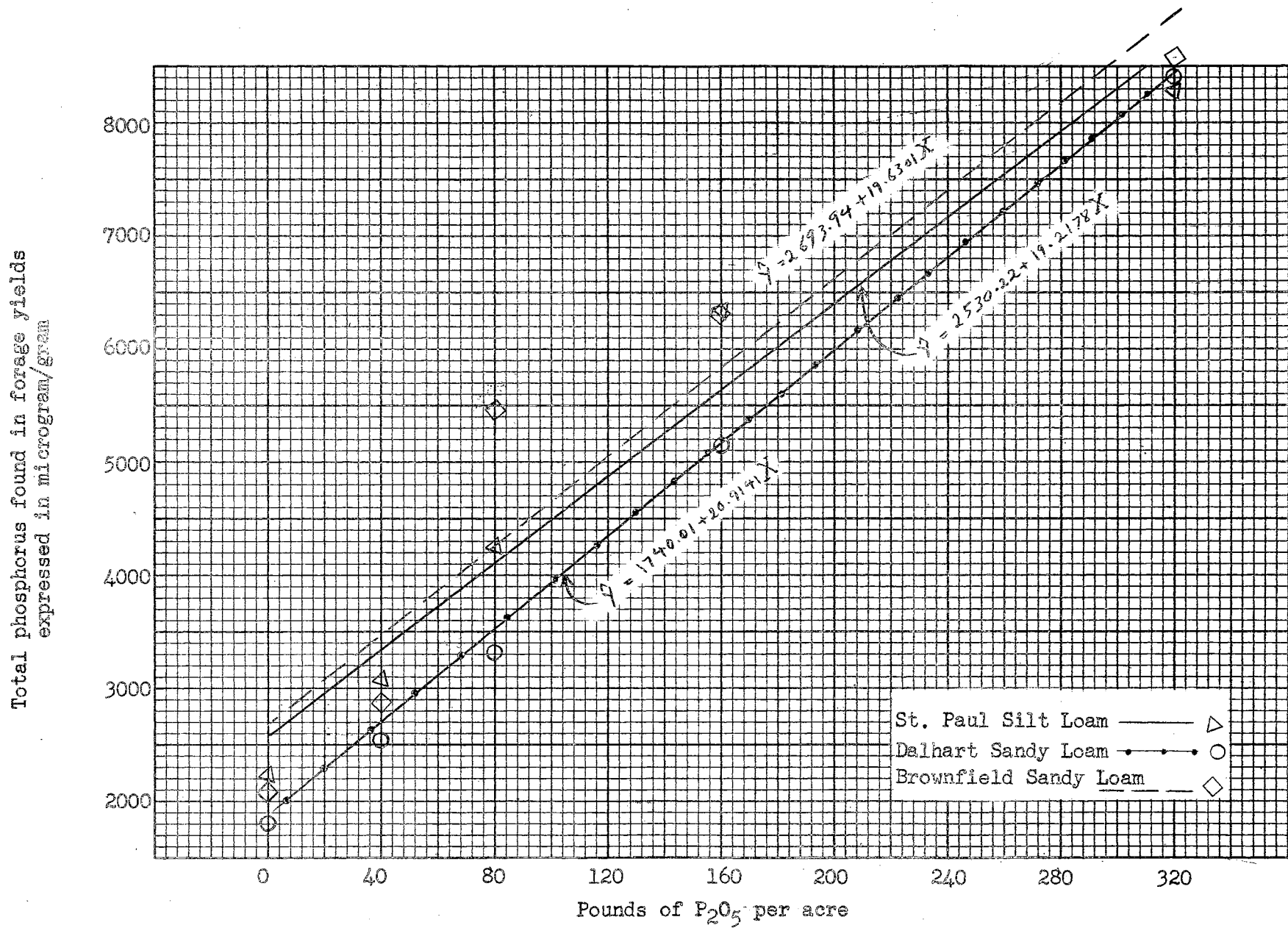
34

Figure 7. Total phosphorus from the forage yield obtained in greenhouse experiment.

V SUMMARY AND CONCLUSIONS

In this investigation a comparison of several rates of phosphorus vs. phosphorus uptake by plants and yield was made for fourteen Oklahoma soils. The regression studies for the forage yield obtained from the greenhouse study, and also total phosphorus taken up by the plants grown in the greenhouse, were determined.

From the results of these experiments it may be concluded that:

1. Significant increase in forage yield due to phosphate fertilizer was obtained only on the following soils; Dill sandy loam, Parsons silt loam, Richfield silt loam, and Okema silt loam.

2. It appears that the soils having pH values from 5.00 to 6.00 and with low C.E.C. values showed better responses to phosphate treatments than soils with high C.E.C. values and higher pH except in the case of the Richfield soil with a comparatively high pH and high C.E.C.

3. In the test for differences between phosphorus fertilizer treatments, Brownfield soil showed some yield responses (significant at the 5% level), whereas very good responses were obtained from soils; Dennis sandy loam, Chouteau silt loam, Parsons, Richfield, and Welch (significant at the 1% level). The rest of the soils did not show a significant difference between the treatments.

4. Total phosphorus in the forage yield was increased by application of phosphate fertilizer. Yield differences among the phosphate treatments were significant at the 1% level in all cases.

5. In a test for the slope of the lines obtained by comparing total phosphorus content of the forage versus phosphorus applications the slope of the lines were significant for all soils. That is, significant increase in total phosphorus content and forage yield was obtained due to an increased rate of phosphorus applications.

6. It appears that limed soils showed better yield responses to phosphorus fertilizer than non-limed soils.

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