STUDIES OF SOLID AND LIQUID PHOSPHORUS FERTILIZERS IN THE FIELD, GREENHOUSE, AND LABORATORY

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This is to certify that the

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Kirk Lawton
Major professor

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A THESIS

Submitted to the School for Advanced Graduate Studies of
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ABSTRACT

Field and greenhouse experiments were conducted to compare the effectiveness of solid and liquid fertilizers in different placements on the yield and phosphorus absorption of several crops. Monoammonium phosphate labelled with P^{32} was mixed with muriate of potash and ammonium nitrate to give a material of approximately 1-2-2 ratio. Applications included solid-banded, solid-mixed, liquid-banded, liquid-dribble, and liquid-spray.

Two months after planting in the greenhouse, the relative order of availability of fertilizer phosphorus to corn plants was solid-banded > liquid-banded > liquid-dribble > liquid-spray. With field beans the order of availability was liquid-banded = solid-banded > liquid-dribble > liquid-spray. Dry matter production was highest when fertilizer was liquid-banded and lowest when it was sprayed. In the case of field beans the method of application did not cause large differences between the dry weight yields except when fertilizer was mixed with soil. Data from the field study of corn in 1956 and 1957 showed the same general trends of fertilizer phosphorus absorption and yield for both years. Liquid materials appeared to behave similar to solids when similar methods of application were compared. Corn yields were highest when liquid was dribbled followed by the banded application, while spray and broadcast applications were least effective.

Five high analysis fertilizers, namely, liquid ammonium metaphosphate, solid ammonium metaphosphate, liquid ammoniated superphosphoric acid, solid diammonium phosphate, and concentrated

superphosphate produced and supplied by the Tennessee Valley Authority were compared in a greenhouse study on limed and unlimed Rifle peat, and Metea sandy loam, using corn and millet as the test crops, the latter being used to measure residual effects. Liquid fertilizers, especially ammoniated superphosphoric acid proved to be more effective in increasing corn yields than solid materials on limed Rifle peat. Solid-banded application was found to be more beneficial than the solid-mixed placement. Liquid-banded application proved to be more effective than when the liquid was dribbled. For millet, yields were much lower for the limed soil than where no lime had been applied. Substantial increase in uptake of phosphorus by plants was noted on the unlimed soil, while the addition of lime depressed phosphorus absorption, especially in the case of corn. Liquid-banded placement effected a greater uptake of phosphorus by the crops, while a much lower uptake of phosphorus by the plants resulted from the use of the solid materials. On the mineral soil, Metea sandy loam, the liquids were found to be superior to the solids when applied in comparable placements. Here again, ammoniated superphosphoric acid gave the highest corn yields. Phosphorus absorption by the crops was increased at higher rate of phosphate application in most cases.

Laboratory incubation studies conducted with Metea sandy loam and Rifle peat when treated with different rates of solid and liquid ammonium metaphosphates showed that these two soils behaved differently as could be expected. Increased additions of liquid ammonium metaphosphate brought about an increased fixation or non-hydrolysis of phosphorus in Metea sandy loam, while release of phosphorus was obtained from Rifle peat. Solid ammonium metaphosphate applied to these two soils was fixed or non-recoverable to different degrees under the laboratory conditions of incubation.

Laboratory experiments set up to determine the vertical and lateral distribution of phosphorus in Metea sandy loam when treated with solid and liquid ammonium metaphosphates at 5, 10, and 20 percent moisture levels in the soil showed that the solid moved more slowly than the liquid. At the 5 percent moisture level phosphate movement was slow, increasing rapidly at the higher moisture levels. The vertical migration of phosphorus exceeded that of lateral distribution, although this disproportion appeared to decrease with distance and time.

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INTRODUCTION

Phosphorus has long been recognized as an indispensable constituent of all living organisms. Because of the tremendously important role that this element plays in animal and plant nutrition, the behavior of phosphorus has received considerable attention at the hands of biological scientists, nutritionists, and agronomists. Plant physiologists have, in recent years, contributed a great deal to the understanding of the manner of utilization of phosphorus by plants, including its absorption by the roots, movement and distribution within the plant, and its physiological function in the storage and transfer of energy in the metabolic reactions. Agronomists have carried on extensive investigations on the hitherto little understood behavior of phosphorus in soil systems, the importance and effectiveness of different sources of phosphorus, and the most effective method, time, and rate of application of phosphate fertilizers for various crops to improve their yield and quality.

In recent years there have been important developments, including granulation, the development of new fertilizers of higher analysis, and precision placement of fertilizer with respect to the seed or plant. A relatively new group of fertilizer materials which have been introduced commercially are the complete liquid fertilizers. Solutions of highly soluble fertilizers have been used for many years as starter liquids for vegetable transplants, but until recently little use has been made of concentrated complete liquid fertilizers under general farming conditions. Of late, attempts have been made by agronomists to compare the relative efficiency of liquid and solid mixed fertilizers in different placements. However, little information has been published regarding such comparisons.

Since most nitrogen and potassium carriers of solid fertilizers are highly water soluble, it is not likely that these components will differ greatly from those in liquid fertilizers as to their availability. Most workers feel that if differences exist between liquid and solid fertilizers such variation in nutrient availability will be the result of differences in behavior of the phosphate component. At present there exists a rather wide range in water solubility of phosphorus in mixed fertilizers and under certain conditions this has been shown to affect yields and fertilizer phosphorus absorption by crops. In the opinion of some agronomists, phosphorus fixation by the soil will be greater from phosphate in the liquid than from solid material, thus reducing the effectiveness of the liquid. Others, however, feel that little or no difference exists. From an agronomic standpoint, therefore, information is needed in answer to the question: How do solid and liquid materials compare as sources of phosphorus under different soil conditions and in relation to various practices? Consequently, this investigation was undertaken in order to study the following points relative to the use of solid and liquid fertilizers:

1. The effectiveness of solid and liquid mixed fertilizers of similar phosphorus composition on yield and fertilizer phosphorus absorption by several crops in the greenhouse and the field.

2. The effect of method of placement on yield and availability of phosphorus from solid and liquid fertilizer sources.

3. The effect of concentration of phosphorus in liquid fertilizer sources on the availability of phosphorus to plants.

4. The diffusion or movement and fixation of phosphate ions from solid and liquid phosphorus compounds in different soils under laboratory conditions.

REVIEW OF LITERATURE

Previous to 1954, commercial production of liquid fertilizers was limited to nitrogen solutions, and liquid phosphoric acid. In the last five years there has been an extremely rapid development in the production and marketing of liquid fertilizers containing nitrogen, phosphorus, and potassium (24).[1] In 1957 over 165 firms were engaged in the manufacture of such liquids (21).

At present liquid fertilizers are usually compounded from furnace grade phosphoric acid (75% H_3PO_4), ammonia, and potassium chloride. This composition limits the analysis of the liquids to about 9-9-9 or without potash to an 8-24-0 analysis (32).

Development of superphosphoric acid:

The phosphoric acid sold as phosphatic fertilizer solution contains about 55 percent P_2O_5 or 75 percent orthophosphoric acid. This acid produced either by the wet process or from phosphorus obtained by the electric furnace method (27) is used for the production of solid and liquid fertilizers.

In recent work by TVA, acid containing 76 percent P_2O_5, which is equivalent to 105 percent orthophosphoric acid is found to have advantages over acids both of lower and higher concentrations. Acids containing about 60 to 75 and 77 to 83 percent P_2O_5 crystallized at ordinary temperatures, whereas that containing about 75 to 77 percent P_2O_5 remained liquid at temperatures low enough to be shipped and

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[1]Numbers in parentheses refer to literature cited.

stored in tanks exposed to the weather. Acid containing about 84 percent P_2O_5 also remained liquid, but it was much more viscous than the acid containing about 76 percent P_2O_5, which has been called superphosphoric acid (28). A given volume of this acid contains 70 percent more P_2O_5 by weight than acid of ordinary concentration, thereby providing for the transportation and storage of considerably more plant food in existing equipment. Also, solutions of ammoniated superphosphoric acid contain polyphosphates in addition to the ortho-phosphate present in liquids produced from ordinary acid. As a result it is possible to produce liquid fertilizers of higher analyses, or conversely, with lower salting out temperatures. Significant amounts of minor elements may be dissolved in liquid fertilizers that contain polyphosphates, whereas such is not true in the case of liquids produced from ordinary acid. When wet process acid is ammoniated in the presence of superphosphoric acid or ammoniated superphosphoric acid, the polyphosphates serve to sequester the impurities in the wet process acid, thus liquid fertilizers free of precipitated solids are obtained (27). Liquid ammoniated superphosphoric acid has been prepared experimentally by reacting superphosphoric acid (76.5% P_2O_5) with ammonium hydroxide at a temperature of 55°F. In this process about 50 percent of the P_2O_5 is in the ortho form at the time the liquid is prepared (21).

Another liquid fertilizer that has been produced by TVA on an experimental basis is liquid ammonium metaphosphate. This material is a clear liquid produced by dissolving NH_3-P_2O_5 reaction product of a 1.04 N:P atomic ratio in water at a temperature of 125 to 150°F. while adding ammonia to maintain a neutral solution (29). Analyses of this fertilizer indicate it contains 16.4 percent N and 79.9 percent P_2O_5.

Solid vs. Liquid Fertilizers:

While there is considerable literature dealing with the effectiveness of solid or dry fertilizers, agronomic reports of studies of the use of liquid fertilizers containing nitrogen, phosphorus, and potassium are rather limited. Lack of such information is due essentially to the fact that complete liquid fertilizers have only recently been produced on a commercial scale. With solid fertilizers, water solubility of the phosphate fraction is now regarded by agronomists (19) as being quite advantageous under certain soil and crop conditions. It is now recognized that the factors of particle size and placement of solid fertilizers must be carefully considered when specific conclusions or recommendations are made with respect to phosphate water solubility (9, 19). Norland et al. (14) grew corn stover and hairy vetch in greenhouse cultures on slightly acid Chester soil to determine the effect of variable proportions of water-soluble phosphorus in fertilizers upon yield and phosphorus uptake. Their data show that increasing the proportion of the water-soluble phosphorus fraction of fertilizer resulted in significantly greater yield and phosphorus uptake. In all but two of the test fertilizers applied, corn stover and hairy vetch gave comparable results.

It is possible that the complete solubility of the liquids is an advantage in some areas where solid fertilizers used have only been partially water-soluble. There appears to be no evidence, however, that the liquids are generally superior to water-soluble solid materials such as diammonium and monoammonium phosphates.

The only agronomic criticism of liquids has been that phosphate is fixed more rapidly when it is in liquid form. Little agronomic data appears to be available on this subject.

The agronomic effectiveness of liquid mixtures is a point on which producers differ widely. About a third state without qualification that liquids are superior to solid mixtures (24). Norland et al. (15) applied several 12-12-12 fertilizers with phosphorus water solubility ranging from 2 to 60 percent of the total phosphorus, calcium metaphosphate, monoammonium phosphate, and a liquid 9-9-9 mixture to Evesboro loamy sand and Davidson silty clay loam 4, 2 and 1 month prior to planting respectively, and on the date of planting to determine the influence of water-solubility, soil type, and time of fertilizer application prior to planting. The first crop of Starr millet indicated a superiority of the highly water-soluble phosphates on both soils irrespective of the time of application. While time of fertilization made little, if any, difference at the first harvest on the Evesboro soil that had a low phosphate fixing capacity, preplanting applications of the more soluble phosphates definitely reduced their effectiveness on the Davidson soil that had a high phosphate fixing capacity. The second cutting showed the same trend with smaller differences. The third showed very small differences between the fertilizers on the Davidson soil, but significant differences persisted on the Evesboro soil. These investigators noted that with fertilization at seeding time on the Evesboro soil liquids gave sensibly the same yields as the solids at the first and second harvests, at the 100 pound P_2O_5 per acre rate, while at the 200 pound application gave significantly higher yields than the solids. On the Davidson soil the comparison was generally somewhat less favorable to the liquid. Mixed placement was recognized as a handicaps to liquids by these authors. From these studies, these workers concluded that phosphate in solution and phosphate in the form of very soluble coarse granules are about equally effective on classes of soils typical of the two soils they studied.

Some of the conditions listed under which liquids may give superior results are: 1) Specific crops only, 2) Certain fertilizer practices such as side-dressing, 3) Dry seasons or cold weather, and 4) Alkaline soils (for the acidic type of liquid mixtures). Some producers state that in their opinion the liquids have no agronomic advantage over the solid type.

The generally recognized advantages of liquid over conventional dry fertilizers are as follows (22):

1. Liquid fertilizers can be handled with small pumps with a saving of labor.
2. Uniform broadcast application is easily obtained by spraying.
3. Materials are completely soluble in water so they can be used in irrigation water and as starter solutions.
4. Uniform mixtures of plant nutrients results from their use.
5. Pesticides are compatible with many liquid fertilizers. Simultaneous application saves time and insures uniform application.
6. The use of liquids simplifies custom mixing of fertilizer grades.
7. Liquids may be used as foliar sprays.
8. The availability of nitrogen and potassium is not decreased when applied to the soil in the liquid form.

The following disadvantages of liquid over conventional dry fertilizers have been recognized by both producer and agronomist (22).

1. Special equipment is required.
2. Special storage containers are necessary.
3. Complete fertilizers in liquid form can be made only in relatively low grades and they contain very small quantities of secondary or minor elements.
4. Application equipment for placing fertilizer in recommended position with respect to the seed in the soil is generally unavailable.

5. Phosphorus fixation (a decrease in solubility or availability) in the soil may be increased.
6. Calcium and magnesium contents of liquid fertilizers have to be kept low to prevent precipitation of other plant nutrients.
7. Rates of actual nutrients applied may be limited because of the large volume of water needed.
8. Liquid fertilizers corrode certain metals.
9. Liquid fertilizers may be more difficult to merchandise.
10. Completely soluble carriers are required for the manufacture of solutions; setting a limitation on carriers which may be used.
11. Grades high in potassium, suitable for several crops growing on light sandy or organic soils are difficult to formulate unless low grade fertilizers are accepted.

In practice, the quantity of liquid N-P or N-P-K fertilizers now being used by farmers represents a small proportion of the total fertilizer consumption. Future developments probably will be determined by the following factors:

1. Success in raising the nutrient concentration above present grades.
2. Reducing the cost of raw materials needed in formulation.
3. Economies and improvements in application methods which may be achieved.
4. Relative effectiveness of solid and liquid fertilizers as a source of phosphorus to crops.

It may be mentioned in this connection that the Tennessee Valley Authority is producing on an experimental scale concentrated phosphorus liquid fertilizers (29). Some of these materials are: liquid ammonium metaphosphate (AMP) (11.0-37.8-0), AMP - solid ammonium metaphosphate (16.3-80.3-0), DAP - liquid diammonium phosphate (7.9-20.0-0), DAP - solid diammonium phosphate (21.0-53.0-0), and ASPA - liquid ammoniated superphosphoric acid (10.15-36.8-0).

The investigators of the Tennessee Valley Authority compared the above five nitrogen-phosphorus fertilizers in greenhouse studies with Brown Top millet and Anderson winter wheat (29). Millet was used as a first crop, followed by wheat to measure residual effects of the materials. In general the liquid fertilizers resulted in higher dry matter yields than the corresponding solid form of the materials. In this respect, ammonium metaphosphate was the least effective of the materials tested, with the liquid being considerably more effective than the solid form. Liquid ammoniated superphosphoric acid was found to be more effective than liquid ammonium metaphosphate. While the yields from the mixed placement of fertilizers were considerably lower than from banding, the same general order of effectiveness of the materials was observed. The yields of the second crop to study the residual effect of the fertilizers were much lower and the response to phosphorus was much less pronounced. Regarding phosphorus absorption, solid ammonium metaphosphate gave the lowest yield of phosphorus, while liquid ammoniated superphosphoric acid was most effective regardless of placement.

Robertson et al. (22) found in one trial on wheat that the solid and liquid forms of complete fertilizer had equal effects on yield. The same authors found similar effects in three trials on oats. With corn grown at one location, the liquid fertilizer plots yielded 20 bushels less corn per acre than did the dry fertilizer plots. At another location, in a fertilizer rate and placement experiment, corn yields were 17 bushels lower where N, P_2O_5 and K_2O, each at 50 pounds per acre, were sprayed on the surface of the soil than where they were injected in the liquid form into the soil near the row before the first cultivation. At twice the rate of the same fertilizer, liquid sprayed on the soil surface was as effective as solid fertilizer, and also produced yields equivalent to those where the lower rate of liquid fertilizer was injected into the soil.

In trials on organic soils, Khouri (7) found that the use of liquid fertilizer resulted in lower yields of onions, carrots, and table beets than were obtained with a similar placement of solid fertilizers.

Many experimental studies comparing fertilizer sources of phosphorus have been carried out over a number of years. In the past decade radioactive phosphorus has been incorporated into fertilizers, thereby allowing evaluation of plant absorption of fertilizer phosphorus. Many reports of comparisons of utilization of phosphorus from various P^{32} labelled phosphate carriers have come from agricultural experiment stations. Using these tracer methods, the superiority of soluble sources of phosphorus on certain soils has been demonstrated by several workers. For example, Dion et al. (3) found monoammonium phosphate supplied significantly larger amounts of phosphorus to wheat and barley than did monocalcium phosphate, and that dicalcium phosphate was inferior to either of these sources on neutral to alkaline soils. Likewise in Colorado, Olsen et al. (16) found that superphosphate furnished more phosphorus to plants than dicalcium or tricalcium phosphate. Speer et al. (25) using tracer procedures showed that superphosphates, monosodium phosphate, monoammonium phosphate, monomagnesium phosphate, and phosphoric acid were readily absorbed by crops grown on Houston Black Clay.

In recent years several metaphosphate fertilizers have been developed by TVA with the idea of stimulating production of high analysis phosphates. Calcium metaphosphate produced in pilot plants has been compared with superphosphate in many regions. However, potassium and ammonium metaphosphates are still considered as experimental materials. Godfrey *et al.* (5) in studies of comparisons of the effect of ammonium orthophosphate, ammonium metaphosphate, and 20 percent superphosphate on Sweet sudan and Iron-Clay cowpeas grown on an acid Planosol and a highly calcareous Grumusol, found ammonium metaphosphate was a very promising high analysis fertilizer on acid soils, and also equally satisfactory (but not superior) on calcareous soils. These results seem to be in agreement with the work of Olson and Dreier (17). In studies of the availability of several phosphate carriers to small grains and subsequent clover in relation to nature of soil and method of placement, Olson *et al.* (18) found the comparative effectiveness of their phosphate carriers as shown by yield and phosphorus uptake to be as follows: ammonium phosphate $\geqq$ concentrated superphosphate $\geqq$ ordinary and ammoniated superphosphate, calcium metaphosphate, and nitric phosphate of high water solubility. Ammoniated superphosphate and calcium metaphosphate were found to be effective only on acid soils and decidedly inferior on calcareous soils. Maximum efficiency of these carriers was obtained with seed placement as compared with broadcast or mixed placement of the phosphate. There were no differences in residual values of these carriers.

It must be pointed out that there has been very little published work on the newer high analysis materials like ammonium metaphosphate and ammoniated superphosphoric acid, and also little effort appears to have been made to tag these new materials with P^{32}.

Several reports have been published on the behavior of calcium and potassium metaphosphates in soils. However, in the literature, no work has appeared on similar studies with ammonium metaphosphate. The Tennessee Valley Authority has produced considerable quantities of calcium metaphosphate, and now attempts are being made to introduce potassium and ammonium metaphosphates to the fertilizer industry.

These concentrated fertilizers, containing over 55 percent P_2O_5, present a decided advantage to farmers since they have several times more plant nutrients per ton than ordinary commercial superphosphate. Thus, the costs of handling, bagging, storing, shipping, and spreading are reduced. While numerous yield comparative tests have been made with calcium and potassium metaphosphates in the field and greenhouse, the chemical properties of the metaphosphates in general and their behavior in soil have not received much attention. This is due primarily to the fact that the metaphosphates have a strong tendency to polymerize into complex products with high molecular weights and their commercial importance has not warranted the requisite research. Nevertheless, of late, the use of metaphosphates as fertilizers, water conditioners, emulsifying agents, and detergents has stimulated new interest in these compounds. There are some reports about the solubility and reversion characteristics of these metaphosphates under laboratory conditions, but little published work is to be found on the behavior of these compounds in soil.

Lysimeter studies by MacIntire *et al.* (11) on the behavior of potassium metaphosphate shows that this compound is readily hydrolyzed to the ortho form. Since the K and NH_4 ions have many similarities in their chemical behavior, it may be inferred that ammonium metaphosphate would hydrolyze to the ortho form in the same fashion, although there is no experimental evidence to corroborate this statement.

Effect of Placement

Placement is an important consideration in studying phosphate fertilizer efficiency. Dean *et al.* (2) found in a greenhouse test ryegrass obtained more phosphorus from superphosphate when it was mixed with the top third of the soil than by band placement or mixing with the entire soil. Mixing with all the soil gave the lowest uptake of phosphorus from the fertilizer.

Nelson et al. (13), working with North Carolina soils, measured the effect of placement on amount of P^{32} taken up from superphosphate by corn and cotton. For cotton, P^{32} uptake indicated a higher efficiency for phosphate placed in bands 3 inches from the row as compared with broadcast for both low- and high-phosphorus soils. However, differences for the sampling dates were generally smaller for the high phosphorus soil. In the case of corn, fertilizer placed in bands 3 inches from the row was utilized to a greater extent than fertilizer broadcast, but it was not appreciably better than when the fertilizer was mixed in the row. There was an early vegetative growth response on both corn and cotton at the 50-lb. rate of P_2O_5 and the magnitude of the response correlated with phosphorus uptake in the early stages. However, manner of placement at the 50-lb. rate had no effect on yields.

Stanford and Nelson (26) studied the effect of placement on uptake of fertilizer phosphorus by corn. Their results showed that placement of fertilizer at seed depth in bands on one or both sides of the seed generally resulted in greater utilization of fertilizer phosphorus than when placed in a single band above or below the seed level. Dry matter yields during early stages of growth also showed seed level placement to be superior to other methods.

Blaser and McAuliffe (1) found that in the case of Ladino clover, superphosphate and calcium metaphosphate were taken up to a greater extent from the drilled than from the broadcast application whereas the reverse effect was noted with orchard grass.

Movement of Phosphorus

When soluble phosphates are added to soil, the phosphorus is rendered insoluble almost as soon as it comes in contact with the soil. It appears that the movement of phosphorus in the soil is quite inappreciable.

Olsen *et al.* (16) studying the movement of liquid phosphoric acid and of treble superphosphate applied to an alkaline soil, found that 82.3 percent of the phosphoric acid remained in the surface 3 inches of soil, while 98 to 99 percent of the treble superphosphate remained within 2 inches of the zone of application. Ulrich and associates (30) also found that liquid phosphoric acid applied at the rate of 2,300 pounds P_2O_5 per acre to a loam of high phosphorus-fixing capacity penetrated to a depth of 11 inches in 43 days, although 86 percent of the amount applied remained in the top 6 inches of soil.

Langguth *et al.* (8) used a soil column to study and compare the chemical availability and movement of phosphates from liquid and dry fertilizers in four widely different California soils. The fertilizers used in this study were a 2-24-0 liquid fertilizer, a 11-48-0 dry fertilizer, and a 0-42-0 superphosphate. These workers found that the availability of phosphate from liquid fertilizers was either equal to or greater than the phosphate availability from dry fertilizers having a highly water-soluble phosphate source. The movement of the phosphate from the liquid fertilizer was essentially the same as that obtained from the dry fertilizers, although the quantity of applied phosphate remaining on the soil surface was greater from solid fertilizers than from the liquid. However, the amount of surface phosphate was only a small fraction of the total applied phosphate.

Extensive investigations have been carried out in order to study several factors affecting movement of phosphates in soil systems, and the results can be summarized as follows:

1. Relatively rapid movement of phosphates occurs only in light textured soils.
2. Phosphate movement is slight in soil systems that are strongly acid or alkaline.
3. Little phosphate movement is observed in soil systems that contain appreciable quantities of iron and aluminum oxides.
4. Greater movement is noted in soil systems which are continuously wet than if they are allowed to dry.
5. Greater movement is observed when phosphates are applied as salts of the monovalent cations or magnesium than when applied as calcium salts.
6. If the phosphates are applied in a water soluble form, the movement observed is roughly proportional to the rate of application.

METHODS AND MATERIALS

Greenhouse Experiments with Corn and Field Beans (1956)

The soil selected for study was the surface 0-7 inch layer of a Metea sandy loam from the University experimental plots at East Lansing, Michigan, where phosphorus deficiency on corn had been previously noted when no phosphate was used. Some of the physical and chemical properties of this soil are given in Table 1.

Soil Containers

Ten wooden boxes having inner dimensions of 45x45x8 inches were filled with sandy loam soil up to 7 inches deep. Each box was divided into two equal sections by means of a wooden separator. The soil was compacted, moistened, and partially dried before placement of fertilizer and planting seeds.

Fertilizer Materials and Methods of Placement

Monoammonium phosphate labelled with P^{32} was supplied by the Fertilizer and Agricultural Lime Section, A. R. S., Beltsville, Maryland. This phosphorus source was mixed with muriate of potash and ammonium nitrate to give a material of approximately 12-24-24 analysis. Specified amounts of this fertilizer were dissolved in water for spray, dribble, and row application. Special equipment designed by the Agricultural Engineering Department of Michigan State University was used to apply radioactive solid and liquid fertilizer in the different placements. This equipment is shown in Plate 1.

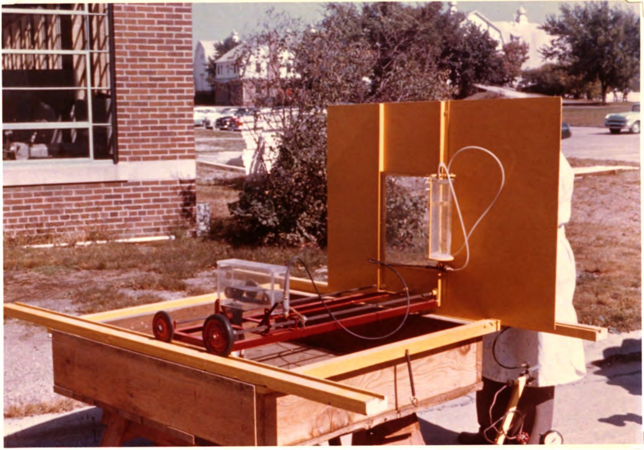

Plate I. Mechanical equipment used in the application of radioactive solid and liquid fertilizer in the greenhouse.

Table 1. Some physical and chemical properties of the soils used in the field, greenhouse, and laboratory studies.

Soil	pH[1]	Percent sand[2]	Percent silt	Percent clay	Exch. cap. me/100 gms.[3]	Exchangeable cations[4] me./100 mgs.				
						Ca	Mg	K	Na	H
Rifle peat	4.3	-	-	-	91.04	46.0	1.33	0.08	0.21	35.0
Metea sandy loam	6.0	68.0	23.6	8.4	4.2	1.65	1.25	0.22	0.06	-

[1]Determined by glass electrode
[2]Determined by the hydrometer method of Bouyoucos
[3]Determined by the neutral normal ammonium acetate method
[4]Analyzed on the Beckman DU flame spectrophotometer

Rates of Application

The solid and liquid materials were applied at rates of 100 and 200 pounds of P_2O_5 per acre. Where liquid was applied, 500 ml. of the fertilizer solution was applied to each half box. At the 100 pounds P_2O_5 per acre rate, 50 pounds of N and 100 pounds of K_2O were applied, while these two rates were doubled when 200 pounds P_2O_5 per acre was used. The fertilizer treatments (2 replications) were as follows:

A. Check no fertilizer
B. Solid in row 100 pounds P_2O_5
C. Solid in row 200 pounds P_2O_5
D. Solid mixed 100 pounds P_2O_5 (fertilizer mixed with top inch of soil)
E. Liquid in row 100 pounds P_2O_5
F. Liquid in row 200 pounds P_2O_5
G. Liquid dribble 100 pounds P_2O_5 (fertilizer dribbled on top of soil over the row)
H. Liquid dribble 200 pounds P_2O_5
I. Liquid spray 100 pounds P_2O_5
J. Liquid spray 200 pounds P_2O_5

Test Plants

Corn was planted in each of two rows 12 inches apart at the rate of 16 seeds per row on April 20, 1956, one day after fertilizer application. The boxes were irrigated by the addition of a measured quantity of distilled water at regular intervals. Plants were harvested at four different stages of growth, namely, 2, 4, 6, and 8 weeks after planting.

Field beans were planted in each of two rows 12 inches apart at the rate of 12 seeds per row on June 28, 1956, the same day as fertilizer was applied. Plants were harvested at three different stages of growth, namely, 2, 4, and 7 weeks after planting.

Radioactive and Chemical Analysis

Dried plant material of each replicate at each sampling date was pressed into pellets using a hydraulic press according to the method employed by Vomocil (31). Specific activity measurements of the pellets were made using an NMC decade scaler and GM counting tube. Standard pellets were prepared by using a known portion of the radioactive phosphorus fertilizer mixed thoroughly with non-radioactive plant material. The activities of the standard pellets were compared with those of the plant material collected from the greenhouse and field experiments. Total phosphorus analysis was made on the same pellet used for radioactive phosphorus analysis by wet ashing the plant material in a 150 milliliter tall form beaker with 15 milliliters of concentrated nitric acid. The sample was digested on an electric hot plate until all the organic matter was destroyed, leaving a clear solution. Then six milliliters of 70 percent perchloric acid was added to the solution and the digestion on the hot plate continued until the oxidation was complete and a clear, colorless solution was obtained. This solution was then taken almost to dryness, cooled, and made up to 100 milliliter volume with 0.05N HCl. The solution was filtered through a Whatman No. 42 filter paper. This method closely follows the wet ash procedure by the perchloric acid method of Piper (20). The phosphorus in solution was determined as molybdenum blue. One milliliter aliquot of the solution was diluted to 10 milliliters, and six drops of ammonium molybdate-hydrochloric acid reagent was added, followed by the same quantity of Fiske-Subbarow (4) reagent. The solution was shaken, and after 15 minutes, the transmittance of the blue color developed was measured in a Coleman Universal Spectrophotometer Model 14, using a red filter (650 mμ).

Field Experiment with Corn (1956)

Soil Area

Metea sandy loam at the University Experimental Farms, East Lansing, Michigan, was selected for the comparison of solid and liquid fertilizers. This was the same soil which was used in the greenhouse study above. The available phosphorus in this soil was low, being only 12 pounds per acre using 0.13N HCl as the extractant.

Fertilizer

Monoammonium phosphate labelled with P^{32} was mixed with KCl and NH_4NO_3 to give a mixed fertilizer of 1-2-2 ratio. The solid and liquid materials listed below were applied at rates equivalent to 100 pounds P_2O_5 per acre.

Treatments:
1. Liquid spray NPK
2. Liquid spray NK
3. Liquid in row NPK
4. Liquid in row NK
5. Liquid dribble NPK
6. Liquid dribble NK
7. Solid in row NPK
8. Solid in row NK
9. Solid broadcast NPK
10. Solid broadcast NK

Method of Application

Special tractor mounted equipment designed by the Agricultural Engineering Department of Michigan State University was used in applying the fertilizer. This equipment is shown in Plate II. For spray treatments the entire plot was sprayed, while for dribble treatments, the liquid was dribbled directly over the seed row. For row treatments, the fertilizer was placed to the side and below the

Plate II. Mechanical equipment used in the application of radio-active solid fertilizer in the field.

seed. For broadcast treatments, the solid was mixed with a small amount of soil and the mixture spread back over the entire plot.

Plot Size, Fertilizing, Planting, and Harvesting

The design of the experiment was a randomized block with two replications per treatment. Each plot consisted of two rows of corn 35 feet long with a 42 inch spacing between rows. Fertilizers were applied on June 3rd and 4th, 1956. Corn seeds of the 90 day early maturing variety (Michigan certified 250) were planted after fertilization in a designated line to the side and below the row applications on June 5th. At the time of planting available moisture was low and germination was rather slow. The entire above ground plant parts were sampled 3 weeks after planting, while leaf samples were taken at periods of 5 and 9 weeks after planting. Corn was harvested on October 13th.

Radioactive and chemical analyses of the corn plant tissue were run as for samples from the greenhouse experiments.

Field Experiments with Corn (1957)

In 1957, experiments were conducted at the same location, namely, the field of Metea sandy loam, which was used in 1956. The same procedures employed in the 1956 experiment were followed, but because of a limited supply of P^{32} labelled monoammonium phosphate, phosphate application rate was reduced to 50 pounds P_2O_5 per acre in order to have four replications.

Fertilizer

Monoammonium phosphate labelled with P^{32} supplied by the Fertilizer and Agricultural Lime Section, A.R.S., Beltsville, Maryland, was mixed with muriate of potash and ammonium nitrate to give a mixed fertilizer of 1-2-2 ratio. In addition, nitrogen and potash fertilizer of a 1-0-2 ratio was used to determine the effect of phosphate in the presence of nitrogen and potassium. The treatments are listed as follows:

1. Solid in row	NPK - 50 pounds P_2O_5 per acre
2. Solid in row	NK
3. Solid mixed	NPK - 50 pounds P_2O_5 per acre
4. Solid mixed	NK
5. Liquid in row	NPK - 50 pounds P_2O_5 per acre
6. Liquid in row	NK
7. Liquid dribble	NPK - 50 pounds P_2O_5 per acre
8. Liquid dribble	NK

Corn (variety Michigan certified 250) was planted on June 6, 1957 one day after application of the fertilizer. Entire plants were sampled 3 weeks after planting, and leaf samples were taken 6 to 9 weeks after planting. Corn was harvested on October 20th, 1957. Radioactive and chemical analyses were carried out as for samples from the previous year.

Greenhouse Experiments with TVA Solid and Liquid Fertilizers

Fertilizers and Soils Used

In order to study the relative effectiveness of solid and liquid fertilizers, five materials supplied by the TVA, the properties of which are listed in tabular form on the next page, were compared in a greenhouse study. Two soils, a 0-7 inch layer of Metea sandy loam from the University experimental plots at East Lansing, Michigan, and a 0-8 inch layer of Rifle peat from Clinton County were selected for this experiment in order to evaluate comparative results from mineral and organic soils. The Metea soil was low in available

phosphorus with a pH of 6.0, while the Rifle peat was strongly acid (pH 4.3), and considered very responsive to the application of phosphate. Some of the chemical and physical properties of these soils are presented in Table 1.

Some physical and chemical properties of the TVA experimental fertilizers used in this greenhouse study were as follows:

Abbreviation	Fertilizer Material	Analysis
SAMP	Solid ammonium metaphosphate[1]	16.3-80.3-0
LAMP	Liquid ammonium metaphosphate[2]	11.0-37.8-0
DAP	Solid diammonium phosphate[3]	21.0-53.0-0
CSP	Solid concentrated superphosphate	0-49-0
ASPA	Liquid ammoniated superphosphoric acid[4]	10.5-36.8-0

[1]This material was a white solid with a bulk density of about 15 pounds per cubic foot. It was prepared by reacting P_2O_5 and gaseous NH_3 at a temperature of 700 F. It had a N:P atomic ratio of 1.05.

[2]This was a clear liquid produced by dissolving NH_3-P_2O_5 reaction product of a 1.04 N:P atomic ratio (16.4Δ N and 79.9Δ P_2O_5) in water at a temperature of 125 F. to 150 F. while adding ammonia to maintain a neutral solution. About 85 percent of the N was in the ammoniacal form and about 30 percent of the P_2O_5 was in the ortho form at the time the liquid was prepared. The liquid had a specific gravity of 1.376 and a pH of 7.1.

[3]Unconditioned plant product.

[4]This was a clear liquid prepared by reacting superphosphoric acid (76.5Δ P_2O_5) with ammonium hydroxide at a temperature of 55° F. About 50 percent of the P_2O_5 was in the ortho form at the time the liquid was prepared. All of the nitrogen should be in the ammoniacal form. The liquid has a specific gravity of 1.394 and a pH of 5.3.

For convenience the above abbreviations for the five fertilizer materials will be used henceforth in this write-up.

Rifle peat was set up in a limed and unlimed series in order to study the effect of lime on phosphorus availability of the several carriers. The peat which was mixed with precipitated calcium carbonate at the rate of 15 tons per acre, was incubated for 4 weeks after being moistened. The soil pH after incubation was found to be 7.2. Tin cans of a 3 gallon size, which were lined with polyethylene plastic were used as soil containers. The soils were mixed with ammonium nitrate and muriate of potash at rates of 50, 200, and 400 pounds of N, and K_2O per acre. Adjustments were made for the nitrogen already present in both solid and liquid ammonium metaphosphate, diammonium phosphate, and ammoniated superphosphoric acid. Three rates of P_2O_5-- 0, 50, and 200 pounds per acre were used with SAMP, LAMP, DAP, CSP, and ASPA as the phosphate sources. Sufficient supplementary nutrients were applied to each container on an acre basis.

Two hundred and fifty pounds of magnesium sulfate, 300 pounds of manganese sulfate, 50 pounds of copper oxide, 30 pounds of borax, 25 pounds of zinc sulfate and 1 pound ammonium molybdate were applied to Rifle peat, while 100 pounds of magnesium sulfate, 500 pounds of manganese sulfate, 10 pounds each of copper and zinc sulfates, 10 pounds of sodium borate, and 1 pound of ammonium molybdate were added to Metea sandy loam.

Fertilizer Application

Three methods of applying the solid and liquid materials were utilized, including: 1) Solid in row, 2) Solid-mixed, 3) Liquid in row, and 4) Liquid-dribble. Each treatment was replicated three times. For solid and liquid row applications, circular depressions were made by pressing the rim of a clay pot into the moist soil.

Appropriate amounts of the solid fertilizer were placed uniformly in the depressions. As for the liquids, specific volumes of the liquid was delivered by means of a graduated pipette. Since the liquids were quite viscous, delivery of these through a pipette was not very satisfactory. Liquid dribble applications were made on the surface in a circular pattern. Seeds were sown about one inch below and two inches away from the circular depressions in which the solid and liquid fertilizer was placed. For solid-mixed application, the appropriate amounts of the fertilizer material was mixed thoroughly with the upper six inches of the soil.

Test Crops

Fertilizers were applied on June 14, 1957, and corn was planted the same day. Twelve seeds were planted in each can. Entire plant samples were taken 3 and 6 weeks after planting, leaving two plants in each can. The remaining plants were harvested when they started to tassel, approximately 8 weeks after planting. The above ground portion of the plants were dried in an oven at 70° C., weighed, and then ground in a Wiley mill. Analyses were made for total phosphorus in the dried plant tissue. Samples taken at the end of 3 and 6 weeks, respectively, were made up of material from three replicates, while the final sampling was of individual replicates.

Immediately after the harvest of corn and without disturbing more than the surface inch of soil, millet was planted in the same cans in order to determine the residual effect of the fertilizers. Entire plant samples were taken at intervals of 4, 6, and 8 weeks after planting, the one after 8 weeks being the final harvest. At the time of planting millet, an additional quantity of nitrogen and potash were applied to each can at the rate of 50 pounds of N and K_2O per acre.

As in the case of corn, replicates of the first two samples were combined for analysis, while the final harvested plants were dried, weighed, and ground separately for analysis. After wet-ashing the ground residue, the molybdenum blue method was employed for the estimation of phosphorus, using amino-naphthol-sulfonic acid as the reducing agent (4).

Phosphorus Movement and Fixation Studies in the Laboratory

Experiment 1

In order to study the relative movement of solid and liquid phosphorus fertilizers, a laboratory experiment was initiated, using Metea sandy loam.

Experimental Factors:

Fertilizers: 1. Solid ammonium metaphosphate

2. Liquid ammonium metaphosphate

Moisture levels: 5, 10, and 20 percent

Sampling intervals: 2, 4, 8, and 16 days

Containers: Special wooden boxes with inner dimensions $3\frac{1}{2} \times 4\frac{1}{2} \times 4\frac{1}{2}$ inches were procured for this experiment. Soil screened through a 2 millimeter sieve was mixed with a calculated quantity of ice flakes to obtain a specific soil moisture level. The soil was then placed in the wooden boxes and allowed to incubate for a week. The boxes had grooves cut in the inner two side walls, the distance between the grooves being 2.0 centimeters. In addition the boxes were provided with a top lid and a hinged side which could be opened or closed as desired. The soil was placed in each box, and compacted sufficiently. The fertilizers were placed in designated depressions, and then covered with soil. The boxes were then closed, the lids sealed, and kept in a chamber where 95 percent relative humidity could be maintained. The samplings at specified intervals were obtained by opening the side facing the grooves, and inserting a steel plate of appropriate dimensions into the grooves. Lateral samplings were obtained by cutting the section of soil on the steel plate by means of a metal frame with partitions 2 centimeters apart.

The soil samples thus obtained were analyzed for extractable phosphorus, using 0.03N ammonium fluoride and 0.25N hydrochloric acid, the soil to extractant ratio being 1:25.

Experiment 2

To evaluate the comparative fixation of phosphorus by soils when they were treated with varying rates of solid and liquid phosphorus fertilizers, incubation studies in the laboratory were conducted, using Metea sandy loam, and Rifle peat, the physical and chemical properties of which are presented in Table 1.

Rifle peat received solid ammonium metaphosphate at the rate of 200, 400, and 800 pounds P_2O_5 per acre, while the rates of liquid ammonium metaphosphate added to the soil were 260, 520, and 1040 pounds P_2O_5 per acre. Solid ammonium metaphosphate was added to Metea sandy loam at the rate of 400, 800, and 1,600 pounds P_2O_5 per acre, and the rate of application of liquid ammonium metaphosphate was 520, 1040, and 2080 pounds P_2O_5 per acre.

The necessary amount of fertilizer was mixed with 300 grams of soil in the case of Metea sandy loam, and 150 grams in the case of Rifle peat, and after being thoroughly mixed, was left in a deep freeze for a week. Then the soil was brought to field capacity by mixing the soil with appropriate quantity of ice flakes. The mixture was placed in a pint jar and sealed. The jars were incubated at room temperature. Samples were taken after 2, 7, 14, and 28 days of incubation. The samples were extracted with 0.03N ammonium fluoride and 0.025N hydrochloric acid and analyzed for phosphorus.

RESULTS AND DISCUSSION

Greenhouse Experiments with Corn and Beans

Dry Weight Yields

The effect of fertilizer applied in liquid and solid form on the growth of corn and field bean plants in the greenhouse is presented in Table 2. Two months after planting it was found that at the lower rate of applied phosphate dry matter production of corn was highest when fertilizer was liquid-banded followed by solid-banded, and lowest when it was liquid-dribbled or liquid-sprayed. At the higher phosphate application the liquid-dribble treatment was most effective followed by the solid-banded application. No logical explanation for this increase in effectiveness of the liquid-dribble application at the higher rate can be given, except that it is possible the seeds were probably placed very close to the line on which the phosphate solution was dribbled, thereby enhancing the availability of phosphorus to plants. This increase in availability of phosphorus to plants would account for the greater growth. Of all the material and application combinations, the liquid-spray and solid-mixed treatments were found to be least effective. In these two cases the fertilizer came in contact with a large volume of soil, thereby minimizing the availability of phosphorus to plants. On the other hand, in the case of liquid-banded, liquid-dribble, and solid-banded applications, the fertilizer was localized in limited areas of close proximity to the developing plants, a situation which would increase the availability of phosphorus to plants. Statistical analysis of data obtained on the yields showed that there was a significant increase due to the various treatments.

Table 2. The dry weights of corn and field bean plants as influenced by method of application of solid and liquid fertilizers to Metea sandy loam in the greenhouse.

Fertilizer treatment	Pounds P_2O_5 per acre	Dry weights of plants in grams per box*	
		Corn	Beans
Solid-mixed	200	264	112
Solid-banded	100	270	150
	200	315	175
Liquid-banded	100	296	158
	200	280	170
Liquid-dribble	100	243	159
	200	325	165
Liquid-spray	100	242	158
	200	265	162
No fertilizer		115	103

*Average of two replicates; statistical analysis of yield data of corn and field beans are given in Appendix Tables Vii and VIII respectively.

A comparison of the dry weights of field bean plants as shown in Table 2 indicates that with the exception of the solid-mixed fertilizer treatment, little difference in growth resulted with solid and liquid fertilizer applied by other methods. Compared with these treatments, a significant depression in growth occurred when solid fertilizer was mixed with the surface inch of soil. Actually for beans with fertilizer applied in this manner, growth was little better than for the no fertilizer treatment.

It is of interest to note that such poor growth did not result from the liquid-spray application, and is somewhat surprising that the solid-mixed and liquid-spray applications did not produce reasonably similar results as they did with corn in the greenhouse. It is possible the phosphorus applied in the liquid-spray form was more readily available to the emerging bean seedlings, thereby giving them a good start, while the phosphorus in the solid-mixed application was not immediately available to the plants due to the fact that the solid fertilizer was mixed with substantially large volume of soil.

The Absorption of Fertilizer Phosphorus by Corn and Beans

The absorption of fertilizer phosphorus by corn and field bean plants from P^{32}labelled solid and liquid phosphorus fertilizers under greenhouse conditions is presented in Tables 3 and 4 respectively. These results shown graphically in figures 1 and 2 appear to be somewhat erratic with respect to the two rates of applied phosphate for the earlier samplings when plants were 3 to 6 inches tall. For example, the data show that 100 percent of the phosphorus in two week old plants of the solid-banded and liquid-dribble treatments (100 pound P_2O_5 per acre rate) came from fertilizer. Although this soil is known to be phosphate deficient, these values are unusually high, especially since

Table 3. The relative absorption of fertilizer phosphorus by corn plants from solid and liquid fertilizers applied by different methods in the greenhouse.

Fertilizer treatment	Pounds P_2O_5 per acre	Percent P in plants from fertilizer*			
		2 weeks	4 weeks	6 weeks	8 weeks
Solid-mixed	200	100.0	70.3	84.2	51.9
Solid-banded	100	100.0	100.0	76.0	57.4
	200	61.5	93.9	92.7	60.3
Liquid-banded	100	60.5	60.6	72.6	44.1
	200	58.1	96.5	68.4	61.6
Liquid-dribble	100	100.0	77.0	59.7	32.1
	200	75.5	90.2	82.2	75.6
Liquid-spray	100	74.0	82.2	50.1	31.0
	200	100.0	81.6	76.1	54.3

*All values are mean of two replicates; individual values are given in Appendix Table V.

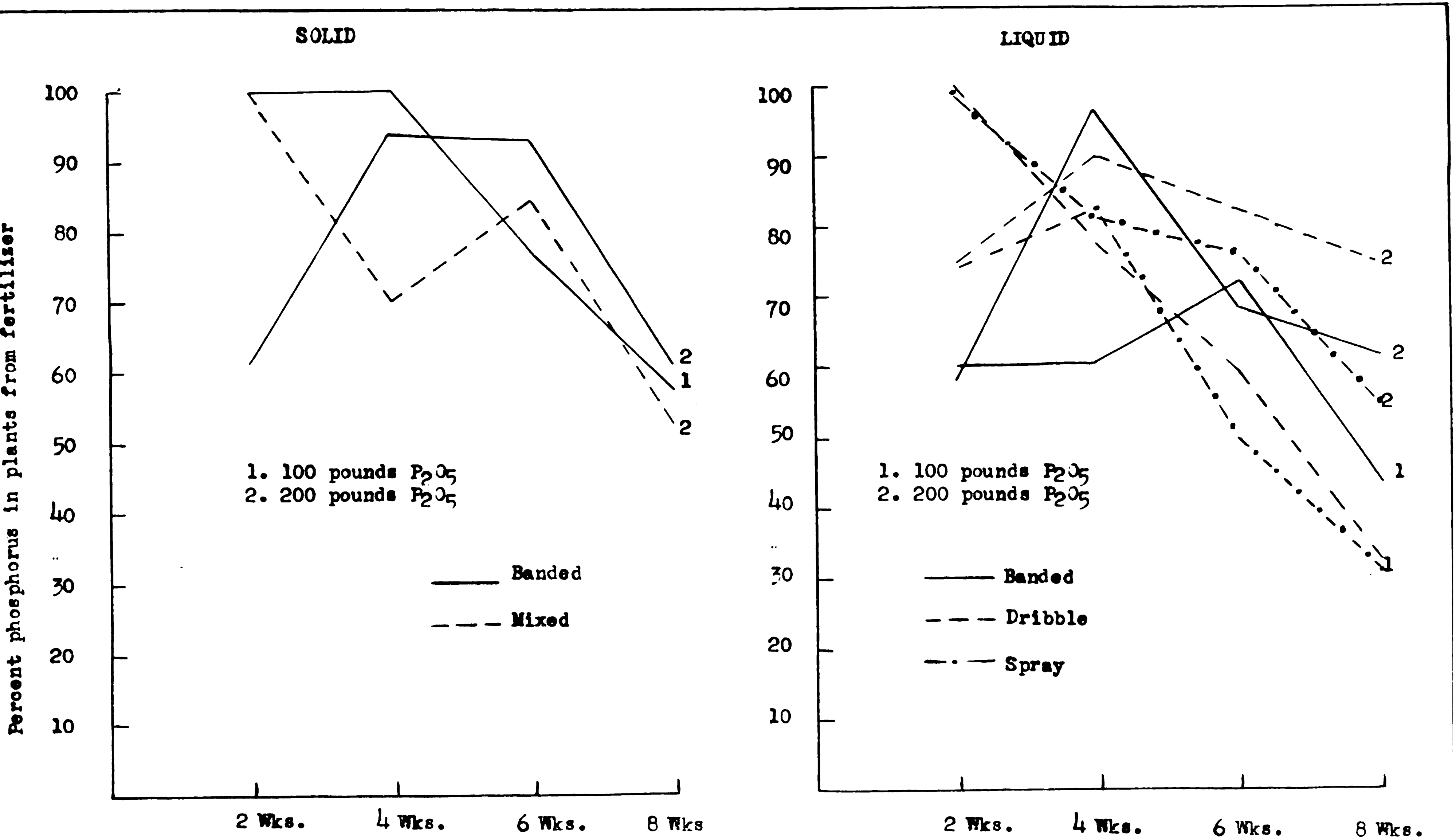

Figure 1. The relative absorption of fertilizer phosphorus by corn plants from solid and liquid fertilizers applied by different methods in the greenhouse.

Table 4. The relative absorption of fertilizer phosphorus by field bean plants from solid and liquid fertilizers applied by different methods in the greenhouse.

Fertilizer treatment	Pounds P_2O_5 per acre	Percent P in plants from fertilizer*		
		2 weeks	4 weeks	7 weeks
Solid-mixed	200	85.4	84.6	42.5
Solid-banded	100	78.0	57.1	30.7
	200	80.3	83.1	42.6
Liquid-banded	100	100.0	60.6	31.0
	200	75.4	73.3	35.3
Liquid dribble	100	64.1	49.1	21.8
	200	96.9	58.4	45.9
Liquid spray	100	58.8	32.8	14.2
	200	56.2	50.3	33.0

*All values are mean of two replicates; individual values are given in Appendix Table VI.

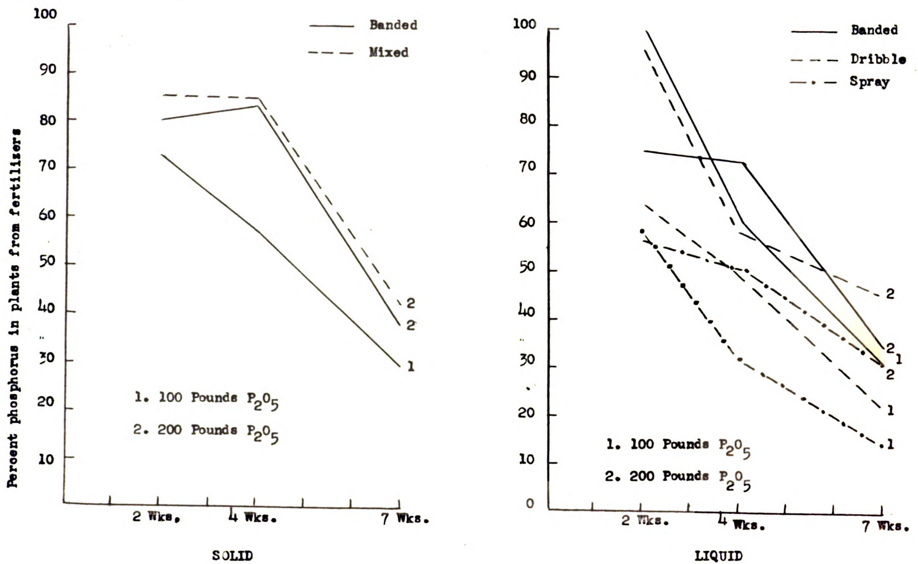

Figure 2. The relative absorption of fertilizer phosphorus by field bean plants from solid and liquid fertilizers applied by different methods in the greenhouse.

the contribution from fertilizer is somewhat lower for high rate of applied phosphate. This variation may have been due in part to settling of the soil mass within some boxes at the start of the experiment with the subsequent development of some cracks and a slightly irregular surface. It is definitely felt that values for fertilizer phosphorus absorption for the six and eight week old corn plants are more reliable and present a more accurate picture of the relative absorption of soil and fertilizer phosphorus.

Two months after planting the relative order of availability of fertilizer phosphorus to corn plants for the 100 pound P_2O_5 per acre treatments was solid-banded > liquid-banded > liquid-dribble > liquid-spray. For the 200 pound P_2O_5 rate this order was liquid-dribble > liquid-banded > solid-banded > solid-mixed > liquid-spray. Upon comparing dry matter yields with the relative proportion of fertilizer and soil phosphorus in corn plants after 8 weeks of growth, the relation appears rather imperfect. Only in the case where liquid fertilizer was dribbled on the soil surface was the growth response from increasing phosphate application related to uptake of fertilizer phosphorus. Yet, except for the solid-banded treatment, the percent of phosphorus in plants derived from fertilizer was distinctly higher for the greater amount of soluble phosphate applied. A number of investigators have obtained similar data with different crops. It has not been uncommon to obtain differential fertilizer phosphorus uptake with various phosphate sources, even though yield response obtained from such sources was nil or was of a positive and uniform character.

In Table 4, a comparison of these same fertilizer treatments for field beans which were in blossom 7 weeks after planting indicates that for the lower rate of applied phosphate, the order of availability

was liquid-banded = solid-banded > liquid-dribble > liquid-spray. This relationship is changed when the 200 pound P_2O_5 treatment is considered being as follows: liquid-dribble > solid-banded > solid-mixed > liquid-banded > liquid-spray. This sequence is different from the order of efficiency for the lower phosphate application in that the liquid-dribble and liquid-banded treatments have reversed their positions. The exact reason for this rather substantial change is not understood. Large differences are noted for final values of percent phosphorus derived from fertilizer for the 100 and 200 pound P_2O_5 per acre application for all treatments except that of liquid-banded.

As was found for corn, the relative proportion of fertilizer and soil phosphorus in two week old field bean plants from the liquid-banded application appears to be reversed for the 100 and 200 pound P_2O_5 per acre rates. However, a more important aspect to note is that with the lower quantity of applied phosphate, there is a steady decrease in percent of fertilizer phosphorus in bean plants over the experimental period. With the higher phosphate rate, this decline did not generally occur until at least one month after planting. This suggests that either phosphate ions from the 200 pound P_2O_5 per acre application migrated into a larger volume of soil or that because of a greater concentration of ions, the availability of fertilizer phosphorus was maintained over a longer period.

In general, with the greenhouse experiments the liquid-spray application was the least effective, whereas phosphorus from the banded application was most available to corn plants, except at the higher rate when the liquid-dribble treatment was most effective in supplying fertilizer phosphorus.

Field Experiments with Corn

The yields of corn in the field experiments for 1956 and 1957 as given in Table 5 followed the same general pattern as that for the greenhouse data. In 1956 the liquid-dribble treatment was most effective followed by the banded applications of solid and liquid fertilizer, while yields of corn grown on plots receiving spray and broadcast treatments were lowest. Because of the variation within the small number of replicates, only the liquid-dribble treatment produced yields significantly higher than those for other fertilizer treatments.

At the end of the 1957 season, the fertilizer treatment which produced the highest corn yield was solid fertilizer banded along the corn row. In contrast to results of the previous year, liquid-dribble treatment was substantially lower than that for the solid-banded treatment. For other fertilizer comparisons, the pattern of yield response followed that for 1956, although the yield of corn in 1957 was considerably lower. One of the reasons for these reduced yields was probably due to the lower rate of phosphate application of 50 pounds P_2O_5 in 1957, while the rate was just double in the previous year. A drought or lack of soil moisture at critical periods of growth was also responsible in part for the low yields.

The relative absorption of fertilizer phosphorus by corn plants from solid and liquid fertilizers applied by different methods in the field for two years are presented in Table 6. The general trends of fertilizer phosphorus uptake were the same as those obtained with corn plants in the greenhouse with the exception of the solid-mixed and liquid-spray applications. For this treatment under field conditions with well developed plants, the percent phosphorus in corn from fertilizer was low relative to values obtained in the greenhouse.

Table 5. The yield of corn (field) as influenced by method of application of solid and liquid fertilizers to Metea sandy loam.

Fertilizer material	1956 Pounds P_2O_5 per acre	1956 Yield bushels per acre[1]	1957 Pounds P_2O_5 per acre	1957 Yield bushels per acre[2]
Solid-mixed	100	59.0	50	33.4
Solid-banded	100	69.0	50	54.6
Liquid- banded	100	68.5	50	45.1
Liquid-dribble	100	75.0	50	42.4
Liquid-spray	100	60.0	50	37.2
No Phosphate	-	57.5[3]	-	34.2[3]

[1]Average of two replicates
[2]Average of four replicates
[3]Average of all NK treatments
Statistical analysis of yield data of corn in 1956 and 1957 are given in Appendix Tables IX and X respectively.

It is likely that continued watering in greenhouse tended to move fertilizer phosphorus toward the root zone, and thus enhance plant absorption.

Nine weeks after planting the liquid-spray and solid-mixed applications were least effective in supplying phosphorus to corn plants, whereas the solid and liquid-banded treatments were most effective followed by the liquid-dribble application. The phosphorus absorption trends during the periods of three and five weeks of growth of corn plants show that phosphorus was about equally available from all fertilizer applications, except that of liquid-spray, which was specially effective in 1956 in supplying fertilizer phosphorus to the young plants. Here again, as in the case of field beans grown in the greenhouse, it appears the phosphorus applied in the liquid-spray application was quite readily available to the emerging seedlings, but after some time declined in availability due to fixation with the soil.

Absorption of fertilizer by corn plants during their early growth in 1957 was quite similar for both solid and liquid fertilizers applied by the several methods. However, five weeks after planting, the availability of P^{32} labelled solid-fertilizer mixed with the soil surface had been markedly reduced as shown in Table 6. Thus the pattern of plant uptake of fertilizer phosphorus was similar to that for the previous year. At the end of nine weeks fertilizer phosphorus absorption was just about the same for solid-banded, liquid-banded, and liquid-dribble applications, while in the case of solid-mixed and liquid-spray applications, the fertilizer phosphorus absorption fell off markedly.

Table 6. The relative absorption of fertilizer phosphorus by corn plants from solid and liquid fertilizers applied by different placements in the field.

Fertilizer treatment	Pounds P_2O_5 Per acre	Percent P in corn plants from fertilizer*		
		3 weeks	5 weeks	9 weeks
			1956 season	
Solid-mixed	100	51.3	17.8	17.4
Solid-banded	100	55.3	52.9	42.0
Liquid-banded	100	50.9	47.6	40.0
Liquid-dribble	100	55.6	46.3	28.9
Liquid-spray	100	81.5	50.8	18.8
			1957 season	
Solid-mixed	50	40.9	16.8**	16.0
Solid-banded	50	49.6	46.2	38.8
Liquid-banded	50	51.9	47.9	36.0
Liquid-dribble	50	54.6	44.8	30.5
Liquid-spray	50	50.8	42.9	18.5

*Values in 1956 are mean of two replicates, while in 1957 of four replicates.

**These were sampled six weeks after planting.

Plate III. Effect of solid-mixed application of NPK and NK fertilizer (100 pounds P_2O_5 per acre) on the growth of corn in the field in 1956 (4 weeks after emergence).

Plate IV. Effect of solid-banded application of NPK and NK fertilizer (100 pounds P_2O_5 per acre) on the growth of corn in the field in 1956 (4 weeks after emergence).

Plate V. Effect of liquid-banded application of NPK and NK fertilizer (100 pounds P_2O_5 per acre) on the growth of corn in the field in 1956 (4 weeks after emergence).

Plate VI. Effect of liquid-dribble application of NPK and NK fertilizer (100 pounds P_2O_5 per acre) on the growth of corn in the field in 1956 (4 weeks after emergence).

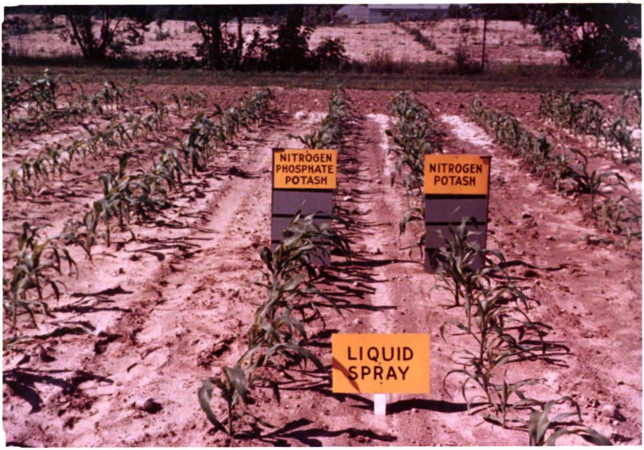

Plate VII. Effect of liquid-spray application of NPK and NK fertilizer (100 pounds P_2O_5 per acre) on the growth of corn in the field in 1956 (4 weeks after emergence).

In general liquid fertilizers appeared to behave similar to solid materials, provided the solid materials were highly soluble and similar methods of placement were compared.

Greenhouse Experiments with TVA Solid and Liquid Fertilizers

Five fertilizers, namely, liquid ammonium metaphosphate (LAMP), solid ammonium metaphosphate (SAMP), liquid ammoniated superphosphoric acid (ASPA), solid diammonium phosphate (DAP), and concentrated superphosphate (CSP) supplied by the TVA were compared in greenhouse studies using corn and millet. The placement of fertilizer included liquid-banded (L-B), liquid-dribble (L-D-R), solid-banded (S-B), and solid-mixed (S-M).

Dry Weight of Crops

The dry weights of corn grown on limed and unlimed Rifle peat as influenced by type and placement of solid and liquid fertilizer are shown in Table 7 and figures 3 and 4. On limed Rifle peat yield increases were statistically significant due to materials, placement, and rates when LAMP and ASPA were considered. However, there was no significant interaction between materials and placement or rate, materials and placement. When the solids were considered, significant increases in yield were noted for materials and placement and rate. Significant interaction was also found between rate and material and rate and placement, while none was evident between material and placement or between rate, material and placement. For liquids applied to unlimed Rifle peat, yield increases were found to be significant due to placement and rate and significant interaction was obtained between placement and rate and between material,

Table 7. Effect of solid and liquid fertilizers applied in different placements on the dry weight yields of corn plants grown on limed and unlimed Rifle peat in the greenhouse (9 weeks after planting).

Fertilizer material	Placement	Pounds P_2O_5 per acre	Dry weight in grams per pot* Limed soil	Unlimed soil
Check		0	23.1	13.8
LAMP	Liquid-banded	50	47.3	52.6
		200	60.0	56.0
	Liquid-dribble	50	38.0	54.0
		200	52.3	67.3
SAMP	Solid-banded	50	38.6	43.3
		200	58.6	55.3
	Solid-mixed	50	26.0	54.6
		200	56.0	51.3
ASPA	Liquid-banded	50	26.0	53.3
		200	71.3	60.6
	Liquid-dribble	50	22.6	59.3
		200	62.0	66.0
DAP	Solid-banded	50	49.3	17.3
		200	48.6	19.3
	Solid-mixed	50	25.3	42.6
		200	49.3	50.6
CSP	Solid-banded	50	40.6	20.6
		200	58.0	30.0
	Solid-mixed	50	34.6	17.0
		200	56.6	28.1

*All values are mean of 3 replications.
Statistical analysis of yield data are given in Appendix Tables XI and XII.

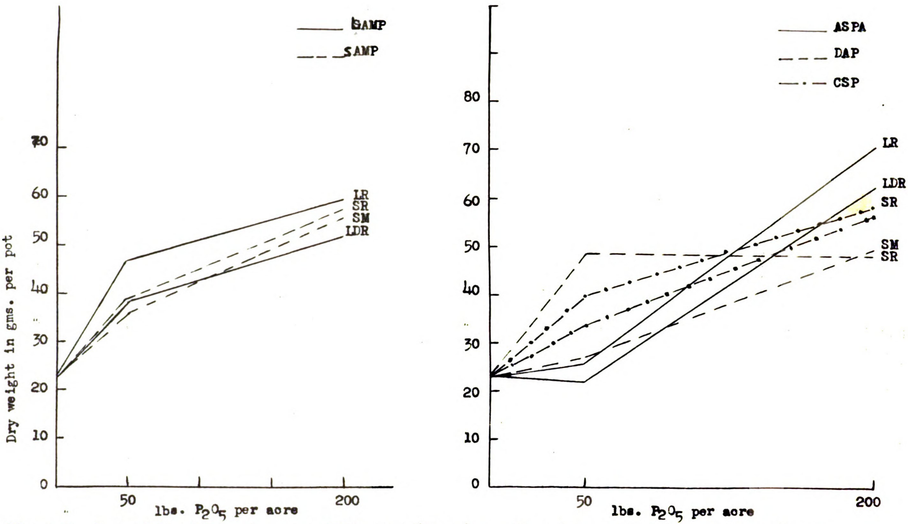

Figure 3. Dry weight yields of corn on Rifle peat (limed) as affected by solid and liquid fertilizers applied in different placements in the greenhouse.

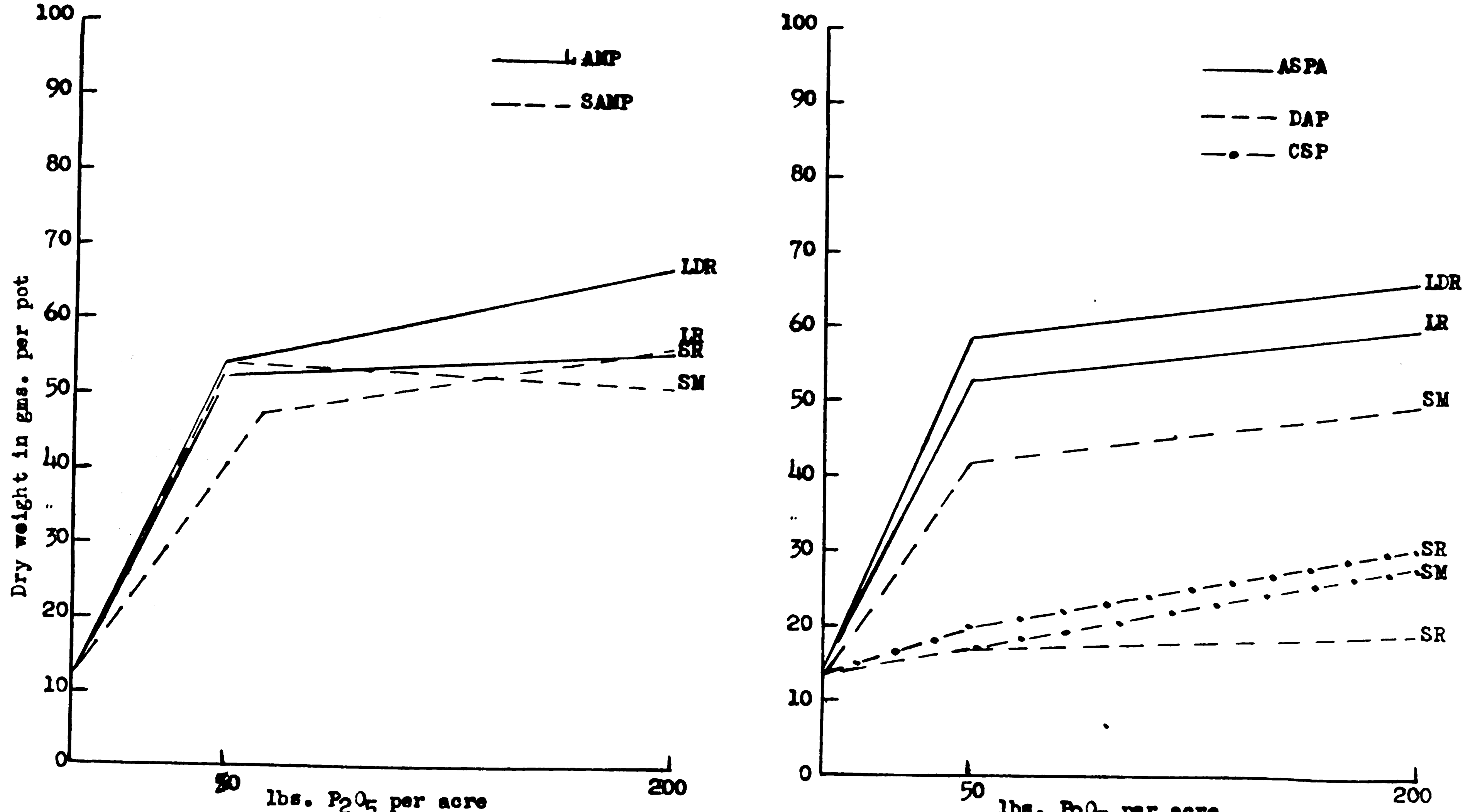

Figure 4. Dry weight yields of corn on Rifle peat (unlimed) as affected by solid and liquid fertilizers applied in different placements in the greenhouse.

placement and rate. With solids, yield differences were significant due to material, placement, and rate, but significant interaction was noted only between placement and material.

The effect of liming appeared to vary somewhat for fertilizers and with rates of applied P_2O_5. For example, at the 200 pound P_2O_5 per acre level, lime was not beneficial except for corn grown on peat treated with CSP. When considering the lower rate of phosphate, growth was distinctly reduced where SAMP and DAP were mixed with limed soil as compared with similar placement on the original acid soil. Apparently the lime reduced the plant availability of these phosphates when mixed with soil, perhaps by formation of dicalcium phosphate or hydroxyapatite. In contrast, for both the 50 pound P_2O_5 per acre solid-banded and solid-mixed treatments of CSP, the effect of lime was to double corn growth. Yet small quantities of ASPA applied in the row or dribbled on the soil surface were decidedly less effective on the limed peat and a similar though not such marked depression was noted for banded LAMP and SAMP at the 50 pound P_2O_5 per acre rate. Lawton and Davis (10) pointed out the effect of liming this soil was to increase the growth of corn up to about pH 6.5 and decrease it with larger quantities of lime. They also suggest that, the effect of liming on growth and plant absorption of phosphorus is minimized at high rates of applied fertilizer.

In most cases the liquid fertilizers resulted in higher dry matter yields than did the solid materials, though this generalization is not so conclusive for limed soil. Of the two liquid materials studied and considering rates and methods of placement, LAMP was slightly more effective than ASPA on limed soil, but of slightly less benefit under acid conditions. For the solid fertilizers, dry matter production of corn was highest for CSP on limed soil, while SAMP was decidedly superior when applied to the original acid soil. As regards the effect of placement, liquid applied in the row was more effective than liquid-dribble application in three out of four cases. For SAMP, DAP, and CSP, banded application resulted in greater growth of corn than when these same phosphates were used in mixed placement. This is in agreement with results obtained by Lawton et al. (9) who reported that soluble phosphate particularly those of a pulverant nature, should be banded for maximum effectiveness.

Data on the dry weights of millet plants grown on limed and unlimed Rifle peat presented in Table 9 show that with 50 pound P_2O_5 per acre application, in all cases liming the soil increased the growth of millet. This was particularly evident when DAP was mixed with the soil, and also for the solid-banded and solid-mixed applications of CSP. But at the higher rate of phosphate, liming the soil brought about a consistent decrease in yield with all fertilizer except DAP and CSP.

When the solid materials were banded at the 50 pound P_2O_5 per acre rate in limed soil, plants receiving CSP produced the highest yield followed by those grown on soil receiving DAP and SAMP. For the unlimed soil the order was SAMP > DAP > CSP, but at the higher rate of phosphate, banded placement of DAP resulted in highest yield followed by CSP and SAMP on the limed soil. On the unlimed soil, the highest yield was obtained with the SAMP treatment and similar results were obtained when the solid materials were mixed with soil.

Phosphorus Absorption by Crops

The uptake of phosphorus by corn and millet from the limed and unlimed series of Rifle peat is given in Tables 8 and 10, and presented graphically in Figures 4, 5, 6 and 7. Information on the phosphorus

Table 8. Effect of solid and liquid fertilizers applied in different placements on the uptake of phosphorus by corn plants grown on limed and unlimed Rifle peat in the greenhouse (9 weeks after planting).

Fertilizer material	Placement	Pounds P_2O_5 per acre	Uptake of phosphorus milligrams per pot* Limed soil	Unlimed soil
Check		0	48.8	20.7
LAMP	Liquid-banded	50	36.5	68.4
		200	61.5	151.2
	Liquid-dribble	50	49.4	81.0
		200	86.3	127.8
SAMP	Solid-banded	50	38.6	37.5
		200	79.1	132.7
	Solid-mixed	50	28.6	76.4
		200	61.6	148.7
ASPA	Liquid-banded	50	80.6	95.9
		200	110.5	215.1
	Liquid-dribble	50	39.2	94.9
		200	80.6	198.0
DAP	Solid-banded	50	44.4	25.1
		200	58.3	112.0
	Solid-mixed	50	41.7	68.1
		200	71.5	166.9
CSP	Solid-banded	50	52.8	50.5
		200	78.3	84.0
	Solid-mixed	50	38.1	28.0
		200	62.3	84.3

*Average of three replications.

Table 9. The residual effect of solid and liquid fertilizers applied in different placements on dry weight yields of millet plants grown on limed and unlimed Rifle peat in the greenhouse (8 weeks after planting).

Fertilizer material	Placement	Pounds P_2O_5 per acre	Dry weight in grams per pot*	
			Limed soil	Unlimed soil
Check		0	7.4	6.5
LAMP	Liquid-banded	50	6.5	5.5
		200	7.1	7.4
	Liquid-dribble	50	8.7	6.9
		200	6.3	6.8
SAMP	Solid-banded	50	8.3	6.8
		200	6.7	9.0
	Solid-mixed	50	8.1	6.3
		200	5.6	10.1
ASPA	Liquid-banded	50	6.7	5.8
		200	8.1	9.2
	Liquid-dribble	50	7.7	6.7
		200	6.5	9.8
DAP	Solid-banded	50	8.6	6.4
		200	9.5	7.6
	Solid-mixed	50	9.2	3.9
		200	7.9	6.3
CSP	Solid-banded	50	9.7	3.9
		200	7.2	4.7
	Solid-mixed	50	9.4	3.7
		200	7.4	6.9

*All values are mean of 3 replications.
Statistical analysis of yield data are given in Appendix Tables XIII and XIV.

Table 10. The residual effect of solid and liquid fertilizers applied in different placements on the uptake of phosphorus by millet plants grown on limed and unlimed Rifle peat in the greenhouse (8 weeks after planting).

Fertilizer Material	Placement	Pounds P_2O_5 per acre	Uptake of phosphorus milligrams per pot*	
			Limed soil	Unlimed soil
Check		0	10.7	8.4
LAMP	Liquid-banded	50	11.0	8.2
		200	12.8	13.7
	Liquid-dribble	50	11.3	8.6
		200	11.3	15.6
SAMP	Solid-banded	50	11.6	12.2
		200	8.1	17.1
	Solid-mixed	50	11.7	10.1
		200	7.6	21.5
ASPA	Liquid-banded	50	8.1	10.4
		200	13.8	22.5
	Liquid-dribble	50	11.9	9.4
		200	10.4	23.0
DAP	Solid-banded	50	12.5	10.6
		200	16.1	24.3
	Solid-mixed	50	13.3	7.0
		200	12.0	14.8
CSP	Solid-banded	50	16.0	6.0
		200	13.7	12.7
	Solid-mixed	50	13.6	7.0
		200	14.1	17.9

*Average of three replications.

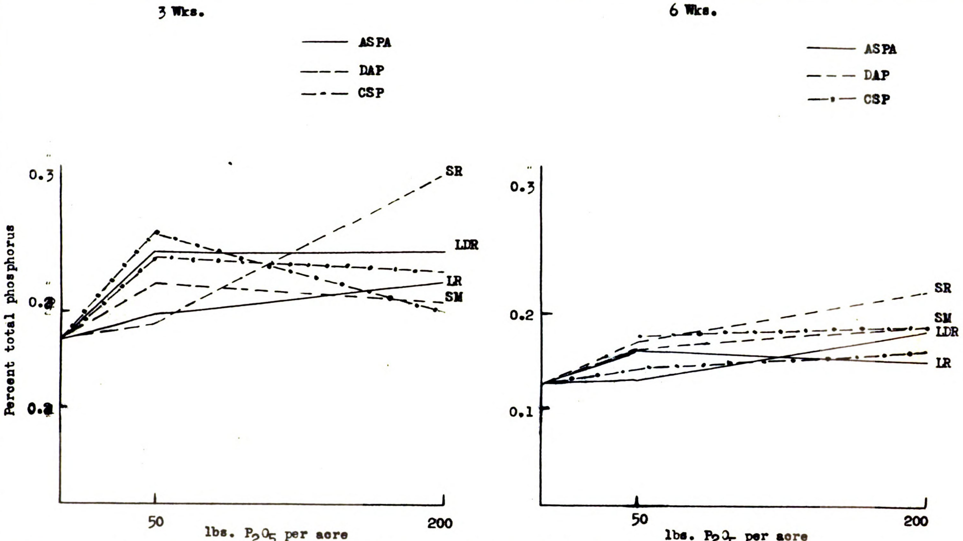

Figure 5. Influence of solid and liquid fertilizers applied in different placements on the total phosphorus content of corn plants grown on Rifle peat (limed) in the greenhouse.

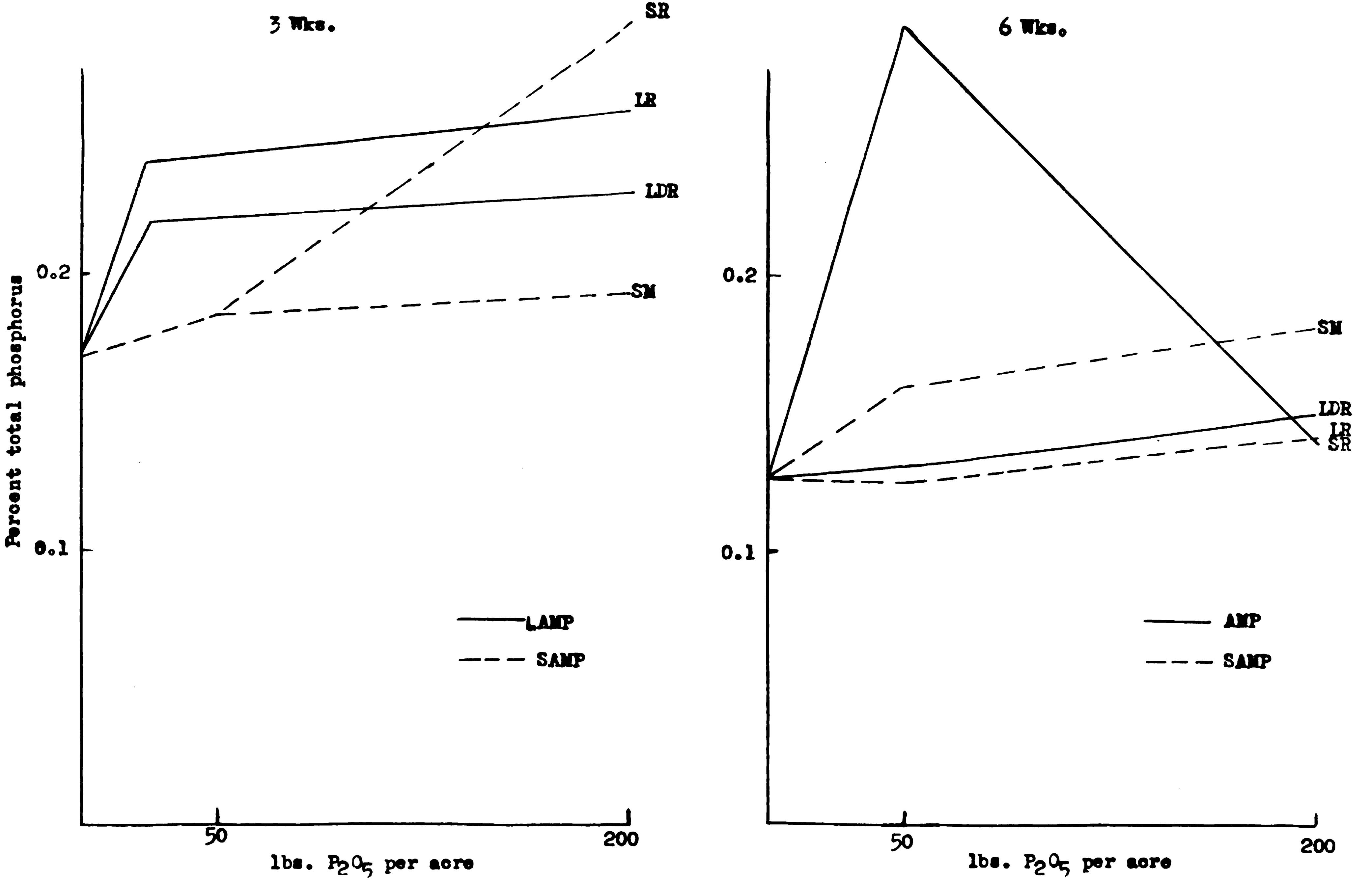

Figure 5. continued.

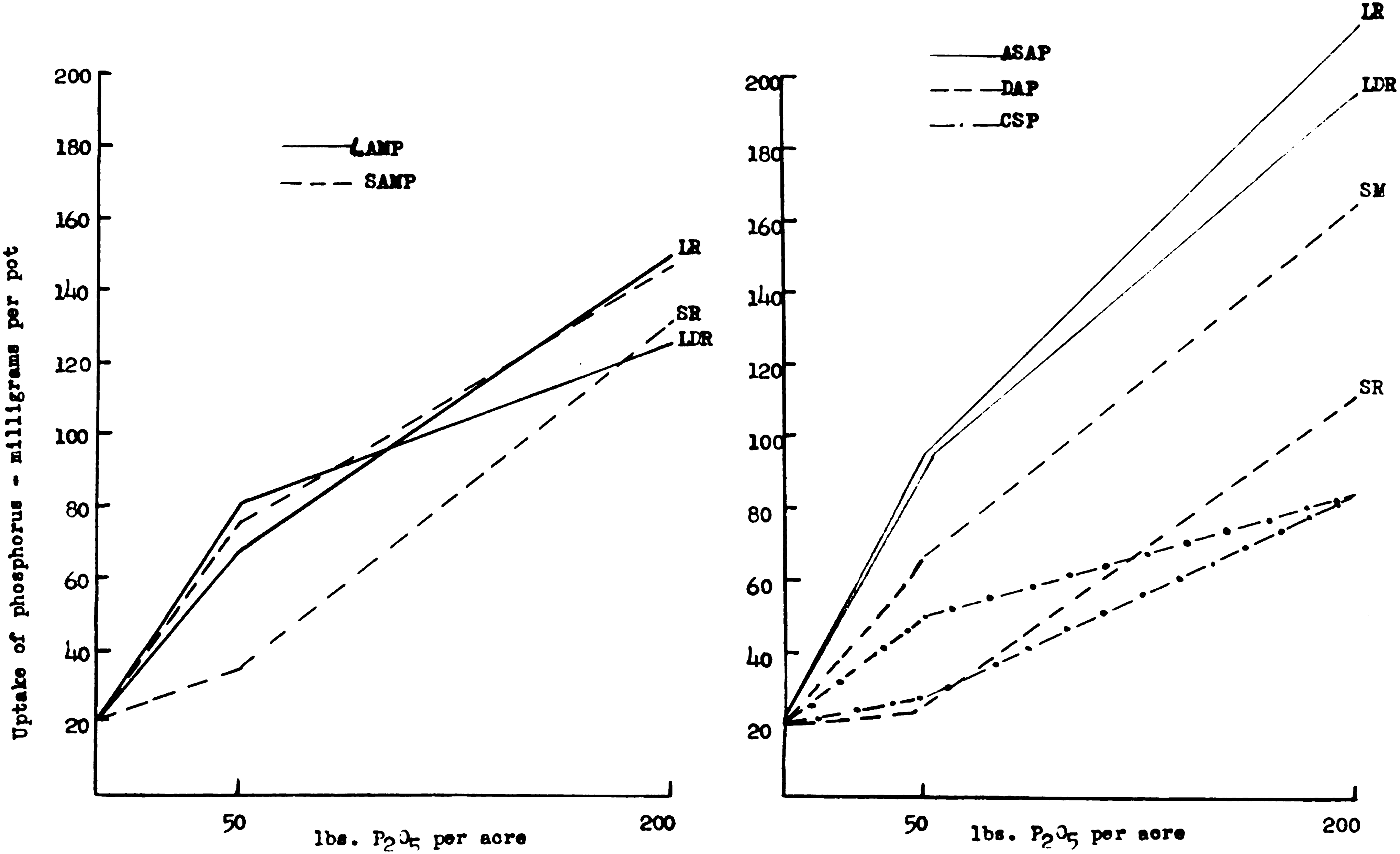

Figure 6. Effect of solid and liquid fertilizers applied in different placements on the uptake of phosphorus by corn plants grown on Rifle peat (unlimed) in the greenhouse (9 weeks after planting).

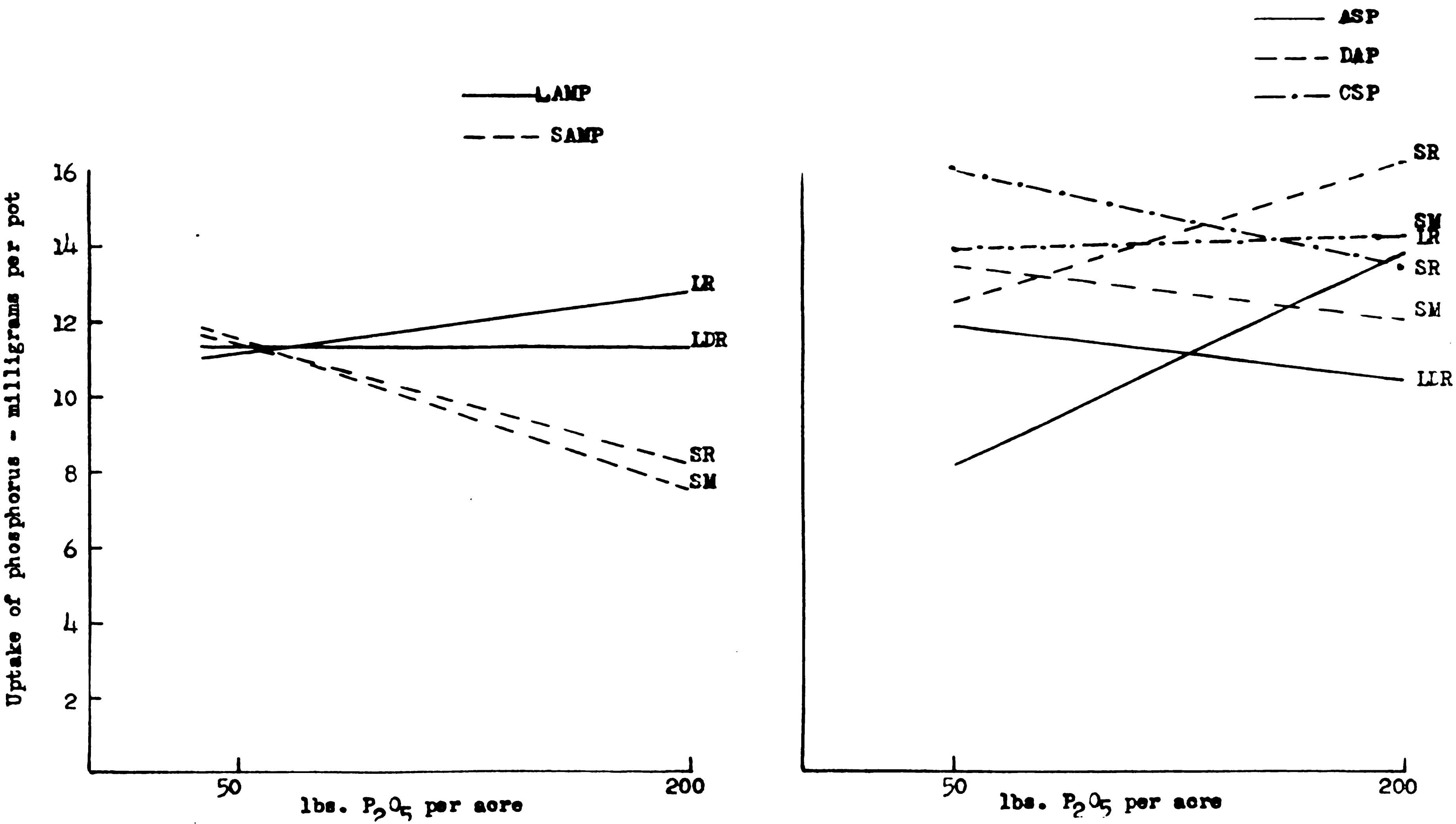

Figure 7. Effect of solid and liquid fertilizers applied in different placements on the uptake of phosphorus by millet plants grown on Rifle peat (limed) in the greenhouse (8 weeks after planting).

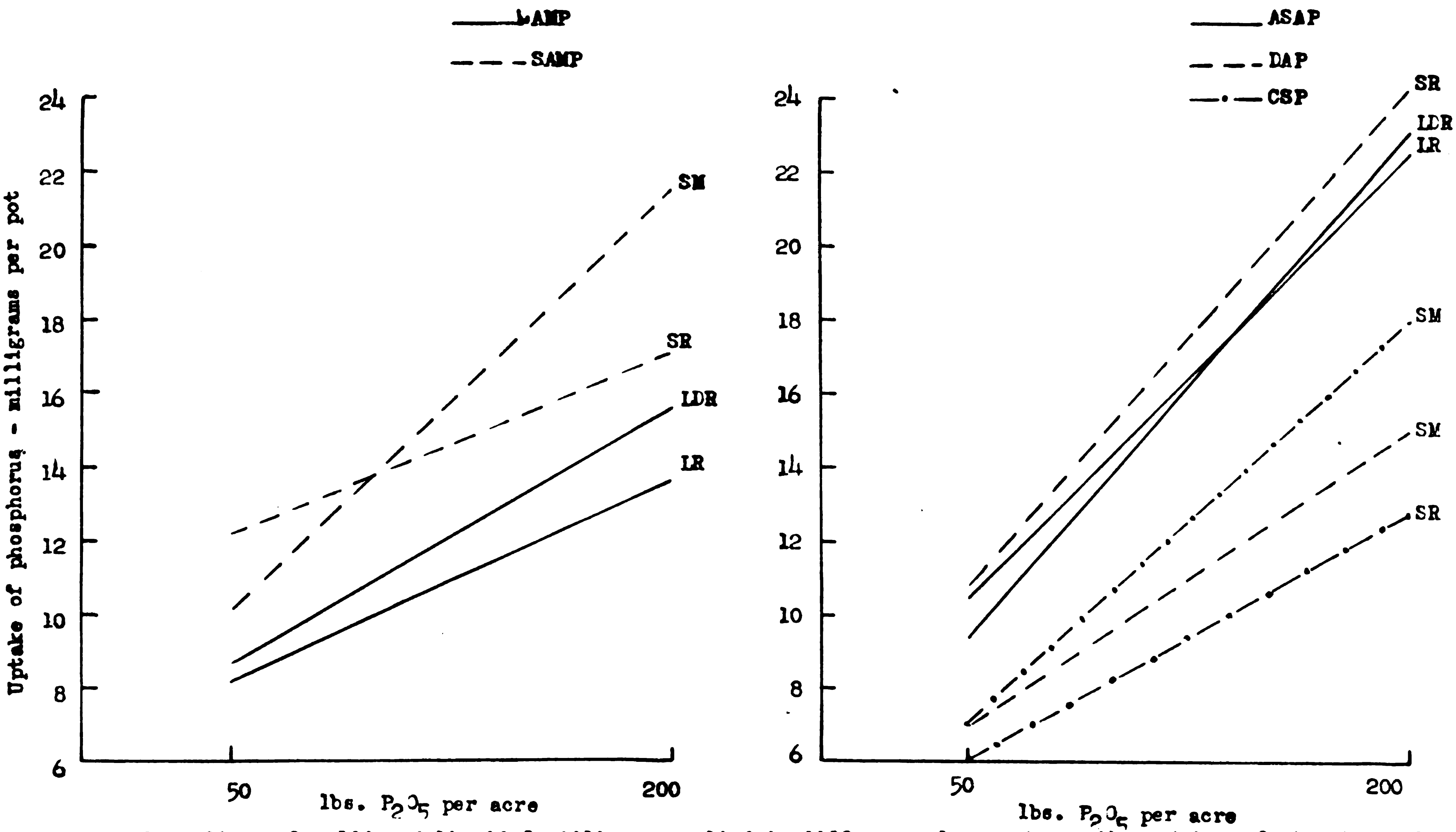

Figure 8. Effect of solid and liquid fertilizers applied in different placements on the uptake of phosphorus by millet plants grown on Rifle peat (unlimed) in the greenhouse (8 weeks after planting).

contents of these crops receiving lime and the varied fertilizer combinations can be seen in Tables I to IV in the Appendix.

The addition of lime to the soil drastically reduced the quantity of phosphorus absorbed by corn for all the fertilizer treatments except the 50 pound P_2O_5 per acre applications of DAP- and CSP-banded and CSP-mixed. This effect of liming on organic soil was pointed out earlier by Lawton and Davis (10). In some cases the phosphorus content of corn was reduced by as much as 4 or 5 times as a result of liming. It is quite evident that dry matter production and plant uptake of phosphorus were not closely related for some fertilizer treatments with unlimed soil. For example, values for phosphorus uptake per pot gradually increased two to three times as the P_2O_5 applied quadrupled, whereas yield differences for similar comparisons were small. On the limed soil, dry weight and phosphorus absorption were rather closely related.

Of the various fertilizers, greatest phosphorus uptake was found with ASPA when rates and methods of application are taken into consideration, although under acid conditions relatively large amounts of phosphorus were removed by corn from all fertilizers except CSP. Liquids might be considered as more efficient sources of phosphorus for corn, although DAP and SAMP were almost equivalent in supplying plant available phosphorus under acid soil conditions.

At low rates of the solid materials, banding appeared to allow greater uptake of phosphorus on limed soil than from unlimed soil, while differences for row and mixed placement at the 200 pound P_2O_5 per acre application were not so marked. This relationship again indicates that with small amounts of applied phosphate, the method of placement is more critical. In contrast, on acid soils, placement is of less importance.

The effect of liming on phosphorus absorption by millet grown on peat soil was the opposite of that found for corn. At the low phosphate application, millet generally removed more phosphorus when grown on limed soils, whereas for corn greatest uptake occurred on unlimed soils. When 200 pounds P_2O_5 was applied, the reverse condition was evident for the millet crop. The addition of lime did not seem to cause large differences in the uptake of phosphorus by millet plants in any of the applications of LAMP, SAMP, and ASPA at the 50 pound P_2O_5 per acre rate. However, for DAP solid-mixed and the CSP treatments, both solid-banded and solid-mixed applications, greater phosphorus uptake by the plants over those on the unlimed soil at the low phosphate rate occurred. For these same fertilizers at the higher phosphate rate, comparing results from limed and unlimed soils at the 200 pound P_2O_5 per acre rate, uptake of phosphorus by millet plants was depressed by liming for all of the placements of LAMP, SAMP, ASPA, and DAP, especially in the case of SAMP, where there was a two to three fold difference in the uptake of phosphorus.

Dry Weight Yields of Corn and Millet Grown on Metea Sandy Loam

Corn

Data on dry weight yields of corn presented in Table 11 show that response to phosphorus application was not very consistent. In many cases where 50 pounds of P_2O_5 was applied, dry matter produced was less than that obtained from the check treatment. With solids, SAMP, DAP, and CSP, differences in corn growth were found to be significant only with a variation in rate of application.

Table 11. Effect of solid and liquid fertilizers applied in different placements on the dry weight yields and uptake of phosphorus of corn plants grown on Metea sandy loam in the greenhouse (9 weeks after planting).

Fertilizer material	Placement	Pounds P_2O_5 per acre	Dry weight grams per pot*	Uptake of phosphorus, milligrams per pot*
Check		0	26.3	18.5
LAMP	Liquid-banded	50	32.6	18.0
		200	31.6	33.2
	Liquid-dribble	50	35.6	28.5
		200	34.0	32.3
SAMP	Solid-banded	50	22.0	23.1
		200	32.6	37.5
	Solid-mixed	50	23.6	24.8
		200	35.0	36.7
ASPA	Liquid-banded	50	31.3	15.6
		200	44.0	48.4
	Liquid-dribble	50	25.0	26.2
		200	28.6	34.3
DAP	Solid-banded	50	30.0	10.3
		200	30.3	34.8
	Solid-mixed	50	20.6	10.5
		200	30.3	31.8
CSP	Solid-banded	50	27.3	38.2
		200	29.3	29.3
	Solid-mixed	50	24.6	34.4
		200	31.0	62.0

*All values are mean of three replications.

In general, the application of liquid fertilizers to the soil resulted in better growth of corn plants than with solid fertilizers. However, if comparison is made between data for the banded placement of liquids and diammonium phosphate, such variation is small. With liquid-banded application of LAMP, increasing the rate of application of phosphate did not result in any appreciable difference in the yield of corn. In contrast, the dribble application of LAMP caused an appreciable decrease in dry matter production as the rate of phosphate applied was increased. When ASPA was applied banded, there was very significant increase in yield at the 200 pound P_2O_5 per acre rate as compared with the 50 pound rate. With the dribble treatment of ASPA, the yield of corn was considerably less than that obtained with the banded application, although significant yield response was obtained from added phosphate in the case of the dribbled treatment. These data are in agreement with those for corn grown on Rifle peat, indicating that phosphorus from the dribble treatment of ASPA was not as available to plants as a result of its surface placement and consequent fixation in the surface soil.

Comparing the two liquid fertilizers, it can be seen that when they are banded in soil at the low rates of application, there was little difference in yield. However, when 200 pound P_2O_5 per acre applications were made, ASPA resulted in substantially higher yield than LAMP. However, when the materials were dribbled, LAMP applied at both rates was superior.

Regarding the application of solid materials, it can be seen that with SAMP, there was a substantial increase in yield when the rate of application was increased from 50 to 200 pounds. The same trend in yield was found when SAMP was banded or mixed, indicating that placement was not a limiting factor as far as fertilizer phosphorus was concerned. When CSP was mixed with the soil, there was an increase in yield with progressive amounts of applied phosphate. Increasing the application of DAP from 50 to 200 pounds P_2O_5 per acre resulted in no increase in yields. However, the solid-mixed application was found to be less effective than the solid-banded application at the low phosphate level. It may be considered that this difference was due to fixation of fertilizer phosphorus in mixed placement with the large volume of soil. However, the availability of phosphorus to corn plants as measured by plant absorption was similar for both placements, indicating this hypothesis does not hold true.

Comparing all the three solid materials, it can be seen that when the fertilizers are banded in soil at the 50 pound P_2O_5 per acre rate, DAP application resulted in best yield of corn followed by CSP and SAMP. At the 200 pound P_2O_5 per acre rate, SAMP produced the best growth. When the same materials were mixed with the soil, the results were somewhat different. At both the 50 and 200 pound rates of phosphate application, SAMP gave better yields.

Phosphorus uptake

The uptake of phosphorus in terms of milligrams per pot shows some interesting results. When LAMP was the phosphorus source, although increasing rates of application did not have any effect on the yield of corn, there was an increase in uptake of phosphorus at the 200 pound rate. Similar results were obtained in the case of banded as well as dribble applications of this phosphate. But in the case of ASPA at the 50 pound rate, due to some reason or other, the phosphorus uptake was less than that from the check treatment when the material was banded. With both banded and dribbled placements, the 200 pound P_2O_5 per acre rate resulted in appreciable increase in the absorption of phosphorus by corn over the lower rate of applied phosphate.

With SAMP when the material was banded or mixed, at the 50 and 200 pound rates, phosphorus uptake was increased. When DAP was the fertilizer material used, at the 50 pound rate, again phosphorus absorption by corn plants in milligrams per pot was less than that obtained from the check plants. This was true in both banded as well as mixed applications of this material. However, when the high rate is considered, there was a marked increased uptake of phosphorus.

With CSP the results were somewhat inconsistent. When the material was banded in the soil, phosphorus uptake decreased with increase in rate of application even though growth remained about the same. But when CSP was mixed with the soil, maximum absorption of phosphorus by plants was noted at the 200 pound rate.

Millet

Dry weight yields.

Yield data and phosphorus absorption by millet plants used to determine the residual effect of the applied phosphates are shown in Table 12. All treatments except CSP as a solid-mixed placement at the low rate of application resulted in increased yield as compared with the check treatment. In contrast to the initial corn crop, yield of millet grown on soil receiving SAMP was somewhat larger than that grown where LAMP was the residual phosphate. However, though reversal of trend cannot be attributed either to differences in phosphorus absorbed by the first crop or to variation in nitrogen level. With ASPA at higher increments of phosphate application, yields were enhanced in both banded and dribbled placements. Comparing the liquids, when

Table 12. The residual effect of solid and liquid fertilizers applied in different placements on the dry weight yields and uptake of phosphorus by millet plants grown on Metea sandy loam in the greenhouse (8 weeks after planting).

Fertilizer material	Placement	Pounds P_2O_5 per acre	Dry weight, grams per pot*	Uptake of phosphorus, milligrams per pot*
Check		0	6.1	14.9
LAMP	Liquid-banded	50	8.5	18.7
		200	8.6	24.1
	Liquid-dribble	50	9.8	25.0
		200	9.2	25.8
SAMP	Solid-banded	50	11.1	23.9
		200	11.2	24.6
	Solid-mixed	50	8.0	19.6
		200	10.4	24.9
ASPA	Liquid-banded	50	6.6	21.8
		200	9.0	21.6
	Liquid-dribble	50	7.2	20.2
		200	11.1	28.9
DAP	Solid-banded	50	11.0	17.6
		200	11.1	21.6
	Solid-mixed	50	9.7	20.4
		200	10.6	20.7
CSP	Solid-banded	50	6.6	10.8
		200	7.2	18.4
	Solid-mixed	50	4.6	10.0
		200	6.6	13.9

*All values are mean of three replications.

they are banded, at the low rate, LAMP gave better yield, whereas at the 200 pound P_2O_5 per acre rate ASPA was found to be superior.

When SAMP was banded, yield decreased with increased rate of application. But when applied mixed, better yield was obtained at the 200 pound P_2O_5 per acre rate. Rate of application did not have any appreciable effect on yield when DAP was used in banded placement. When mixed with the soil at the 200 pound rate, this fertilizer produced vigorous growth. In both banded and mixed applications of CSP increasing rate of application resulted in enhanced growth, a general yield response of millet to phosphate was less evident than with corn.

Phosphorus uptake.

In all cases with the exception of CSP, at the low rate of phosphate application, increased uptake of phosphorus by plants occurred. With LAMP, phosphorus uptake by millet plants was increased with a higher increment of phosphate.

With SAMP, increasing the rate of phosphate application from the 50 to the 200 pound rate enhanced phosphorus absorption by plants in the solid-mixed placement.

When DAP was used in banded placement, there was an increased uptake of phosphorus with the higher rate of phosphate application, but when this material was mixed with soil, there was very little difference. With CSP applications, there was an enhanced absorption of phosphorus by millet plants as the rate of added phosphate was increased. This increase was noted in both banded as well as mixed applications of the fertilizer.

Summarizing the residual effect of these solid and liquid phosphates on the yields and phosphorus uptake by millet plants it can be mentioned that differences in yields were quite small due to placement in most cases. Residual phosphate was absorbed in varying degree by plants, and an increased uptake of phosphorus as related to rate of application was noted when CSP was banded or mixed. However, in the case of corn plants, increased additions of CSP was found to depress phosphorus uptake. From the results obtained in the case of millet plants, it is likely that the fertilizer became uniformly distributed in the soil, thus facilitating more absorption of phosphorus without causing any apparent ill-effects on the growth of plants.

Laboratory Incubation Studies

Incubation studies were conducted in the laboratory in order to study the behavior of solid and liquid ammonium metaphosphates when applied to Rigle peat and Metea sandy loam, the same soils used in the greenhouse and field experiments. Data in Table 13 indicate the amount of fixed and non-hydrolyzed phosphorus in Metea sandy loam which received different rates of solid and liquid ammonium metaphosphates. In the case of liquid ammonium metaphosphate at the 227 pound P per acre rate the amount of fixed and non-hydrolyzed phosphorus was fairly constant during the 2, 7, 14, and 28 days of incubation, although there was some increase in non-recoverable phosphorus at the end of 14 days. It appears that considerable amounts of metaphosphate are hydrolyzed to orthophosphate. Calculations of the quantity of phosphorus fixed of that applied as ammonium metaphosphate necessarily precludes the assumption that there has been complete hydrolysis of metaphosphate to ortho phosphate forms. This may not be true as pointed out in the following discussion. As the rate of added phosphorus was doubled and quadrupled, the rate of fixation and non-hydrolysis of phosphorus also appeared to increase. At the 454 pound P per acre rate, the amount of

Table 13. The amount of fixed and non-hydrolyzed phosphorus in Metea sandy loam which received different rates of solid and liquid ammonium metaphosphates.

Fertilizer	Pounds P per acre	Pounds P per 2 million pounds of soil fixed and non-hydrolyzed after different periods of incubation* (Number of days)				Percent P fixed and non-hydrolyzed of that added
		2	7	14	28	28
Liquid ammonium metaphosphate	227	26.6	26.6	39.6	26.6	11.7
	454	203.2	203.2	128.1	128.2	28.4
	908	381.4	431.4	356.4	396.4	43.7
Solid ammonium metaphosphate	175	100.0	75.0	45.0	45.0	25.7
	350	200.0	215.0	191.0	190.0	54.3
	700	345.0	465.0	275.0	309.0	44.1

*Values for fixed P represent (pounds P added + pounds P per acre in original soil) - (pounds per acre removed in extraction with 0.03N NH_4F + 0.025N HCl).

non-recoverable phosphorus was greater during the first 7 days of incubation after which it diminished. In the case of solid ammonium metaphosphate at the 175 pound P per acre rate, the amount of fixed non-recoverable phosphorus was reduced as the length of incubation was increased. However, as the rate of added phosphorus was increased two to four times, greatest fixation and non-hydrolysis occurred after 7 days of incubation followed by a distinct decrease after the 2 and 4 week incubation periods. No explanation with definite proof can be given for this decrease in fixation and an increase in hydrolysis. It appears a fair portion of the metaphosphate undergoes hydrolysis to the orthophosphate form.

Since the phosphorus fixation studies with solid and liquid ammonium metaphosphates were confined to only one mineral soil, very few generalizations can be made in regard to the comparative fixation of liquid and solid phosphates, and also since the rates of applied phosphorus varied somewhat for the two forms, it is difficult to make strict comparisons. However, from the results obtained in this study, it appears likely that solid ammonium metaphosphate is fixed to a greater extent or is hydrolyzed more slowly than the liquid form when large additions of these fertilizers to the soil are concerned.

It is interesting to note that as the amount of phosphorus added as LAMP to the Metea soil was doubled, the percent fixed and non-hydrolyzed of that added more than doubled. Likewise, as the quantity of phosphorus mixed with the soil was quadrupled, the percent fixed and non-hydrolyzed of that added was increased by almost four times. This means that for the latter comparison, the actual quantity of phosphorus fixed and non-hydrolyzed increased 16 times. These data suggest that the fixing capacity of this soil had by no means saturated with respect to added liquid ammonium metaphosphate. It is questionable whether all the metaphosphate was hydrolyzed to orthophosphate in the 28 day period.

The same trend is apparent with solid ammonium metaphosphate, where in as the amount of added phosphorus was doubled from 175 to 350 pounds per acre, the quantity fixed and non-hydrolyzed amounted to slightly more than four times. This resulted in non-recovery of 54.3 percent of the intermediate rate of applied phosphate. In contrast to the liquid form, with the rate of SAMP at the 700 pound P per acre rate, the extent of non-recovery decreased, even though the percent of phosphorus fixed and non-hydrolyzed of that added was quite similar for the two forms (43.7 vs 44.1 percent).

Values for the fixed and non-hydrolyzed phosphorus from Rifle peat when treated with different rates of solid and liquid ammonium metaphosphates are presented in Table 14. In the case of liquid ammonium metaphosphate applied at the rate of 114 pound P per acre the amount of non-recoverable phosphorus increased during the 7 and 14 day periods of incubation, but decreased sharply at the end of 28 days. However, the next two treatments, 227 and 454 pound per acre, resulted in release of phosphorus from Rifle peat. Several explanations may account for this release of phosphorus from this soil. First, there may have been a breakdown of organic phosphates as a result of incubation. Secondly, since the pH of the medium was around 4.5, mineralization could have been stimulated by the addition of the nitrogen and phosphorus in the fertilizer. These results seem to be in agreement with similar findings obtained by McCall et al. (12). Also, there may have been a greater hydrolysis of the metaphosphate to the ortho form. However, solid ammonium metaphosphate appears to behave quite differently when applied to Rifle peat. The results presented in Table 14 show that the

Table 14. The amount of fixed and non-hydrolyzed phosphorus in unlimed Rifle peat which received different rates of solid and liquid ammonium metaphosphates.

Fertilizer	Pounds P per acre	Pounds P per 500,000 pounds of soil fixed and non-hydrolyzed after differend periods of incubation*				Percent P fixed and non-hydrolyzed of that added
		Number of days				
		2	7	14	28	28
Liquid ammonium metaphosphate	114	4.8	21.8	28.05	6.1	5.36
	227	10.4**	28.9**	16.7**	16.7**	7.3**
	454	58.55**	49.0**	42.0**	43.2**	7.62**
Solid ammonium metaphosphate	87	44.5	58.5	13.25	7.0	6.44
	174	10.0	11.12	10.25	14.25	8.1
	348	107.0	11.5**	29.0	29.0	6.66

*Values for fixed P represent (pounds P added + pounds per acre in original soil) - (pounds per acre recovered with 0.03N NH_4F + 0.025N HCl).

**Denotes release of phosphorus during incubation.

amount of fixed and non-hydrolyzed phosphorus was essentially the same at both the 87 and 348 pounds P per acre applications at the end of 28 days of incubation, although there was a 26.5 percent increase at the 174 pound rate. No release of phosphorus from Rifle peat was observed when different rates of solid ammonium metaphosphate was added. More studies would be required to more clearly evaluate the behavior of solid ammonium metaphosphate in organic soils.

Phosphorus Distribution Studies in Metea Sandy Loam

Laboratory experiments were set up to study the vertical and lateral distribution of phosphorus in Metea sandy loam when treated with solid and liquid ammonium metaphosphates at 5, 10, and 20 percent moisture levels.

Data on the distribution of phosphorus at various distances and depths from the place of application with time at 5 percent moisture are shown in Table 15. The values represent the amount of phosphorus extracted from the soil after different periods of incubation. It may be mentioned that this extraction procedure could include phosphorus in fertilizer residues at the time of sampling and drying.

The results obtained with solid ammonium metaphosphate indicate that there was a uniform distribution of phosphorus both laterally as well as vertically at the end of 4 days. During the 8 and 16 days incubation periods the amount of extractable phosphorus in the lateral distribution decreased indicating fixation exceeded diffusion.during this period. In the vertical distribution phosphorus concentration as measured remained more or less the same. The distribution of phosphorus with solid ammonium metaphosphate at 10 and 20 percent moisture levels are shown in Tables 16 and 17 respectively. It can be seen that increase in soil moisture has enhanced the distribution values of phosphorus both in the vertical and lateral samplings. Here again, phosphorus concentration within lateral distribution decreased with time, while for the vertical distribution values for phosphorus were slowly reduced with both distance and time.

Table 15. Distribution of phosphorus at various distances and depths from the place of application with time in Metea sandy loam at 5 percent moisture.

Fertilizer	Days of incubation	Ppm. Phosphorus in the Soil*								
		Depth 0-2 cms.			Depth 2-4 cms.			Depth 406 cms.		
		center	0-2 cms	2-4 cms	center	0-2 cms	2-4 cms	center	0-2 cms	2-4 cms
Solid ammonium metaphosphate	4	100.0	95.0	80.0	100.0	80.0	80.0	85.0	78.0	78.0
	8	110.0	90.0	90.0	95.0	75.0	65.5	102.5	90.0	62.5
	16	102.5	65.0	60.0	95.0	62.5	62.5	90.0	55.0	55.0
Liquid ammonium metaphosphate	4	237.5	175.0	137.5	240.0	110.0	100.0	190.0	95.0	80.0
	8	190.0	102.5	100.0	175.0	100.0	100.0	158.0	85.0	85.0
	16	160.0	102.5	95.0	137.5	95.0	78.0	125.0	85.0	90.0

*Phosphate determined after extraction with 0.03N ammonium fluoride and 0.025N hydrochloric acid minus amount of P present in original soil.

Table 16. Distribution of phosphorus at various distances and depths from the place of application with time in Metea sandy loam at 10 percent moisture.

Fertilizer	Days of incubation	Ppm. Phosphorus in the Soil*								
		Depth 0-2 cms.			Depth 2-4 cms.			Depth 4-6 cms.		
		center	0-2 cms	2-4 cms	center	0-2 cms	2-4 cms	center	0-2 cms	2-4 cms
Solid ammonium metaphosphate	4	135.0	112.0	102.5	147.5	120.0	100.0	130.5	100.0	95.0
	8	120.0	105.0	102.5	140.0	120.0	95.0	128.0	100.0	95.0
	16	115.5	102.5	85.0	130.0	102.5	95.0	112.0	96.0	95.0
Liquid ammonium metaphosphate	4	287.5	190.0	175.0	337.5	165.0	145.0	300.0	156.0	137.5
	8	245.0	175.0	162.5	266.0	160.0	150.0	237.5	160.0	123.0
	16	230.0	158.0	145.0	200.0	145.0	137.5	198.0	137.5	119.0

*Phosphate determined after extraction with 0.03N ammonium fluoride and 0.025N hydrochloric acid minus amount of P present in original soil.

Table 17. Distribution of phosphorus at various distances and depths from the place of application with time in Metea sandy loam at 20 percent moisture.

Fertilizer	Days of incubation	Ppm. Phosphorus in the Soil*								
		Depth 0-2 cms.			Depth 2-4 cms.			Depth 4-6 cms.		
		center	0-2 cms	2-4 cms	center	0-2 cms	2-4 cms	center	0-2 cms	2-4 cms
Solid ammonium metaphosphate	4	182.5	145.0	130.0	202.5	145.0	126.0	175.0	112.5	109.0
	8	190.0	137.5	109.0	175.0	120.0	102.5	175.0	102.5	98.0
	16	175.0	135.0	105.0	160.0	112.5	100.0	165.0	106.0	95.0
Liquid ammonium metaphosphate	4	322.5	230.0	195.0	300.0	175.0	167.0	287.5	190.0	160.0
	8	302.0	190.0	190.0	290.0	170.0	162.5	237.5	175.0	145.0
	16	265.0	170.0	152.5	210.5	175.0	135.0	195.0	154.0	122.5

*Phosphate determined after extraction with 0.03N ammonium fluoride and 0.025N hydrochloric acid minus amount of P present in original soil.

The distribution values for phosphorus with liquid ammonium metaphosphate at the 5, 10, and 20 percent moisture levels are shown in Tables 15, 16, and 17 respectively. At 5 percent moisture, the amount of extractable phosphorus in the vertical dimension decreased gradually with distance from the fertilizer source, although the decrease was more rapid and more marked with time. Within the lateral distribution considerably less phosphorus was found with progression of time of incubation and distance from the fertilizer source. Lawton et al. (9) suggest that fertilizer phosphorus concentration increases with time in the dissolution of superphosphate granules. However, their measurements were based on the total fertilizer phosphate ions present and not just those extractable by a specific solution.

As the moisture content of the soil increased, greater diffusion of phosphorus occurred in both the vertical and horizontal dimensions. Here also, the same general distribution pattern was observed, although the values were appreciably increased due to higher soil moisture levels.

In summary, data obtained in this laboratory phosphorus distribution studies seem to indicate that in the soil studied, phosphate ions from solid fertilizer move more slowly than from the liquid form. Movement was slow under conditions of low soil moisture. The extent of vertical and lateral movement of phosphorus was enlarged considerably at higher soil moisture contents. The vertical distribution of phosphorus was found to be more extensive than the lateral distribution. The concentration of extractable phosphorus at a specific distance from the fertilizer source decreased with time. Likewise, as the distance from the fertilizer source increased, the quantity of fertilizer phosphorus extracted was found to decrease. From the results of this study it is apparent that applied phosphorus is retained pretty much within the first few inches of soil.

SUMMARY AND CONCLUSIONS

Field and greenhouse experiments were conducted to compare the effectiveness of solid and liquid fertilizers in different placements on the yield and phosphorus absorption of several crops. Monoammonium phosphate labelled with P^{32} was mixed with muriate of potash and ammonium nitrate to give a material of approximately 1-2-2 ratio. Applications included solid-banded and solid-mixed, liquid-banded, liquid-dribble, and liquid-spray.

Two months after planting in the greenhouse, the relative order of availability of fertilizer phosphorus to corn plants was solid-banded > liquid-banded > liquid-dribble > liquid spray. With field beans the order of availability was liquid-banded = solid-banded > liquid-dribble > liquid-spray. Dry matter production was highest when fertilizer was liquid-banded and lowest when it was sprayed on the soil surface. In the case of field beans, the method of application did not effect large differences between the dry weight yields except when fertilizer was mixed with soil resulting in growth rather similar to the no fertilizer treatment.

Data from the field study of corn in 1956 and 1957 showed the same general trends of fertilizer phosphorus absorption and yield as found in the greenhouse. Liquid materials appeared to behave similar to solids when similar methods of application were compared. Corn yields were highest when liquid was dribbled followed by the banded application of solid or liquid, while spray and broadcast applications were least effective.

Five TVA fertilizers, solid ammonium metaphosphate, liquid ammonium metaphosphate, solid diammonium phosphate, solid concentrated superphosphate, and liquid ammoniated superphosphoric acid were compared in greenhouse studies with corn and millet, the latter crop being used to measure residual effect of these fertilizers. The soils studied were limed and unlimed Rifle peat and Metea sandy loam. The applications included liquid-banded, liquid-dribble, solid-banded, and solid-mixed.

Liquid fertilizers, especially ammoniated superphosphoric acid increased the dry weight of corn much more than the solid materials on the limed Rifle peat. Diammonium phosphate, and in particular, concentrated superphosphate, decreased growth of corn on the unlimed soil. For corn plants solid-banded application was found to be more beneficial than the solid-mixed treatment, and liquid-banded application proved to be more effective than the liquid-dribble treatment. In the case of millet, the yields were much lower for the limed soil than where no lime was applied. On the unlimed soil the phosphorus content of crops was substantially higher than where lime had been applied, and this depression was especially notable for corn. With the use of liquid fertilizers, the uptake of phosphorus by the crops was substantially higher especially for the liquid-banded application, while a much lower uptake of phosphorus by the plants resulted from the use of the solid materials.

On the mineral soil, Metea sandy loam the liquids were found to be superior to the solids applied in comparable placements. Here also ammoniated superphosphoric acid gave the highest corn yields. With few exceptions the phosphorus absorption by corn and millet increased as greater amounts of phosphate were applied.

Laboratory incubation studies conducted with Metea sandy loam and Rifle peat treated with different rates of solid and liquid ammonium metaphosphates showed that these two soils behaved differently as could be expected. Increased additions of liquid ammonium metaphosphate enhanced the amount of fixed and non-hydrolyzed phosphorus with progression of incubation time, while release of phosphorus was obtained from Rifle peat. Solid ammonium metaphosphate applied to these two soils was fixed or hydrolyzed to different degrees under the laboratory conditions of incubation. The results showed that the solid form was fixed or non-recoverable to a greater extent on the mineral soil than on the organic soil.

Laboratory experiments set up in order to determine the vertical and lateral distribution of phosphorus in Metea sandy loam when treated with solid and liquid ammonium metaphosphates at 5, 10, and 20 percent moisture levels show that phosphate ions from solid fertilizer move more slowly than from the liquid form. Movement was slow under conditions of low soil moisture. The extent of vertical and lateral movement of phosphorus was enlarged considerably at higher soil moisture contents. The vertical distribution of phosphorus was found to be more extensive than the lateral distribution, and the concentration of extractable phosphorus at a specific distance from the fertilizer source decreased with time. Likewise, as distance from the fertilizer source increased, the quantity of fertilizer phosphorus extracted was found to increase.

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APPENDIX

Table I. Influence of solid and liquid fertilizers applied in different placements on the total phosphorus content of corn plants grown on limed Rifle peat in the greenhouse.

Fertilizer material	Placement	Pounds P_2O_5 per acre	Percent total Phosphorus* 3 weeks	6 weeks	9 weeks
Check			0.17	0.125	0.11
LAMP	Liquid-banded	50	0.24	0.29	0.13
		200	0.26	0.14	0.08
	Liquid-dribble	50	0.22	0.13	0.13
		200	0.23	0.15	0.16
SAMP	Solid-banded	50	0.185	0.13	0.10
		200	0.29	0.14	0.13
	Solid mixed	50	0.185	0.16	0.11
		200	0.195	0.18	0.11
ASPA	Liquid-banded	50	0.195	0.16	0.31
		200	0.23	0.15	0.15
	Liquid-dribble	50	0.26	0.13	0.08
		200	0.26	0.18	0.13
DAP	Solid-banded	50	0.195	0.17	0.09
		200	0.34	0.22	0.12
	Solid-mixed	50	0.23	0.16	0.16
		200	0.21	0.18	0.14
CSP	Solid-banded	50	0.28	0.17	0.13
		200	0.20	0.17	0.13
	Solid-mixed	50	0.26	0.14	0.11
		200	0.24	0.16	0.11

*Average of three replications.

Table II. Influence of solid and liquid fertilizers applied in different placements on the total phosphorus content of corn plants grown on unlimed Rifle peat in the greenhouse.

Fertilizer material	Placement	Pounds P_2O_5 per acre	Percent total Phosphorus* 3 weeks	6 weeks	9 weeks
Check			0.17	0.17	0.15
LAMP	Liquid-banded	50	0.39	0.22	0.13
		200	0.50	0.39	0.27
	Liquid-dribble	50	0.44	0.21	0.15
		200	0.66	0.43	0.19
SAMP	Solid-banded	50	0.36	0.22	0.12
		200	0.76	0.50	0.24
	Solid-mixed	50	0.39	0.17	0.14
		200	0.57	0.13	0.29
ASPA	Liquid-banded	50	0.66	0.23	0.18
		200	0.57	0.43	0.35
	Liquid-dribble	50	0.52	0.25	0.16
		200	0.63	0.51	0.30
DAP	Solid-banded	50	0.66	0.80	0.14
		200	1.34	0.76	0.58
	Solid-mixed	50	0.46	0.36	0.16
		200	0.72	0.48	0.33
CSP	Solid-banded	50	0.55	0.27	0.24
		200	0.60	0.39	0.28
	Solid-mixed	50	0.19	0.24	0.16
		200	0.36	0.62	0.30

*Average of three replications.

Table III. The residual effect of solid and liquid fertilizers applied in different placements on the total phosphorus content of millet plants grown on limed Rifle peat in the greenhouse.

Fertilizer material	Placement	Pounds P_2O_5 per acre	Percent total Phosphorus* 4 weeks	6 weeks	9 weeks
Check			0.23	0.18	0.14
LAMP	Liquid-banded	50	0.23	0.18	0.17
		200	0.24	0.17	0.18
	Liquid-dribble	50	0.24	0.23	0.13
		200	0.28	0.14	0.18
SAMP	Solid-banded	50	0.26	0.27	0.14
		200	0.18	0.15	0.12
	Solid-mixed	50	0.26	0.18	0.14
		200	0.24	0.14	0.13
ASPA	Liquid-banded	50	0.23	0.16	0.12
		200	0.19	0.19	0.17
	Liquid-dribble	50	0.28	0.27	0.15
		200	0.18	0.15	0.16
DAP	Solid-banded	50	0.26	0.15	0.14
		200	0.21	0.14	0.17
	Solid-mixed	50	0.27	0.16	0.14
		200	0.23	0.16	0.15
CSP	Solid-banded	50	0.21	0.16	0.16
		200	0.21	0.16	0.19
	Solid-mixed	50	0.25	0.12	0.14
		200	0.19	0.15	0.19

*Average of three replications.

Table IV. The residual effect of solid and liquid fertilizers applied in different placements on the total phosphorus content of millet plants grown on unlimed Rifle peat in the greenhouse.

Fertilizer material	Placement	Pounds P_2O_5 per acre	Percent total Phosphorus* 4 weeks	6 weeks	9 weeks
Check		0	0.19	0.18	0.13
LAMP	Liquid-banded	50	0.32	0.14	0.15
		200	0.23	0.23	0.18
	Liquid-dribble	50	0.34	0.16	0.12
		200	0.24	0.26	0.23
SAMP	Solid-banded	50	0.50	0.15	0.18
		200	0.23	0.21	0.19
	Solid-mixed	50	0.47	0.13	0.16
		200	0.11	0.25	0.21
ASAP	Liquid-banded	50	0.53	0.14	0.18
		200	0.22	0.21	0.24
	Liquid-dribble	50	0.42	0.15	0.14
		200	0.20	0.20	0.23
DAP	Solid-banded	50	0.26	0.14	0.16
		200	0.18	0.23	0.32
	Solid-mixed	50	0.16	0.13	0.18
		200	0.25	0.19	0.23
CSP	Solid-banded	50	0.16	0.12	0.15
		200	0.17	0.17	0.27
	Solid-mixed	50	0.23	0.13	0.19
		200	0.16	0.17	0.26

*Average of three replications.

Table V. The relative absorption of fertilizer phosphorus by corn plants from solid and liquid fertilizers applied by different methods in the greenhouse.

Fertilizer treatment	Pounds P_2O_5 per acre	Percent P in plants from fertilizer: 2 weeks	4 weeks	6 weeks	8 weeks
Solid-mixed	200	100.0	75.4	82.0	51.9
		100.0	65.2	86.4	51.9
Solid-banded	100	100.0	100.0	79.0	55.4
		100.0	100.0	73.0	59.4
	200	78.0	90.8	96.6	57.1
		55.0	100.0	88.8	63.5
Liquid-banded	100	52.0	54.3	74.6	45.2
		69.0	66.9	70.6	43.0
	200	54.0	100.0	72.0	60.6
		62.2	93.0	64.8	62.6
Liquid-dribble	100	100.0	84.0	61.2	32.6
		92.0	70.0	58.2	31.6
	200	70.0	86.2	86.0	75.2
		81.0	94.2	78.4	76.0
Liquid-spray	100	68.0	76.0	52.0	30.5
		80.0	88.4	48.2	31.5
	200	100.0	91.0	80.0	53.1
		100.0	72.2	72.2	55.5

Table VI. The relative absorption of fertilizer phosphorus by field bean plants from solid and liquid fertilizers applied by different methods in the greenhouse.

Fertilizer treatment	Pounds P_2O_5 per acre	Percent P in plants from fertilizer 2 weeks	4 weeks	7 weeks
Solid-mixed	200	90.8	82.0	43.0
		80.0	87.2	42.0
Solid-banded	100	82.1	64.3	31.7
		73.9	53.6	29.9
	200	78.2	86.2	43.6
		82.4	80.0	41.6
Liquid-banded	100	100.0	64.6	31.9
		100.0	56.6	30.1
	200	72.6	70.0	36.2
		78.2	76.6	34.4
Liquid-dribble	100	66.8	52.4	21.0
		61.4	45.8	22.6
	200	100.0	60.0	46.7
		93.8	56.8	45.1
Liquid-spray	100	52.3	30.0	15.9
		65.3	35.6	12.5
	200	59.1	52.9	32.5
		63.3	47.7	33.5

Table VII. Analysis of variance of the dry weights of corn plants as influenced by method of application of solid and liquid fertilizers to Metea sandy loam in the greenhouse.

Source	DF	SS	MS	F	L.S.D.* 5%
Total	19	63071			
Reps	1	224	224	1.11	
Treatment	9	61040	6782	3.37*	32.1
Error	9	1807	201		

Table VIII. Analysis of variance of dry weights of field bean plants as influenced by method of application of solid and liquid fertilizers to Metea sandy loam in the greenhouse.

Source	DF	SS	MS	F	L.S.D. 1%
Total	19	11917			
Reps	1	328	328	2.71	
Treatment	9	10502	1167	9.64**	24.9
Error	9	1087	121		

Table IX. Analysis of variance of the dry weights of field corn as influenced by method of application of solid and liquid fertilizers to Metea sandy loam (1956).

Source	DF	SS	MS	F	L.S.D.
Total	19	257.75			
Reps.	1	48.67	48.67	74.88	
Fertilizer	1	39.20	39.20	60.31	
Error A	1	0.65	0.65		N.S.
Placement	4	23.89	5.97	0.567	
F x Pl	4	61.20	15.30	1.45	
Error B	8	84.14	10.52		

Table X. Analysis of variance of dry weight yields of field corn as influenced by method of application of solid and liquid fertilizers to Metea sandy loam (1957).

Source	DF	SS	MS	F	L.S.D.	
					1%	5%
Total	39	3797.88				
Reps.	3	473.97	157.99	3.60		
Fertilizer	1	637.60	637.60	14.51*	6.67	
Error A	3	131.78	443.93			
Placement	4	1215.58	303.90	6.30**		7.17
F x Pl.	4	180.36	45.09	0.934		
Error B	24	1158.59	48.27			

Table XI. Analysis of variance of corn yields as influenced by liquid fertilizers applied in different placements to limed and unlimed Rifle peat in the greenhouse.

Source	DR		SS		MS		F	
	limed	unlimed	limed	unlimed	limed	unlimed	limed	unlimed
Total	23		6566	813				
Reps.	2		26	8	13	4	4.33	0.200
Material	1		92	32	92	32	30.67*	1.60
Error A	2		6	41	3	20		
Placement (Pl)	1		330	216	330	216	41.25	14.40*
Materials Pl.	1		7	1	7	1	0.875	0.067
Error B	4		32	59	8	15		
Rate	1		4676	352	4676	352	311.72**	117.33**
Rate x Mat.	1		1247	4	1248	4	83.13**	1.33
Rate x Pl.	1		7	33	7	33	0.467	11.00*
Rate x Mat. x Pl.	1		22	42	22	42	1.47	14.00**
Error C	8		122		15			

limed (L.S.D.)		unlimed (L.S.D.)	
LSD A	3.04		
LSD B	3.21	LSD B	4.38
LSD C	3.65	LSD C	1.63

Table XII. Analysis of variance of corn yields as influenced by solid fertilizers applied in different placements to limed and unlimed Rifle peat in the greenhouse.

Source	DF		SS		MS		F	
	limed	unlimed	limed	unlimed	limed	unlimed	limed	unlimed
Total	35	35	5235	8290				
Reps.	2	2	19	2	10	0.5	1.25	
Material	2	2	115	4658	58	2329	7.25*	145.56**
Error A	4	4	34	63	8	16	--	--
Placement	1	1	529	850	529	850	18.24**	38.64**
Pl. x Material	2	2	96	1623	48	812	1.66	36.91**
Error B	6	6	176	130	29	22	--	--
Rate	1	1	3173	380	3173	380	137.96	14.62**
Rate x Material	2	2	270	62	135	31	5.87*	1.19
Rate x Pl.	1	1	387	15	387	15	16.83**	0.58
Rate x Mat. x Pl.	2	2	161	190	80	95	3.48	3.65
Error C	12	12	275	318	23	26	--	--

Limed (L.S.D.)		Unlimed (L.S.D.)	
LSD A	3.21	LSD A	4.5
LSD B	4.40	LSD B	3.8
LSD C	3.48	LSD C	3.7

Table XIII. Analysis of variance of millet yields as influenced by liquid fertilizers applied in different placements to limed and unlimed Rifle peat in the greenhouse.

Source	DF		SS		MS		F	
	limed	unlimed	limed	unlimed	limed	unlimed	limed	unlimed
Total	23		30.15	59.9				
Reps.	2		2.18	0.93	1.09	0.46	0.649	1.48
Material	1		0.57	9.13	0.57	9.13	0.339	29.45*
Error A	2		3.36	0.62	1.68	0.31		
Placement (Pl.)	1		0.51	2.04	0.51	2.04	2.68	13.60**
Materials x Pl.	1		0.07	0.24	0.07	0.24	0.368	1.60
Error B	4		0.75	0.60	0.19	0.15		
Rate	1		3.76	26.04	3.76	26.04	2.47	24.11**
Rate x Mat.	1		1.00	8.64	1.00	8.64	0.658	8.00*
Rate x Pl.	1		5.51	2.05	5.51	2.05	3.62	1.90
Rate x Mat. x Pl.	1		0.26	0.95	0.26	0.95	0.171	0.88
Error C	8		12.18	8.66	1.52	1.08		

Limed (L.S.D.)		Unlimed (L.S.D.)	
LSD A	N.S.	LSD A	0.978
LSD B	N.S.	LSD B	0.438
LSD C	N.S.	LSD C	0.979

Table XIV. Analysis of variance of millet yields as influenced by solid fertilizers applied in different placements to limed and unlimed Rifle peat in the greenhouse.

Source	DF		SS		MS		F	
	limed	unlimed	limed	unlimed	limed	unlimed	limed	unlimed
Total	35		69.77	153.74				
Reps.	2		0.58	0.66	0.29	0.33	0.034	0.635
Material	2		15.62	74.11	7.81	37.06	9.08*	71.27**
Error A	4		3.42	2.09	0.86	0.52		
Placement	1		2.20	0.19	2.20	0.19	2.82	2.11
Pl. x Material	2		0.98	15.47	0.49	7.74	0.063	86.00**
Error B	6		4.68	0.53	0.78	0.09		
Rate	2		21.94	43.12	21.94	43.12	31.34**	119.78**
Rate x Material	2		8.14	4.04	4.07	2.02	5.81*	5.61*
Rate x Pl.	1		1.24	7.65	1.24	7.65	1.77	21.25**
Rate x Mat. x Pl.	2		2.56	1.60	1.28	0.80	1.83	2.22
Error C	12		8.41	4.28	0.70	0.36		

Limed (L.S.D.)		Unlimed (L.S.D.)	
LSD A	1.05	LSD A	0.817
LSD C	0.608	LSD B	0.2448
		LSD C	0.4356

Plot Diagram I

I	L.D.	S.B.	L.S.	L.R.	L.S.	L.R.	S.M.	S.B.	L.D.	S.M.	L.D.
	NPK	NPK	N	NPK	NPK	N	N	N	N	NPK	NPK

II	L.D.	S.M.	S.B.	S.M.	L.R.	S.B.	L.R.	L.S.	L.S.	L.R.
	N	NPK	NPK	N	NPK	N	NPK	NPK	N	N

L.D. = liquid dribble
L.R. = liquid in row
L.S. = liquid spray
S.B. = solid banded
S.M. = solid mixed

Field Experiment with corn(solid and liquid fertilizer)
(1956)

Plot Diagram II

I	S.B. NPK	S.B. NK	L.S. NPK	L.S. NK	L.D. NPK	L.D. NK	L.R. NPK	L.R. NK	S.M. NPK	S.M. NK
II	L.D. NK	L.D. NPK	S.B. NPK	S.B. NK	L.R. NPK	L.R. NK	S.M NPK	S.M. NK	L.S. NPK	L.S. NK
III	S.M. NPK	S.M. NK	L.R. NPK	L.R. NK	L.S. NPK	L.S. NK	S.B. NPK	S.B. NK	L.D. NPK	L.D. NK
IV	L.S. NPK	L.S. NK	L.D. NPK	L.D. NK	L.R. NK	S.B NPK	S.B. NK	L.R. NPK	S.M. NPK	S.M. NK

S.B. = solid banded ; S.M. = solid mixed
L.D. = liquid dribble; L.R. = liquid in row

Field Experiment with corn (1957)

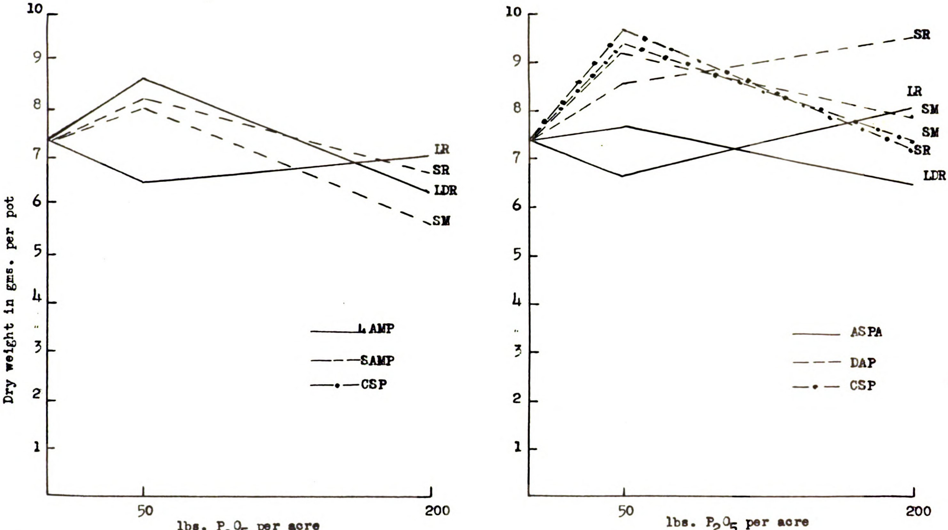

Figure 9. The residual effect of solid and liquid fertilizers applied in different placements on the dry weight yields of millet plants grown on Rifle peat (limed) in the greenhouse.

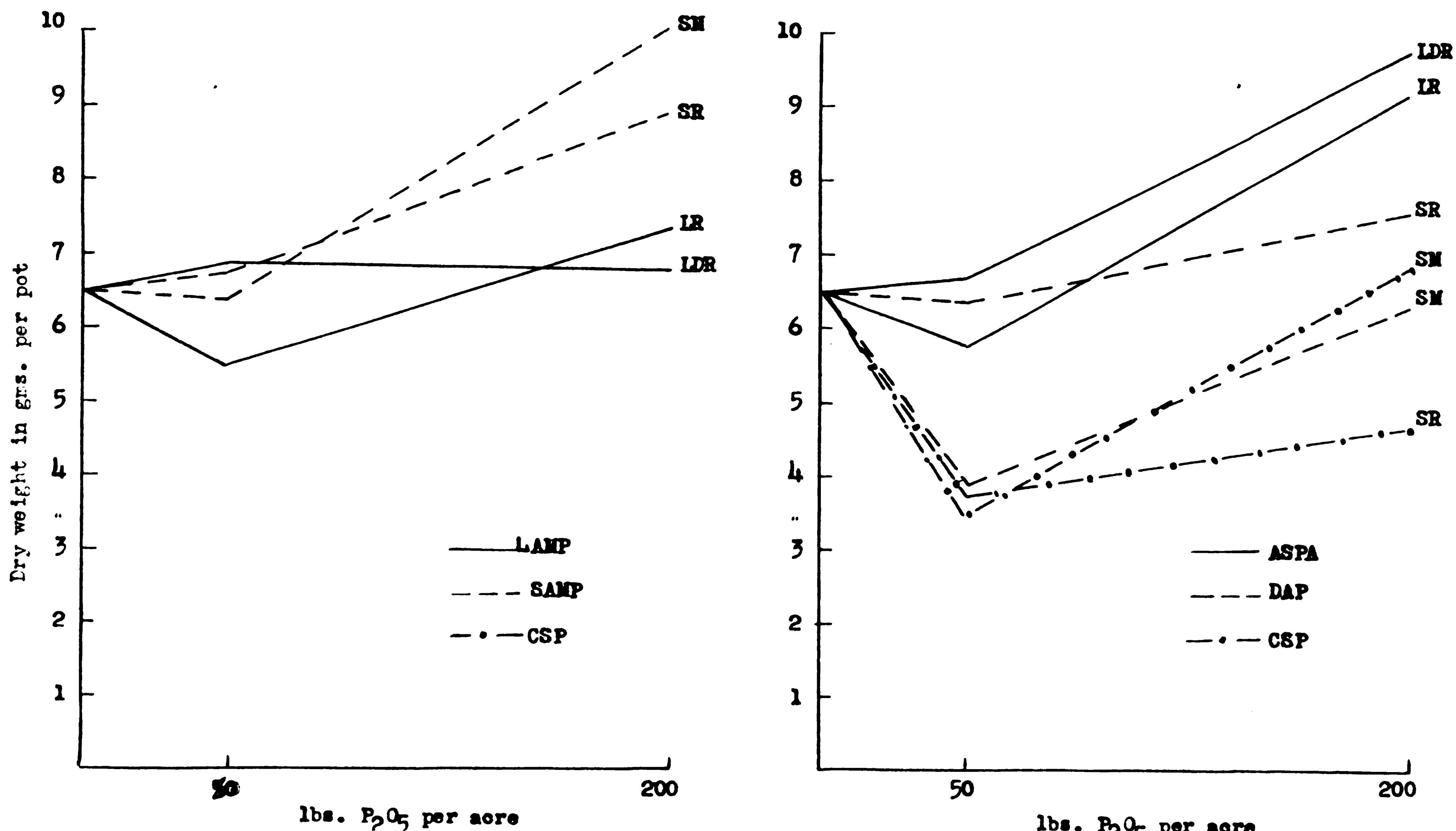

Figure 10. The residual effect of solid and liquid fertilizers applied in different placements on the dry weight yields of millet plants grown on Rifle peat (unlimed) in the greenhouse.

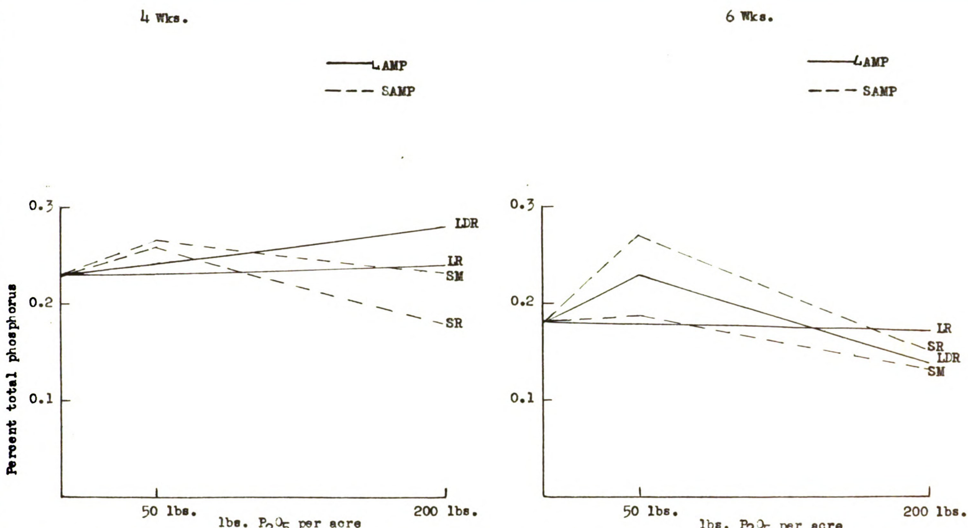

Figure 11. The residual effect of solid and liquid fertilizers applied in different placements on the total phosphorus content of millet plants grown on Rifle peat (limed) in the greenhouse.

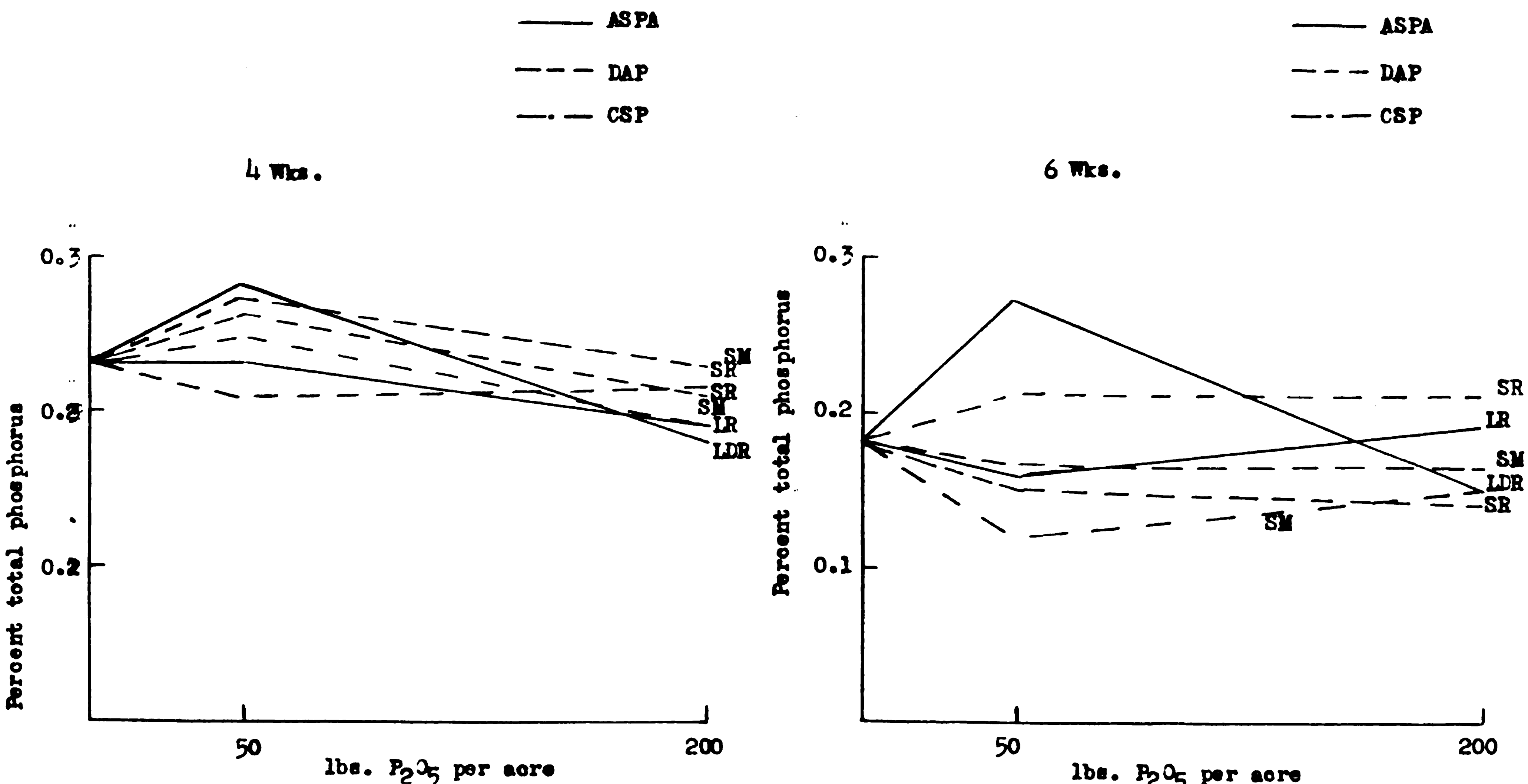

Figure 11, continued.

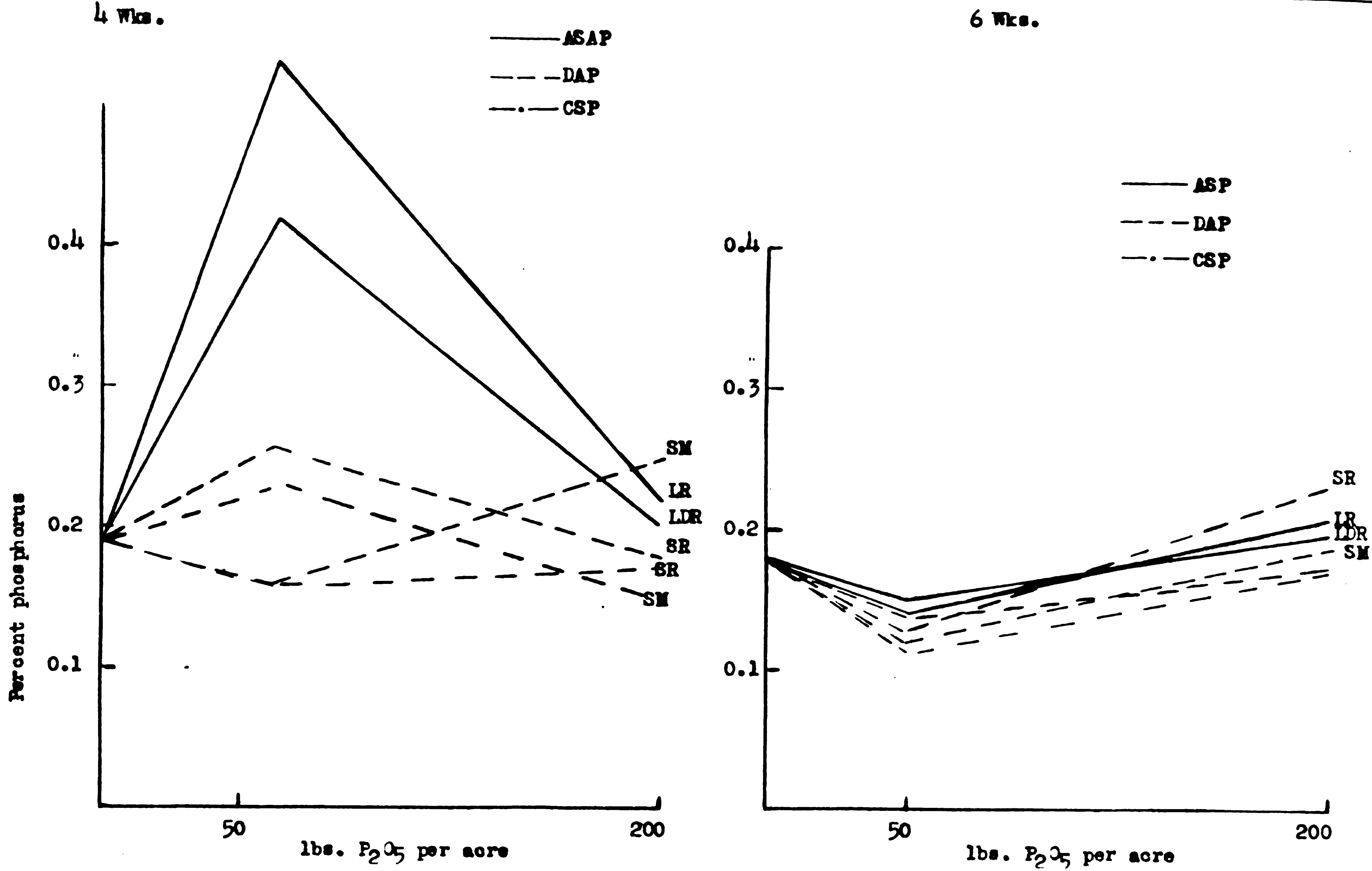

Figure 12. The residual effect of solid and liquid fertilizers applied in different placements on the total phosphorus content of millet plants grown on Rifle peat (unlimed) in the greenhouse.

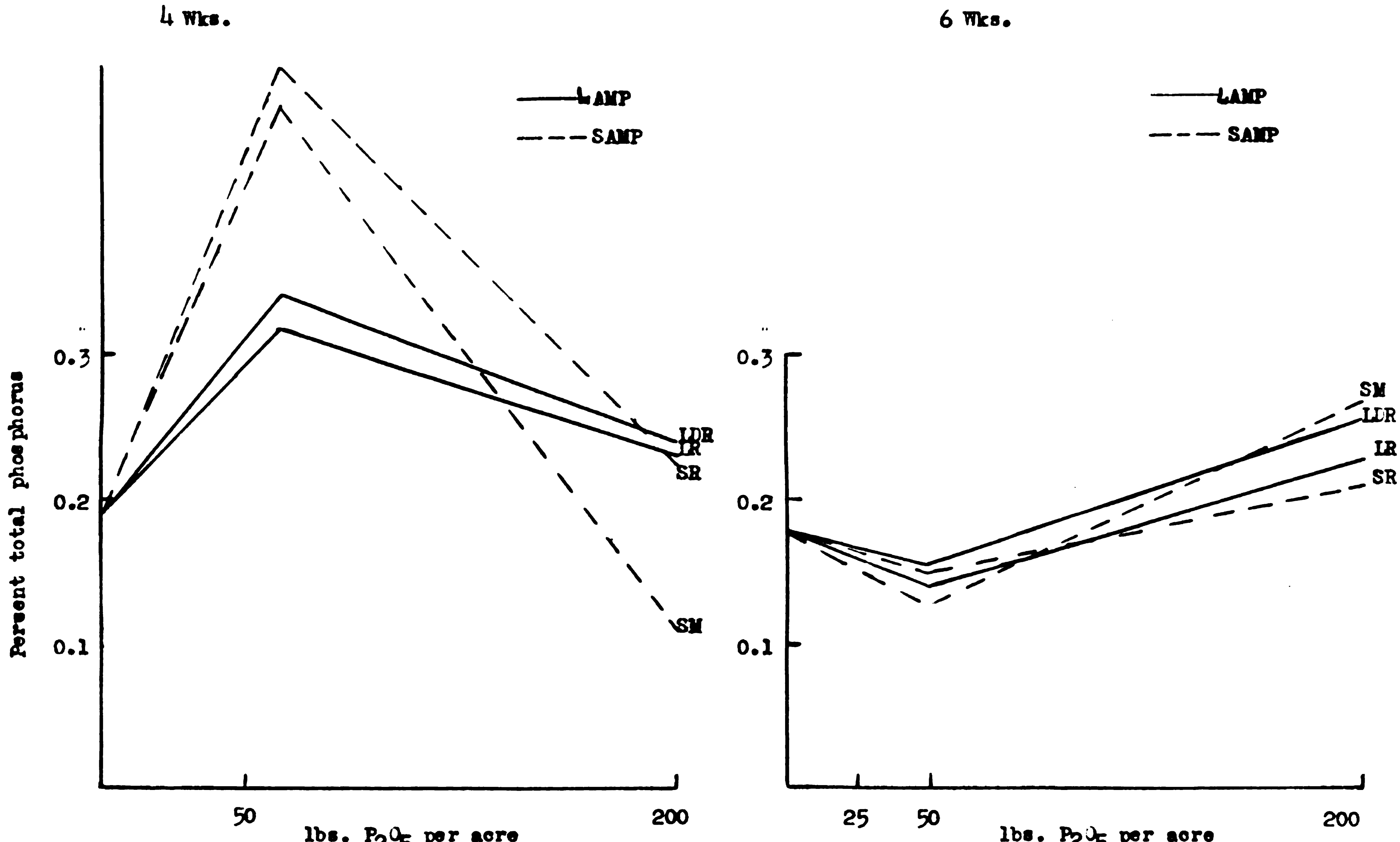

Figure 12. continued.

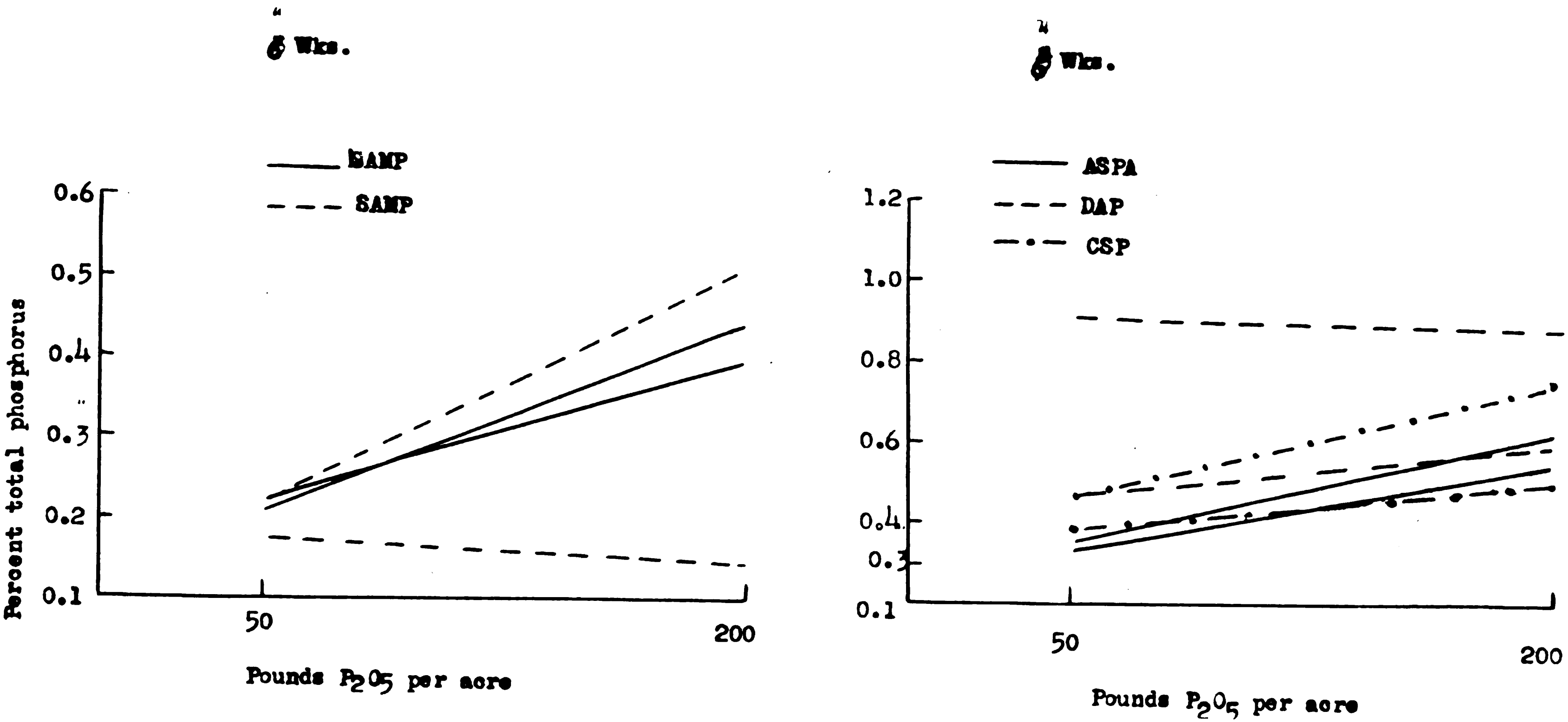

Figure 13. Influence of solid and liquid fertilizers applied in different placements on the total phosphorus content of corn plants grown on Rifle peat (unlimed) in the greenhouse.

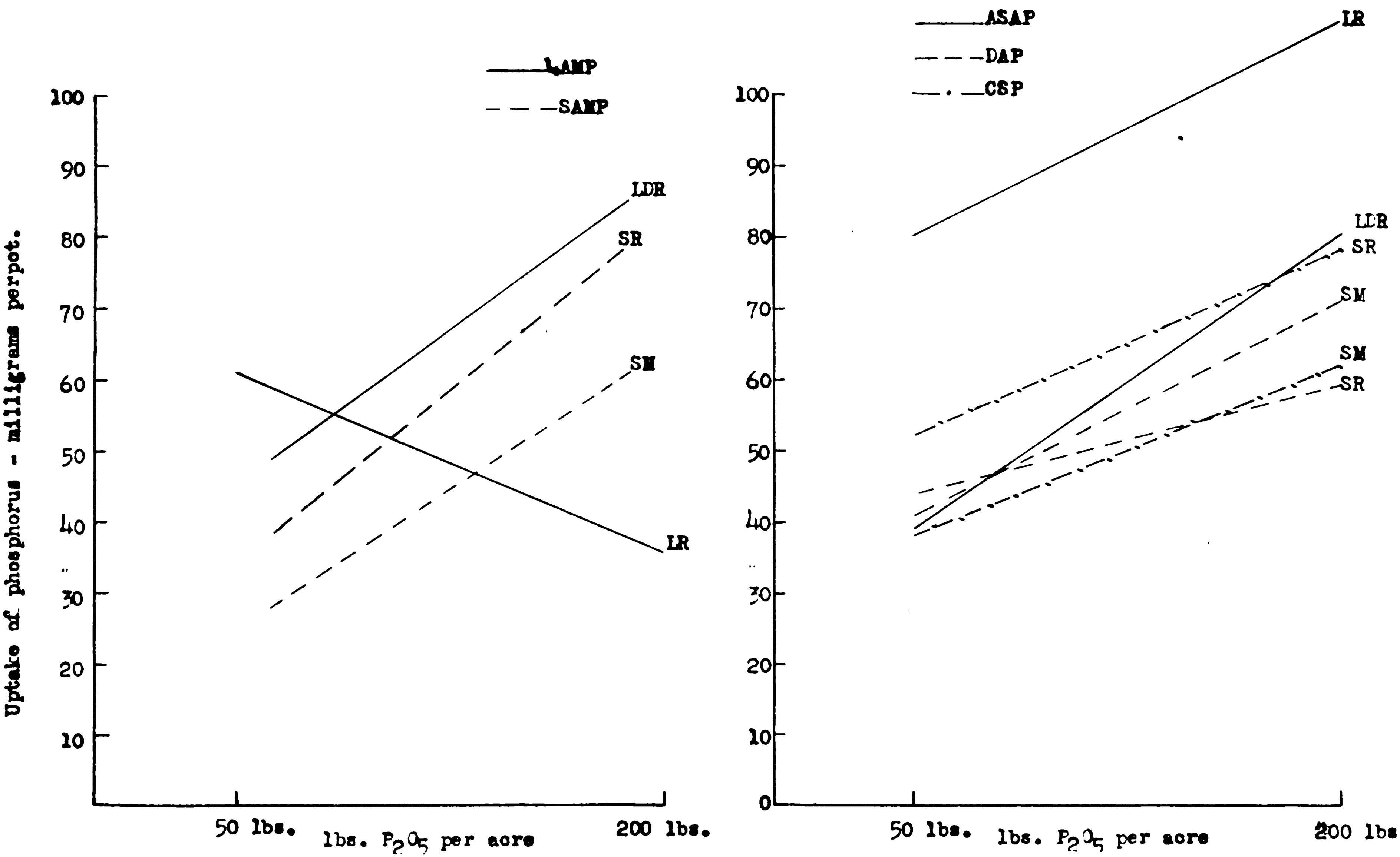

Figure 14. Effect of solid and liquid fertilizers applied in different placements on the uptake of phosphorus by corn plants grown on Rifle peat (limed) in the greenhouse (9 weeks after planting).