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THE INFLUENCE OF SOIL MOISTURE CONDITIONS ON THE ABSORPTION
OF PHOSPHORUS BY PLANTS FROM CALCAREOUS SOILS

by

T. J. Denman

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soil Science

UTAH STATE AGRICULTURAL COLLEGE
Logan, Utah

1955

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INTRODUCTION

Phosphorus is one of the major plant nutrients secured from the soil. The object of many investigations has been to discover the nature of the processes by which the soil supplies phosphorus to plants, and to determine the influence of soil factors upon these processes. Although much knowledge has been gained, these processes and the effects of soil factors upon them are still not clearly defined.

One factor which profoundly affects plant growth is the amount and relative availability of soil moisture. The results of some investigations have suggested that this factor may also have considerable influence on the absorption of phosphorus by plants.

The purpose of this investigation was to study the influence of soil moisture condition on the absorption of phosphorus by plants from calcareous soils. Information pointing toward answers to the following questions was sought.

(1) Can plant roots penetrate into soil having a moisture content of permanent wilting percentage or less and absorb phosphorus from applied fertilizer?

(2) Is plant absorption of phosphorus from applied fertilizer influenced, in any consistent manner, by the moisture condition of the soil?

REVIEW OF LITERATURE

Relationships between soil moisture and the absorption of phosphorus and other nutrients

Apparent relations between soil moisture conditions and plant absorption of certain of the major plant nutrients have often been observed. However, relatively few experiments have been designed specifically for studying these relations. Wadleigh and Richards (1951), reviewing the effect of soil moisture on nutrient availability, reported that, "Most experimental evidence shows that for a given level of fertility, decreasing soil moisture supply is associated with a definite increase in nitrogen content of the plant tissue, a definite decrease in potassium content, and a variable effect upon the content of phosphorus, calcium, and magnesium," (p. 437).

The results obtained by many workers are in accord with the statement of Wadleigh and Richards concerning nitrogen and potassium, but some workers have found a negative relation or no relation between the soil moisture level and the absorption of phosphorus. Miller and Duley (1925), using all possible combinations of two different soil moisture levels applied for three consecutive thirty-day periods, found that corn plants grown at the higher soil moisture levels contained a lower percentage of phosphorus than those grown at the lower soil moisture levels. In a study of the effect of varying amounts of irrigation water on the composition of snap beans, Janes (1948) found decreasing phosphorus percentage of the beans to be associated with increasing amounts of

irrigation water applied. McMurtrey et al. (1947) found that the most outstanding differences in the composition of tobacco leaves from tobacco grown under different moisture regimes were the higher potassium content of the leaves from the high moisture treatments and the higher nitrogen content of the leaves from the low moisture treatments. They found no correlation between phosphorus content of the leaves and the moisture conditions under which the plants were grown.

Some workers have found a positive relation between soil moisture level and absorption of phosphorus by plants. Daniel and Harper (1935) studied the relation between effective rainfall and the calcium and phosphorus content of alfalfa and prairie hay over a period of several years. They found, consistently, that high effective rainfall was associated with low calcium content and high phosphorus content of the hay while low effective rainfall was associated with high calcium content and low phosphorus content. Darkis et al. (1937) studied the chemical composition of tobacco produced under varying weather conditions. They found that an increase in seasonal rainfall tended to increase the potassium and phosphorus content of the tobacco while a decrease in seasonal rainfall tended to increase the nitrogen, calcium, magnesium, and sulfate in the tobacco. The average phosphorus content of the tobacco was approximately 21 percent higher in wet than in dry seasons. Emmert (1936), studying the effect of drought on the nutrient levels in the tomato plant, found that plants grown under dry soil moisture conditions contained a lower percentage of phosphorus and a higher percentage of nitrogen than those grown under more favorable moisture conditions. Thomas et al. (1942, 1943) made a study of the nitrogen, phosphorus, and potassium nutrition of tomatoes and snap beans at different levels of fertilization and irrigation. They found that percent phosphorus

increased and percent nitrogen decreased with increasing amount of irrigation water applied.

Snider (1945), comparing the phosphorus contents of Korean lespedeza and Kentucky bluegrass in dry and wet seasons, found that the phosphorus content of both was considerably greater in the wet seasons. Tinsley (1953) grew tobacco in soil in the greenhouse at three different moisture levels and found that the phosphorus percentage of the plants was highest at the high moisture level, lower in the medium moisture level plants, and lowest in the plants from the lowest moisture level. Volk (1947), using corn to study moisture translocation by plants from one soil zone to another, found that low soil moisture levels were associated with low phosphorus content of corn plants. Haddock (1952) found low soil moisture tension in irrigated, calcareous soils correlated with high phosphorus content of sugar beet petioles while high soil moisture tension was correlated with lower phosphorus content. Haddock et al. (1955) observed that increased phosphorus content of canning peas was associated with increased amounts of water applied to irrigated, calcareous soils. Smith (1952) conducted greenhouse and field studies with calcareous Utah soils and observed a positive relationship between soil moisture level and plant absorption of fertilizer and soil phosphorus.

The above citations indicate that apparently there is a rather general relation between the nitrogen and potassium content of plants and the level of soil moisture at which they are grown. They indicate, also, that on many soils of widely varying types, there appears to be a positive relationship between phosphorus content of plants and the level of soil moisture at which they are grown. This positive relation does not hold under all conditions, as Wadleigh and Richards (1951)

have noted, but there are enough observations of this phenomenon under widely varying conditions to indicate that it is worthy of study. However, it should be recognized that in most of the instances cited only a generally moist or dry condition prevailed in the soil, and there was no precise measurement or control of the soil moisture level.

There is, also, some implicit evidence for the positive relation between phosphorus absorption and soil moisture. This includes fertilizer placement studies which show better utilization of deeply placed fertilizer in dry years than that which is placed shallow, (Stanford and Pierre, 1953; Olsen et al., 1950).

Reasons for differences in phosphorus absorption by plants at different levels of soil moisture

There are many possible reasons for the different effects of moisture on phosphorus absorption by plants. Among these are the inherent differences among the plants themselves such as differences in rooting habit, rate of growth and extensiveness of the root system, rate of shoot growth, and proportion of roots to shoots. "Since the most efficient zone of absorption is usually near the root tip, the number of tips is an important factor in absorption, . . . and those plants which develop the most extensively branched and most deeply penetrating root systems are best able to obtain large quantities of water and minerals," (Kramer, p. 121, 1949). Bingham (1951) grew lettuce and barley plants in solution cultures and found that a concentration of approximately 1.0 parts per million of phosphate was necessary to obtain maximum lettuce growth, but barley made maximum growth at concentrations of 0.5 parts per million or greater. He reasoned that the difference in response to different phosphate concentrations may have resulted from differences in

the shoot-root ratios. These were 7.0 for lettuce and 2.8 for barley plants which made maximum growth. Assuming that root absorbing surface is proportional to root weight, sufficient phosphorus for maximum growth of barley shoots could be supplied by a slower rate of absorption.

Stage of development of the plant and the parts of the plant chosen for analysis also affect the evaluation of the influence of soil moisture on phosphorus absorption by plants. Kramer (1949) discusses an experiment in which it was discovered that the ratio of roots to shoots of cotton was approximately tripled by removal of both bolls and vegetative buds. Later other workers found that boll formation is accompanied by reduced movement of sugars to the roots, which no doubt results in curtailed root growth and thus reduced absorption of minerals. Arnon and Hoagland (1943), growing tomato plants in nutrient solutions with limited phosphorus supply, observed that if the plants were allowed to develop fruits, the vegetative portions had a much lower phosphorus content than the vegetative portions of those plants which were not allowed to develop fruit.

Nutrient balance in the soil or growth medium has considerable influence on the absorption of phosphorus. Arnon (1939), studying the effect of ammonium and nitrate nitrogen on the mineral composition of barley, observed that the plants supplied with nitrogen in the ammonium form had, under all the conditions tested, a higher phosphorus content than those supplied with nitrate form. Competition between the rapidly absorbed nitrate and the more slowly absorbed phosphate ion was offered as a possible explanation for the lower phosphate absorption from the nitrate cultures. Stanford and Pierre (1953) report unpublished results obtained by Dumenil and Hanaway in Iowa, which show the effect of nitrogen, phosphorus and potassium fertilization on yield and phosphorus content of corn leaves. Phosphorus fertilizer alone had no effect on the

phosphorus percentage in the leaves, but phosphorus and nitrogen together increased the phosphorus content approximately 27 percent. Potassium had no effect on the phosphorus content of the leaves. Stanford and Pierre report that other workers have found that nitrogen fertilization may increase the phosphorus content of corn leaves.

It is apparent that these and probably other plant and environmental factors must be taken into account when evaluating the effects of soil moisture on phosphorus absorption by plants.

Contact exchange vs. absorption from the soil solution

A knowledge of the processes operating in the soil to supply phosphorus to the plant root surfaces and the extent of each process is essential to understanding the effect of moisture on phosphorus absorption. Two processes may be involved in the movement of phosphate ions from the soil to the root surface. These two processes are, 1) a direct exchange of ions between the root surfaces in contact with soil particle surfaces, and 2) absorption of the ions from the soil solution. It is not known which, if either, process predominates in the absorption of phosphorus from soils. Very likely, both may occur, and assumptions as to the predominance of one or the other in soils are based on very incomplete and scanty evidence. However, an examination of the findings and conclusions of other workers may provide some basis for a decision as to whether a particular process could provide enough phosphorus for plant needs.

Before proceeding further in this discussion, a definition of what is meant by the term "soil solution" should be given. This is generally considered as that liquid which can be displaced from a soil column, at a moisture content of field capacity or less, by applying water, alcohol,

or some other displacing liquid at the top of the column and catching the eluate which drips from the bottom until some of the displacing liquid appears in the eluate. Whether this liquid is actually representative of that solution which we envision as being the source of phosphorus for the plant is a moot point. However, it would seem gratuitous to assume that it is not.

Parker (1927) found that since the displaced soil solutions of many productive soils contain only a trace of inorganic phosphorus, it seemed necessary to assume that plants do not obtain all of their phosphorus from the soil solution. He offered as possible explanations of the phosphorus adequacy of these soils 1) a solvent action of plant roots on solid phase phosphates and 2) a Donnan equilibrium with a higher phosphate concentration near the soil particle surfaces. Tidmore (1930a, 1930b) found that plants made better growth in soil which had a displaced solution containing 0.02 to 0.03 parts per million of phosphate than in a solution culture containing 0.1 parts per million phosphate. He felt that this indicated that plants growing in soil could obtain phosphate which is not in the displaced solution, and he speculated that the following possibilities might explain the differences between soil and solution culture: 1) soil-root contact, 2) solvent action of carbon dioxide produced in root respiration, 3) extent of root system, 4) plant differences, and 5) higher phosphate concentration around the soil particles. Arnon and Hoagland (1940) state that the concentrations of phosphate in displaced soil solutions may sometimes be so low that the absorption of phosphate by the plant cannot be accounted for by examination of the displaced solution.

Contact exchange between soil and roots has never been demonstrated to actually occur in the manner which Jenny (1951) has postulated for

cations. In fact, Dean and Rubins (1945), growing barley plants in clay-water suspensions with the roots of some of the plants separated from contact with the clay by collodion bags, found no evidence of a contact exchange effect on phosphorus absorption.

McAuliffe et al. (1947), Olsen (1953), and Seatz (1954) have demonstrated that soils contain phosphorus which is apparently adsorbed on the surfaces of soil particles and is easily exchangeable with P^{32} -labelled phosphate. Olsen (1953) found a very high correlation in 25 western soils between the amount of easily exchangeable phosphorus (surface phosphorus) and A-values (Fried and Dean, 1952). Olsen et al. (1954), studying the residual phosphorus availability in three calcareous soils, found a high correlation of A-values with the amount of surface phosphorus and the amount of available phosphorus in the soils as determined by 1:10 soil:water extraction, the sodium bicarbonate method, and the Bray method.

The above-mentioned results obtained by McAuliffe (1947), Olsen (1953), and Olsen et al. (1954) seem to indicate that if surface phosphorus is highly correlated with phosphorus absorption by plants, then root-soil contact exchange may be the predominant process operating to supply roots with soil phosphorus. This is not necessarily true. It should be noted that Olsen et al. (1954) in their residual phosphorus studies found, also, that other methods of determining phosphorus availability gave high correlations with plant absorption. Among these methods was the 1:10 soil:water extract. Using this method, Bingham (1949) and Martin and Buchanan (1950) found a good correlation between response to phosphorus fertilization and soil deficiency as determined with this method. A total of 267 soils were used in their studies.

Bingham (1951) also found a high correlation between phosphorus content of the water extract and relative yields of lettuce and barley as determined by the method of Jenny et al. (1950). Burd (1948), using a 1:50 soil:water ratio with only momentary shaking, obtained a high correlation between phosphorus content of this extract and dry matter yield of oats grown in greenhouse pots. Thorne (1946) grew barley and tomato plants in bentonite-calcium carbonate-sand cultures. Phosphorus concentration of a composite of two 1:15 water extracts of the medium was determined. He found that phosphorus uptake was closely correlated to water solubility in the culture media and that the concentration of phosphorus in the tomato plants was directly proportional to the water-soluble phosphorus removed in the extracts.

These correlations of phosphorus absorption by plants with phosphorus concentration of the water extracts may be considered as favoring the idea of principal plant absorption of phosphorus from the soil solution. Even the fact that surface phosphate was highly correlated with plant uptake does not detract from this idea, since the easily replaceable phosphate ions could come into solution rapidly to replace a deficiency caused by plant absorption. It must be admitted that this is only inferential evidence for principal absorption from solution, but it lends some support to this argument.

Overstreet and Dean (1951), in discussing the availability of soil anions in terms of contact exchange and absorption from soil solution, say, "Judging from the rather scanty information available, it is not improbable that plants absorb anions from soils through the medium of the soil solution," (p. 82). Arnon (1953) takes the view that in the early work on phosphorus insufficient weight was given to the positive findings about the efficiency of higher plants in absorbing phosphate

from extremely dilute nutrient solutions, and undue emphasis was placed on the few exceptions in which good crops were obtained from soils whose solutions contained very low concentrations of phosphorus. It is his opinion that, "A fresh appraisal of the evidence offers no compelling arguments against the view that the water-soluble phosphate is the source of phosphorus for plants grown under natural conditions in soils," (p. 5).

Factors affecting the phosphorus status of the soil solution

Since the effect of moisture on the hypothetical contact exchange of phosphorus between root and soil surfaces is unknown, perhaps it is justifiable to tentatively take the view of Arnon (1953) and Overstreet and Dean (1951), that the principal absorption of phosphorus takes place through the medium of the soil solution, and consider those factors which affect the phosphorus status of that solution.

What is the phosphorus concentration of the soil solution? Burd and Martin (1924), Burd (1948), Burgess (1922), Hibbard (1923), Pierre and Parker (1927), and Pierre and Pohlman (1933) are some of the workers which have determined the phosphorus content of displaced soil solutions. In solutions from mineral soils, these workers have found phosphate concentrations ranging from less than 0.02 parts per million to 12 parts per million of solution.

Two important factors which affect the phosphorus status of the soil solution are the rate at which phosphorus is absorbed and the total quantity absorbed by plants. Stout and Overstreet (1950) calculated, in one instance, that complete renewal of the phosphate in the soil solution would be necessary ten times each day to supply plants growing in greenhouse pots of soil whose solution contained one part per million phosphate. They viewed this figure as conservative. They apparently

assumed that the roots of the plants were in effective contact with all the soil solution in the pots. Kramer (1949), using the figures given by Dittmer for the average daily rate of extension of roots of a four month old rye plant, calculated that from 1.6 to 2.9 liters of water would be available to the plant daily, depending upon the moisture holding characteristics of the soil. He assumed that the soil was at field capacity and that the roots and root hairs would be in contact with a soil cylinder 2 millimeters in diameter. Further calculations by the author can reveal if this amount of solution is sufficient to provide enough phosphorus for normal plant growth. If an initial concentration of 1 part per million of phosphate and complete removal by the plant are assumed, 1.6 to 2.9 milligrams of phosphate would be available for plant absorption each day. This would supply enough phosphate each day for production of 0.32 to 0.58 grams (dry weight) of plant material containing 0.5 percent phosphate. In four months this would amount to 38 to 70 grams total dry weight for the rye plant. It seems reasonable that the weight of a four months old rye plant could fall within this range. Probably the plant could remove most, but not all, of the phosphate from the soil solution. Results obtained by Parker and Pierre (1928), growing corn plants in solution culture with low concentrations of phosphate, indicate that in these cultures the corn could not reduce the concentration below about 0.025 parts per million. The rye plant could remove approximately 97 percent of the phosphate from the soil solution if it could reduce the solution to this concentration. In this case, complete renewal of the phosphate in the soil solution would be necessary only once each day.

Up to this point calculations have been made upon the basis of complete renewal of the phosphorus in the soil solution only once, or

a few times each day. Considering the speed of most chemical reactions, it seems reasonable to assume that as the phosphorus in the soil solution is depleted, rapid replenishment should occur. The rapidity of replenishment may be the key to the ability of plants to thrive in those soils whose solutions are extremely low in phosphorus. This may also be the reason for the close correlation between surface phosphorus values and A-values, since the surface phosphorus is easily replaceable and could enter solution rapidly to replace that absorbed by plants.

It appears then, that another factor to be considered in the phosphorus status of the soil solution is the rate at which the phosphorus from the solid phase can come into solution. Burd (1918) and Stewart (1918) made water extracts of cropped and uncropped soils. They observed great dissimilarities in the phosphate content of the extracts of different soils, but in any one soil there was no difference between the phosphate concentration of extracts from cropped and uncropped areas. Burd concluded that either the plants absorbed insoluble phosphates or the soils replaced the phosphates as rapidly as they were required by the plants. McAuliffe *et al.* (1947) added P^{32} as phosphate to a soil suspension which had been allowed to come to equilibrium. Neither the amount of phosphate or solution added with it was enough to affect the phosphate concentration of the suspension. It was found, in all cases, that within five minutes, over two-thirds of the P^{32} -phosphate had equilibrated with phosphate ion from the solid phase. Seatz (1954), using the same technique, found that in all cases 86 percent or more of the P^{32} -phosphate had exchanged with solid phase phosphate within ten minutes. Presumably, phosphate from the solid phase could enter solution, to replace that absorbed by plants, just as rapidly as the above-mentioned exchange with P^{32} -phosphate occurs.

Cole et al. (1953) cite instances of the long periods of time required for equilibrium to be established in reactions involving calcium phosphate compounds. Olsen (1953) also cites such instances and states that Basset found that equilibrium was not established between mixtures of calcium hydroxide and tricalcium phosphate suspensions within 12 to 14 months.

The effect of soil moisture on the rate at which the soil can supply phosphorus is not known, but it can be predicted that as the moisture films in the soil become less continuous, the quantity of phosphorus that can diffuse to a point in a given time will decrease. This is suggested by the work of Lawton and Vomocil (1954) and Heslep and Black (1954). Both studied the diffusion of phosphates through acid soils using P^{32} as a tracer. They found that the rate of diffusion of the P^{32} was increased by increasing the soil moisture content and by increasing the degree of compaction of the soil. Heslep and Black (1954), using a silt loam soil adjusted to different moisture contents, measured the extent of diffusion of fertilizer P^{32} from a band in one month. Only 4 percent of the fertilizer P^{32} was found further than one centimeter from the band in soil containing 9.1 percent moisture; 12 percent, in soil containing 12.5 percent moisture; 22 percent, in soil containing 19.4 percent moisture; and 34 percent, in soil containing 27.5 percent moisture. The moisture equivalent of the soil was 17.3 percent. Heslep and Black used three calcareous soils in supplementary experiments for which no data were given, but they state that the extent of phosphorus diffusion in these soils was much less than that which occurred in the acid soils.

The above citations indicate that three factors which determine the phosphorus supplying power of a soil are the concentration of the soil

solution, the rate at which solid phase phosphates can enter solution, and the rate of diffusion of phosphates through the soil. They also indicate that the rate at which phosphates enter solution may be rapid, or the rate may be extremely slow when the dissolution and formation of calcium phosphates is involved.

Effect of moisture on the phosphorus status of the soil solutions of calcareous soils

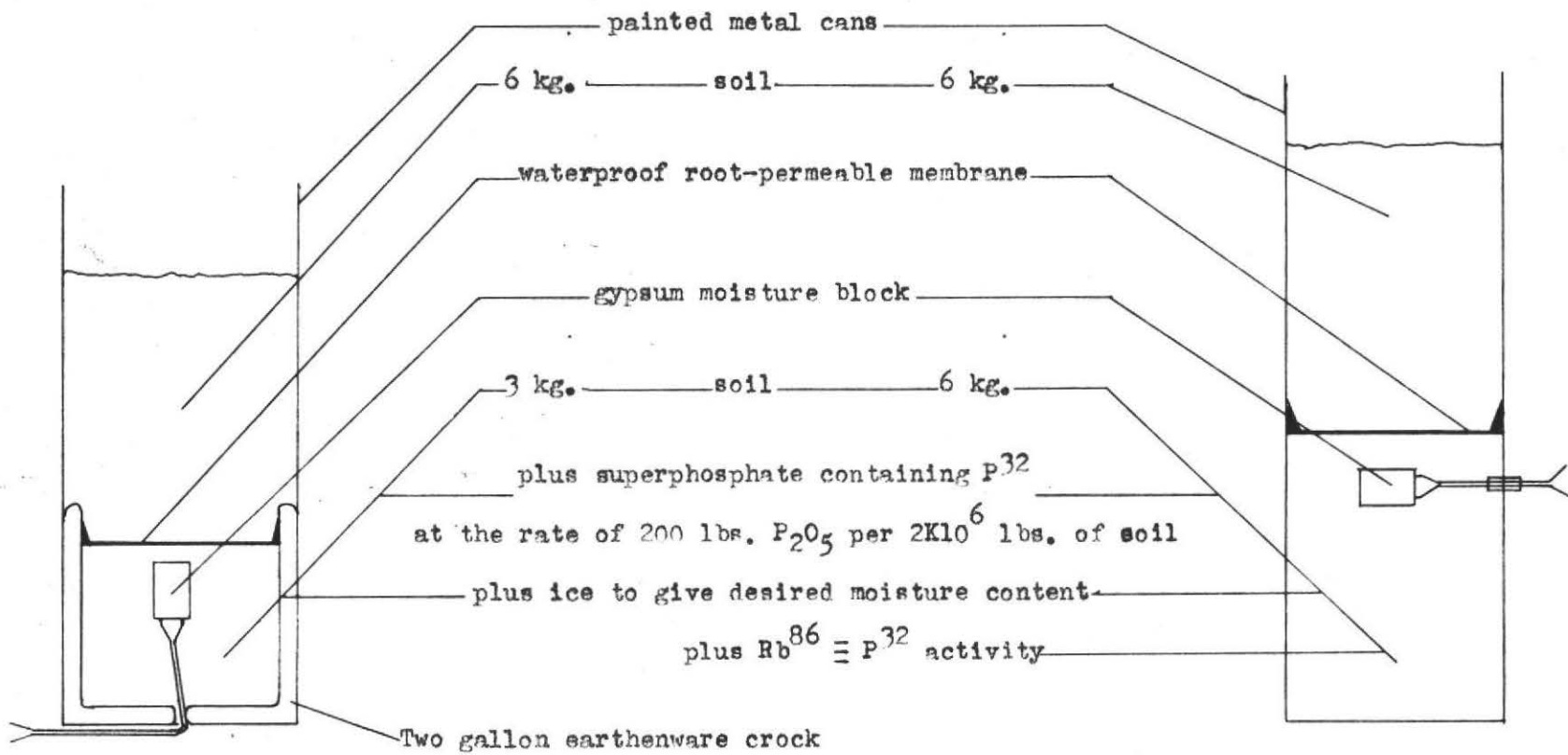
Calcareous soils contain an excess of solid phase calcium carbonate and are usually well supplied with native calcium phosphates. The depressing effect of solid phase calcium carbonate on the solubility of calcium phosphates is easily understood from a qualitative point of view and has been demonstrated by Benne et al. (1936), Burd (1948), and Cole et al. (1953). Because of the low solubilities of calcium phosphates in basic solutions and the relatively high concentrations of calcium ion in the soil solutions of calcareous soils, the concentration of phosphate ion in these solutions will remain at a constant low level, if the concentrations of calcium and hydrogen ions remain constant. It is not known whether the calcium ion concentration and pH of the solutions of calcareous soils remain constant through the moisture range from field capacity to permanent wilting percentage. Reitemeier and Richards (1944) determined pH, calcium ion concentration, and concentrations of other ions in pressure membrane extracts obtained from a calcareous soil at two different moisture contents. These moisture contents spanned, approximately, the middle one-half of the available moisture range. There was no substantial difference in either pH or calcium ion concentration between the extracts. It can be hypothesized that if the calcium concentration and pH of the soil solution remain constant over the available moisture range, then the phosphorus

concentration should remain constant, and the amount of phosphorus available for plant absorption at any instant will be directly related to the quantity of available moisture in the soil.

A test of the above hypothesis requires 1) that known, definite quantities of soil solution be present in the soil where plants roots are growing, 2) that plant absorption occur only for an instant, and 3) that the phosphorus absorbed only during that instant from a soil containing a known quantity of soil moisture be determinable. In soils, it is impossible to fulfill the second requirement. It is possible, however, to prepare portions of soil which contain known amounts of soil moisture and to determine the quantities of applied fertilizer phosphorus absorbed from those portions. Hunter and Kelley (1946a) have devised an asphalt-paraffin-cheesecloth membrane which apparently offers little resistance to plant root penetration, but maintains a water-proof seal around roots after they have penetrated the membrane. Hunter and Kelley (1946a, 1946b) and Smith (1952) have successfully used this type of membrane to separate adjacent soil sections which were maintained at different moisture levels. If portions of soil containing superphosphate fertilizer labelled with P^{32} are adjusted to definite moisture contents, these portions can be separated from the remainder of the soil by such membranes. The moisture could be removed from these portions only by plant roots which penetrated the membranes and grew through the soil, and the amount of fertilizer phosphorus absorbed by plants could be determined by measuring their P^{32} content.

PROCEDURE

To study the effect of different soil moisture conditions on the absorption by plants of phosphorus from applied fertilizer, two experiments were conducted in the greenhouse. In both experiments, the plants were grown in large cans in which the soil was separated into two sections. A waterproof, root-permeable, asphalt-paraffin-cheese-cloth membrane (Hunter and Kelley, 1946a) was used to separate the soil in the cans into an irrigated upper portion and a lower portion which had been made up to a predetermined moisture content. In preparing the lower portion of soil, superphosphate labelled with radioactive P^{32} was mixed with the soil at the rate of 200 pounds of P_2O_5 per two million pounds of soil. In order to bring the soil to the desired moisture content and to obtain uniform distribution of the moisture, the soil was chilled to a temperature below $0^{\circ} C.$ and mixed with the proper amount of crushed ice. A gypsum moisture block was placed in each of the lower sections so that changes in the moisture content of the soil could be detected. The membranes covering the lower soil sections were sealed to the sides of the containers with generous amounts of heated asphalt-paraffin mix. The arrangements used in the two experiments to enclose the lower soil sections were slightly different. Diagrams of the arrangements used in the experiments are shown in figure 1. The soil used was a Millville silty clay loam obtained from the Greenville experimental farm at Logan, Utah. The soil was taken from an unfertilized area of a field where crops had responded to phosphorus fertilization. Some chemical and physical characteristics of the soil are given in table 1.



Experiment 1

Experiment 2

Figure 1. Diagram showing design of containers used for growing plants.

Table 1. Some chemical and physical characteristics of Millville silty clay loam.

pH	7.85
Lime content	27.4 percent
Moisture contents	
Air-dry	2.7 percent
15-atm.	12.8 percent
1/3 atm.	25.7 percent

The amount of fertilizer phosphorus absorbed by the plants was determined by assaying samples of the plant material for their P^{32} content.

Experiment 1

The object of the first experiment was to determine if plants with tap or fibrous types of root growth could absorb phosphorus from fertilizer applied in soils with a moisture content of permanent wilting percentage or less. A second objective was to determine if the amount of fertilizer phosphorus absorption was related to the soil moisture content.

Six different moisture treatments were applied in the lower soil sections. These were 2.7 percent (air-dry), 5 percent, 7 percent, 9 percent, 11 percent, and 13 percent. The highest moisture content was slightly above the 15-atmosphere percentage. Twelve cans each of corn, wheat, alfalfa, and sugar beets -- a total of 48 cans -- were used. Each moisture treatment was duplicated in each set of twelve. The soil moisture in the upper sections was maintained as near optimum as possible throughout the experiment.

After the lower section of each can was sealed with the asphalt-paraffin membrane, six kilograms of soil was placed in the upper section of the cans. The upper soil in the cans was wetted, and the corn, wheat, alfalfa, and sugar beets were planted on 10 December 1953.

The specific activity of P^{32} in the soil at the time of planting is given in table 2.

At the end of eight weeks, 4 February 1953, the plants were harvested.

Samples of the dried, ground plant material were weighed and ashed and the amount of P^{32} in them determined.

Table 2. Data on P³² in superphosphate fertilizer used

Fertilizer used in	Specific Activity per gram of P ₂ O ₅ on pile date mc./gm.	Half-lives between pile date and planting date	Specific Activity per gram of fertilized soil on planting date mc./gm.	Half-lives between pile date and assay	Fraction of pile date activity remaining at assay
Expt. 1	0.2	4.4	9.43×10^{-7}	8.5	0.002754
Expt. 2	0.2	3.9	1.52×10^{-6}	7.9	0.004189

Experiment 2

The primary objective of this experiment was to determine if the amount of applied fertilizer phosphorus absorbed by corn plants is related to the available moisture content of the fertilized soil. A second objective was to determine if the soil moisture condition of an unfertilized portion of the soil can influence the amount of applied phosphorus absorbed from a fertilized portion. A third objective was to determine if Rb^{86} cation absorption by corn plants is related to the available moisture content of the soil in which it is placed.

The specific activity of P^{32} in the soil at the beginning of this experiment is given in table 2.

In addition to the superphosphate, Rb^{86} adsorbed on an ion exchange resin was added to the lower soil portions in this experiment. The Rb^{86} activity added to each soil portion was equal to the P^{32} activity calculated to the pile date of the Rb^{86} . Rb^{86} was used in this experiment because 1) it was felt that information on plant absorption of a cation similar to potassium ion could be obtained, 2) Rb absorption should not influence phosphorus absorption, and 3) it is a gamma emitter and can be determined separately from P^{32} .

Five soil moisture treatments were applied in the lower soil portions. These were 26 percent, 22 percent, 18 percent, 14 percent, and 11 percent.¹

1. The actual average moisture contents for each treatment in the second experiment were 30.4 percent, 26.1 percent, 22.0 percent, 16.5 percent, and 12.0 percent, respectively. The balance used to weigh the ice and soil was defective. This is the reason for the discrepancies between the desired and actual moisture contents. Initial moisture determinations were not made in the first experiment, but since the same balance was used to weigh the soil and ice, it must be assumed that the 13 percent and 11 percent levels were actually near 15 percent and 12 percent.

These percentages correspond, respectively, to one-third atmosphere percentage (approximately field capacity), two-thirds of available moisture remaining, one-third of available moisture remaining, one percent above fifteen-atmosphere percentage, and two percent below fifteen-atmosphere percentage. Fifteen-atmosphere percentage is an approximation of the permanent wilting percentage. An additional set of the 26-percent soil moisture treatments, to which no superphosphate or Rb⁸⁶-resin was added, served as controls. The five moisture treatments plus a control made a total of six treatments applied to the lower soil sections.

It was planned that the upper soil sections would be maintained as near optimum moisture content as possible until the roots of the corn plants became well established in the lower soil sections. Thereafter, no water would be added to one-half of the cans while the remainder were maintained at optimum moisture until the end of the experiment. The plants were to be harvested when the moisture in the lower soil sections of the dry cans was approaching the permanent wilting percentage.

Shortly after beginning the experiment, it became apparent that because of the high transpiration rates of the corn plants, the soil moisture in both sections of the can would be removed very rapidly. Therefore, the plan to allow one-half of the cans to dry to the permanent wilting percentage was altered, and all the upper soil sections were maintained at optimum moisture until the end of the experiment. It was decided that the plants were to be harvested when the lower soil sections were approaching permanent wilting percentage.

The original statistical design used was a randomized split-plot with three blocks. The plots consisted of two cans of one lower soil-section moisture treatment. These were split between one each of the

optimum and dry upper-moisture treatments. Each block consisted of six plots. Each combination of upper and lower soil moisture treatments was replicated three times, once in each block. However, the change in planned treatment of the upper soil section changed the design so that each treatment was replicated six times, twice in each block. The total number of cans used in this experiment was 36 -- six treatments, each replicated six times.

On 24 January 1953 corn was planted in soil in waxed paper cartons. After the corn plants were well established, they were thinned to three plants per carton. The corn was grown in these cartons until 5 March 1953 when the cartons were removed and the corn was transplanted into the cans in which the experiment was run.

As in the first experiment, the soil was separated into upper and lower sections by a waterproof asphalt-paraffin membrane as shown in figure 1. The corn plants and their associated soil were placed in the upper part of the cans, and enough air-dry soil to make the weights of the upper portions to six kilograms was added. The dry weights of soil in the upper and lower sections of the cans, including the soil associated with corn transplants, were approximately equal. The upper portion of the soil was wetted to settle it around the transplant.

The cans were arranged in three rows of twelve on a center bench in the greenhouse, with each row making up a block of the statistical design. The rows and the cans within the row were shifted to new positions each week to minimize shading effects.

The gypsum moisture blocks in the lower portions of soil were read once each week and a record of the readings kept. The upper soil sections were watered as observation indicated and a record kept of the amount of water added to each can.

The corn plants were grown in these cans for 7 weeks and harvested on 22 April 1953. At the time of harvest, the soil in the lower sections of all the cans had not approached permanent wilting percentage, but it was felt that the activity of the phosphorus would be too low to measure if the harvest was delayed longer.

The plants were dried and ground and samples were assayed for P^{32} and Rb^{86} and analyzed for total phosphorus.

RESULTS AND DISCUSSION

Experiment 1

The results obtained in the first experiment are given below.

1) The alfalfa and beet seedlings damped off soon after germinating, and these cans were discarded.

2) The wheat seedlings appeared to be infected by fungus and developed symptoms similar to foot rot of wheat. This delayed their establishment and development.

3) The corn germinated and grew vigorously for 8 weeks until harvest.

4) The roots of corn and wheat penetrated various distances into all but one of the lower soil sections which contained 11 and 13 percent moisture.¹ However, in only one case, did the roots penetrate into a lower section which contained 9 percent moisture. No roots were found in any of the other soil sections which contained 9 percent or less moisture.

5) The amount of P^{32} in the plant material was so small, and the radioactivity of the P^{32} had reached such a low level that it could not be measured accurately (see table 3).

The low activity indicated that the specific activity of P^{32} in the plant material should be increased if it was to be measured quantitatively. This could be done by decreasing the length of time between the beginning of the experiment and the assay of the plant

1. See footnote on page 22.

Table 3. Typical data obtained in assay of plant material for P³² in Experiment 1

Moisture content of lower soil section percent	Counter A		Counter B	
	Corn		Wheat	
	Wt. sample gms.	Counts per 100 seconds above background	Wt. sample gms.	Counts per 100 seconds above background
13*	0.400	15.3	0.300	5.4
	0.400	9.1	0.300	1.5
11*	0.400	9.4	0.300	5.8**
	0.400	7.2	0.300	3.4
9	0.400	9.8**	0.300	3.3**
	0.400	9.7**	0.300	1.8**
2.7	0.400	11.6**	-----	---

P in fertilizer to 1000 p.p.m. of P in plant material	-----	150	-----	39.7

* See footnote page 22.

** Roots of these plants did not penetrate into lower soil section.

material for radioactivity, by increasing the amount of radioactive fertilizer available to each plant, and/or by placing the radioactive fertilizer in soil with a moisture content of permanent wilting percentage or higher. See table 2 for data on activity of P^{32} in the fertilizer and soil.

It appeared that of the four plants used, corn would be the best plant to use in further experiments of this type since it was easily established, made rapid growth, and did not become diseased under the conditions of the experiment.

Experiment 2

In this experiment it was not possible to achieve the objectives. The membranes in about half of the cans were faulty. As in the previous trial, the activity in the plant material was low and a quantitative assay was possible on only three samples. The limited data obtained are given in table 4.

Since the amounts of phosphorus absorbed from the fertilizer could not be determined, the dry weights and phosphorus content of the plant material and the total amount of phosphorus absorbed per can were the only quantities measured. These were compared with the total amount of water applied per can to see if any trends could be detected (see table 5). No trends were indicated by any of these comparisons.

Since this experiment failed to produce any significant results, an examination of the reasons for this failure may prove helpful in designing other experiments of this type.

The principal difficulty encountered in both experiments was the extremely small quantity of radioactivity in the plant material at the time of assay. This could be corrected by the use of a higher ratio

Table 4. Counts obtained with a solution-counting type Geiger-Mueller Counter in the three samples from Experiment 2 which had enough activity for assay

Sample*	Wt. of sample gms.	Counts per second above background		
		Total	Rb ⁸⁶	P ³²
AW2	5.00	1.63	0.72	0.80
AX1	5.00	1.38	0.71	0.63
BX1	5.00	1.14	0.68	0.50
Others	5.00	0.00 to 0.72 counts/second		
Rb or P in fertilizer = to 200 p.p.m. in plant material	---	---	29.34	1.52

* AW2 and AX1 contained 30.4 percent moisture in the lower soil section. BX1 contained 26.1 percent moisture in the lower soil section. The membrane in AX1 was not effective.

Table 5. Averages for each soil moisture treatment (6 cans) of some quantities which were compared in Experiment 2

Moisture content of lower soil section treatment		Dry weight of plant material	Total P in plant material	Total P removed per can	Water used for irrigation
Desired Percent	Actual Percent	gms.	Percent of dry weight	mgms.	liters
26*	30.5	24.8	0.099	24.6	7.48
26	30.4	27.3	0.111	30.3	7.07
22	26.1	25.3	0.089	22.5	7.61
18	22.0	22.7	0.083	18.9	7.48
14	16.5	22.1	0.090	19.9	6.88
11	12.0	22.3	0.083	18.5	7.50

* Control — no fertilizer added.

of radioactive fertilizer to soil, by using a fertilizer with a higher specific activity of P^{32} , and by reducing the length of the period between the time the P^{32} is received and assay of the plant material for radioactivity (see table 2). The period between receipt and assay of the P^{32} may be shortened by having plants with well established root systems ready to be transplanted into the containers used, and by decreasing the amount of soil that the plant roots must permeate. The latter measure would also reduce the quantity of water that each plant must remove to bring the soil to a specified moisture percentage.

Another defect of the experiment was the failure of many membranes. It is believed that this was the result of high temperatures in the greenhouse and increased temperatures of the cans in the outer rows, on which direct sunlight was falling. The high temperatures softened the asphalt-paraffin mixture enough so that the seal between the membrane and the can could be broken if there was any stress on the membrane from the weight of the soil in the upper section. This could be corrected by protecting the cans from direct sunlight and by lowering the greenhouse temperature. Only one membrane failed in the first experiment, but the greenhouse temperatures were considerably lower because of seasonal differences in the amount of sunlight received.

A third defect of the experiment was the inadequate control of the soil moisture in the irrigated upper sections. It was desired to keep the moisture level of the upper soil sections near optimum throughout the experiment. Moisture control was made difficult by high temperatures and low humidity in the greenhouse and by increased temperatures of the cans which were in direct sunlight. All of these factors contributed to high rates of transpiration by the plants and high rates of evaporation from the soil. On some days one watering per day was not sufficient to

keep the plants supplied with ample water. This difficulty could be overcome by decreasing the temperature of the greenhouse, by protecting the containers from direct sunlight, and by controlling the humidity so as to minimize transpiration. This control of humidity should have the additional advantage of providing some control over the rate of moisture removal by plants from the lower soil sections. This would also provide some control of the length of time which roots are in contact with the soil solution of a soil at a given moisture content.

A fourth defect was the possibly inadequate aeration of the lower soil sections. The only possible gas exchange with the atmosphere, in those lower sections in which the membrane was effective, was around the wire from the moisture block which passed through a hole in the side of the can. A piece of rubber tubing filled the hole and made an almost air-tight seal around the wire. The reason for restricting the gas exchange was to minimize drying of the soil by evaporation. This defect could be corrected by aeration of the lower soil section with moist air to minimize evaporation.

Other improvements could be made to provide better control of environmental conditions. More uniform illumination of the plants would minimize shading effects and differences in transpiration rates. The use of tensiometers would give more precise control of the soil moisture level in the irrigated sections of the containers.

SUMMARY

A review of the literature on the effect of soil moisture conditions on nutrient absorption by plants reveals the following information about phosphorus. In many soils, an increase in soil moisture level is associated with increased phosphorus absorption. It is not known whether root-soil contact exchange or absorption from the soil solution is the predominant process operating to supply plant roots with soil phosphorus. Some workers take the view that principal plant absorption of phosphorus is probably from the soil solution. Factors which affect the phosphorus status of the soil solution are the total demand and rate of demand for phosphorus by plants, concentration of phosphorus in the soil solution, and rate of replenishment of the soil solution from solid phase phosphates. Assuming hypothetical complete removal by plants of phosphorus from the soil solution before any renewal occurs, calculations indicate that under some conditions complete renewal of the phosphorus in the soil solution would be necessary many times each day. Rate of replacement from the solid phase may be very rapid if surface phosphorus is involved or very slow if the dissolution of calcium phosphates is involved. Moisture content has a marked influence on the rate of diffusion of phosphate through soils. Solid phase calcium carbonate in calcareous soils has a depressing effect on the solubility of calcium phosphates.

Two experiments were conducted in the greenhouse to study the influence of soil moisture condition on the absorption of phosphorus by plants from calcareous soils. Plants were grown in large cans in which a fertilized portion of soil made to a desired moisture content

was separated from the irrigated portion by a waterproof, root-permeable membrane. Quantity of phosphorus absorbed from applied fertilizer containing P^{32} was used as the criterion for determining the influence of moisture.

Neither of these experiments yielded any significant information on the object of the study. The activity of P^{32} in the plant material was so low that it could not be determined if any of the fertilizer phosphorus had been absorbed by the plants. In the first experiment, corn and wheat roots penetrated various distances into soils with moisture contents slightly below the 15-atmosphere percentage. Corn was the only plant used which made vigorous growth and did not become diseased under the conditions of the experiment. In the second experiment, many of the membranes leaked. No trends could be detected in comparisons of percent phosphorus in the plant material and total phosphorus absorbed per can with total amount of irrigation water used per can. Other difficulties were encountered in the experiments.

The difficulties encountered and defects in these experiments are discussed. Methods for increasing the P^{32} activity in the plant material and suggestions for prevention of membrane leakage are recommended. Other improvements in technique are suggested.

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