Phosphorous Uptake by Oat Seedlings from Phosphorus Fertilizer Applied to a Subsoil as Affected by Soil Moisture

Dean E. Wesley
PHOSPHORUS UPTAKE BY OAT SEEDLINGS FROM PHOSPHORUS FERTILIZER APPLIED TO A SUBSOIL AS AFFECTED BY SOIL MOISTURE

A thesis submitted in partial fulfillment of the requirements for the degree Doctor of Philosophy, Major in Agronomy, South Dakota State University 1965
PHOSPHORUS UPTAKE BY OAT SEEDLINGS FROM PHOSPHORUS
FERTILIZER APPLIED TO A SUBSOIL AS
AFFECTED BY SOIL MOISTURE
Abstract

DEAN E. WESLEY

Under the supervision of Associate Professor Fred E. Shubeck

The uptake of phosphorus by oat seedlings from phosphorus
fertilizer applied to a silt loam subsoil was measured at various
levels of soil moisture stress using a short term constant moisture
experiment. Soil moisture tensions up to 6 atmospheres were devel­
oped by evaporation of the soil moisture to the desired moisture
tension in an environmental chamber.

"Fertilizer P" uptake decreased rapidly with initial increases
in soil moisture tension. Uptake of "fertilizer P" was a linear
function of the soil moisture content. The data suggest that thick­
ness of soil moisture films was the major factor controlling uptake.
Uptake of "fertilizer P" became inconsequential when the soil reached
the vicinity of the wilting point. The availability of the phosphorus
fertilizer was only affected by soil moisture tension during the
uptake period and not by soil moisture treatment during the initial
soil-fertilizer reaction period previous to phosphorus uptake.
This thesis is approved as a creditable and independent investigation by a candidate for the degree, Doctor of Philosophy, and is acceptable as meeting the thesis requirement for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser

Date

Head, Agronomy Department

Date
ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. Fred Shubeck for his guidance and encouragement throughout the course of the investigation. Appreciation is also expressed to Dr. D. Kenefick for his suggestions and the use of his facilities.

Special appreciation is expressed to the author's family for their sacrifice and patience.

Appreciation is expressed for the fellowship granted the author under the National Defense Education Act of 1958.

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This study is an outgrowth of a preliminary investigation by Hovland and Wesley (16) to determine environmental conditions required by plants to establish vegetative cover on highway backslopes. From the nutritional phase of this study it was determined that nitrogen and phosphorus were the only deficient elements in the four exposed subsoils that were investigated.

Deficient nutrients are supplied to exposed subsoils by the application of commercial fertilizer. The fertilizer is usually applied on the soil surface and seldom worked more than a few inches down into the soil. In the Northern Great Plains, this zone of fertilizer placement dries out rapidly and may remain dry for extended periods of time during the growing season. Phosphorus is relatively immobile in the soil and remains in the vicinity of application for an entire season. Under these conditions, plants growing in infertile subsoils may not be able to absorb enough fertilizer phosphorus to sustain growth even though moisture condition below the fertilized layer is sufficient. Therefore, it was essential to determine the effect of moisture stress on fertilizer phosphorus uptake and its relation to stand failures.

It was the purpose of this investigation to study the effect of increasing soil moisture tensions on the uptake of fertilizer phosphorus by plants grown on subsoil materials.
LITERATURE REVIEW

Nutrient Accumulation in Plants in Relation to the Soil Moisture Supply

The absorption and accumulation of nutrients from soils by plant roots are dependent on soil moisture. Wadleigh and Richards (28) have presented a detailed review of the subject. They concluded soil moisture content affects the availability of nutrients in two ways. First, changes in soil moisture films have an influence on nutrient availability by their effect on the concentration of the solutes in the soil solution. Second, moisture conditions influence the growth and physiological activity of root systems, thus the utilization of mineral nutrients by plants.

Emmert and Ball (11) found under greenhouse conditions that tomato plants grown in a "dry" soil accumulated nitrate nitrogen and potassium but showed a marked decrease in the uptake of phosphorus as compared to a soil with optimum moisture. In a later experiment conducted to check the previous work, Emmert (10) found that tomato leaves from plants grown in the greenhouse under relatively low soil moisture conditions (just enough moisture to keep the plants from wilting on normal days) were again higher in nitrogen and potassium and lower in phosphorus than those grown under moist conditions (soil moisture maintained at about field capacity). Connell et al. (5) obtained just the opposite effect with regard to phosphorus uptake. They investigated the effect of moisture tension on the uptake of nutrients by tomato plants from soils under greenhouse conditions. The soils were
irrigated to about 0.01 to 0.02 bars suction and then allowed to dry
down to 0.2, 0.6 or 5.0 bars suction before irrigating again. Their
results indicated that the drier the soil the greater the concentration
of P in leaf tissue.

Daniel and Harper (6) correlated effective seasonal rainfall
with total Ca and P content in alfalfa and prairie hay. The prairie
hay samples were collected over a period of five years and the alfalfa
samples were collected for two years. They reported that during peri-
ods of high rainfall the calcium content of the plants decreased and
phosphorus content increased. When the effective rainfall was low, the
Ca content of the plants increased and the phosphorus content decreased.

Haddock (14) conducted experiments on irrigated calcareous soils
for four years in Utah. Data were taken on the soluble phosphorus con-
tent of sugar beet petioles and were related to soil moisture condi-
tions and fertilizer application. His data showed a marked increase in
phosphorus content of beet petioles after irrigation. Immediately fol-
lowing sampling of petioles, soil moisture tension was decreased by
irrigation on two plots while a third plot remained unirrigated. The
plots were sampled approximately twenty days after irrigation. The
sampling showed a marked increase of phosphorus in the beet petiole on
the irrigated plots while the phosphorus content of the beet petioles
from the unirrigated plot continued to decline. The author concluded
that low soil moisture tension was closely associated with increased
quantities of soluble phosphorus in the sugar beet petioles.
Haddock and Linton (15) reported that phosphorus content of pea vines was influenced by soil moisture. The experiment was conducted in the field on calcareous Millville loam (pH 8.0) at Logan, Utah. Two methods of irrigation, sprinkle and furrow, were employed. Four soil moisture conditions were established: \( W_1 \) - irrigated once with five inches of water, \( W_2 \) - irrigated twice with eight inches of water, \( W_3 \) - irrigated eight times with ten inches of water, and \( W_4 \) - irrigated fourteen times with twelve inches of water. Their data showed that with an increase in the quantity of water applied there was a corresponding increase in P content of the pea vines.

In contrast, Jane (19) showed that with an increase in the amount of water applied to irrigated snap beans there was a decrease in P content. Miller and Duley (21) obtained the same result when they compared P content of corn leaves grown at optimum moisture levels to P content of leaves grown at minimum moisture levels.

The availability and uptake of soil and fertilizer phosphorus was studied by Power et al. (23) with dryland spring wheat under four moisture regimes in a field experiment in eastern Montana. The investigators found that phosphorus absorption by spring wheat was influenced by soil moisture and application of fertilizer phosphorus. A high supply of moisture at seeding time plus additional precipitation during the growing season increased total P uptake at all stages of growth. Fertilizer P uptake, however, was increased by additional precipitation only at the tillering stage. The authors suggested that fertilizer P uptake might be limited by dry surface conditions and
postulated that without effective precipitation between seeding and heading, fertilizer P would not be used by spring wheat.

Boatwright et al. (2) conducted an experiment designed to evaluate the influence of wetting of the soil on P uptake at various stages of plant growth. Spring wheat was grown in greenhouse pots watered from the bottom by capillarity. The surface two inches of soil was divided by a wax membrane to prevent capillary movement from below, and was watered until one week prior to P application. P32 was placed one inch below the surface of the dried layer at four growth stages. Water was added immediately and P uptake measured at various time intervals. Wheat plants did not absorb fertilizer P from a dry soil. There was a lag in fertilizer P uptake at all stages of growth after watering and the length of lag increased with age of plants. Fertilizer P was found in small amounts in plants grown on soil which had been wet less than eighty hours.

It was concluded that showers and weather conditions which do not allow the fertilizer zone to remain wet for three to four days probably contribute little to fertilizer P uptake by wheat.

Effect of Fertilizer Placement on Nutrient Uptake

Increased yields of corn were obtained from subsoil shattering and deep placement of fertilizer on Putnam silt loam soil in Missouri by Woodruff and Smith (32). They observed that nutrients became limiting before water during periods of drought and suggested that deep placement may correct this condition. Jamison and Thornton (18) found that lime and triple super phosphate applied to the subsoil gave
significant corn or alfalfa yield increases in some cases, but if the surface soil was adequately fertilized the increases over surface treatment alone were small and of questionable value. Kohnke and Bertrand (20) studied subsoil fertilization in some soils of Indiana. Yield increases from subsoil fertilization were substantial but not consistent. Englebert and Truog (12) studied subsoiling and deep incorporation of lime and fertilizer on Almena silt loam in Wisconsin. Yields of oats and corn were not increased in any case but increased vigor was noted in some years. Robertson et al. (24) reported increases in corn yields from subsoiling and deep placement of fertilizer on Florida soils with organic hardpans and compact surface clay zones. The advantages of deeper rooting and larger plants, gained from subsoil fertilization, were lost when drought periods lasted twenty-five days. But on soils with no root-impeding layer, surface placement of fertilizer was as good as deep placement.

In the research cited above, emphasis was placed on making the subsoil a more desirable medium for plant growth by deep placement of fertilizer. However, Eck and Fanning (9) approached the problem from the standpoint of making fertilizer more available to plants. The purpose of their study was "to determine the effect of fertilizer placement in relation to the soil moisture supply on yield and nutrient uptake of grain sorghum." The soil moisture content of the soil profile increased with depth. Phosphorus uptake increased with an increase in depth of placement of fertilizer, thus with increasing soil moisture content. Their conclusion was that phosphorus fertilizer should be
placed deep enough to insure its being in moist soil longer than the initial growth period if it is to be effective.

Haddock (14) conducted a field experiment on irrigated calcareous soils in Utah to determine the effect of deeper placement of fertilizer on the soluble phosphorus content of sugar beet petioles as related to soil moisture conditions. Fertilizer was broadcast on the surface or placed six inches below the surface and four inches to the side of the seed. He noted that when the soil was maintained in a moist condition, the broadcast treatment on the surface of the soil was readily available to sugar beet plants. When the soil was kept dry, phosphorus was found in relatively low quantities in beet petioles even when fertilizer phosphorus was broadcast or placed in bands six inches below the surface. The author felt that the data indicated that conditions of soil moisture are as important in making phosphorus available to sugar beets as application and placement of fertilizer.

**Nutrient Uptake by Plant Roots as Influenced by Moisture Using Short Term Constant Moisture Uptake Methods**

Field studies of the nature previously cited met experimental difficulties because the soil moisture content fluctuated and the equilibrium changed between adsorbed ions and those in solution. This is possibly the cause of the conflicting data cited. Short term, constant moisture type experiments tend to eliminate these difficulties and allow a more desirable control of the numerous interacting factors because the tension in the entire root zone is maintained relatively constant (7, 8, 13, 22).
Very few experiments have been published regarding the effect of soil moisture on the uptake of phosphorus using techniques by which moisture tension in the root zone has been held relatively constant throughout the uptake period.

Dean and Gledhill (8) used rye seedlings and an excised root technique to determine the effect of soil moisture on the absorption of phosphorus by plant roots. Their results were rather inconclusive. They observed a decline in P uptake as moisture tension decreased, but the reverse took place under some conditions.

Olsen et al. (22) investigated the absorption of phosphorus from surface soils by corn seedlings as affected by soil moisture tensions using a short term-constant moisture method. It was found that P absorption by corn seedlings decreased with increasing soil moisture tension and the uptake of phosphorus was a linear function of the soil moisture content. The factors which appeared to control P uptake in relation to soil moisture tension were thickness of moisture film, diffusion path length, degree of hydration and elongation of roots.

Review of Procedures for Establishment of Soil Moisture Tensions

The most difficult problem in working with constant moisture experiments is establishing a constant and uniform soil moisture tension throughout the soil mass. Methods of establishing moisture tension levels in soils used in short term uptake studies were reviewed and evaluated for possible use in this study.
Waugh and Corey (29) developed an apparatus designed to control the moisture level in soils used in short term uptake studies. The device was used to control moisture tensions in thin layers (3 cm. thick) of test soil.

A five-inch beveled filter disc was sealed into a six-inch glass funnel using rubber cement to make it airtight. A water column was made by attaching one end of a piece of Tygon tubing to the funnel and the other end to a reservoir. The entire assembly was filled with water. The filter disks used had air-bubbling valves of approximately 70 cm. of suction. Therefore, tension could be regulated to a maximum of 70 cm. of water suction by varying the length of the Tygon tubing water column. Two hundred grams of the soil to be tested (approximately 3 cm. in depth) was placed inside a bottomless, pint cottage cheese carton in contact with the filter disk. Water moved from the filter disk into the soil by capillarity and came to equilibrium at the given moisture tension.

This method could not be used in this study since P uptake was to be measured at tensions equivalent to field capacity (about 350 cm. H₂O) and greater.

Danielson and Russell (7) developed desired moisture tensions in the familiar pressure cooker and pressure membrane apparatuses. The equivalent of 600 g. of oven dried soil was used for preparing each level of soil moisture tension. After equilibrium in the pressure apparatus the soil was transferred to containers in which moisture studies were to be conducted. Olsen et al. (22), cited earlier,
used this method for establishing their soil moisture tension. The major faults in this method were (1) it was impossible when transferring the soil from the pressure apparatus to the containers to pack it uniformly in the container and yet not puddle the soil, and (2) the degree of puddling increased with increasing moisture content resulting in great differences in soil structure between moisture treatments.

Beaton and Read (1) established moisture tension levels from 0.4 to 6.0 bars by applying a measured volume of water, with a fine spray atomizer, to a known quantity of air-dry soil spread evenly in a thin layer on a sheet of rubber dental dam. This wetted soil was thoroughly mixed by kneading it while held in the rubber sheet. They then transferred the equivalent of 200 g. of air dry soil to round, 12 oz. waxed cardboard cartons and performed their uptake studies. The same difficulties arose using this method as with the method used by Danielson and Russell. Packing difficulties and degrees of puddling of the soil arose in handling of the soil during the mixing and transfer operation.

Therefore, for the establishment of any desired soil moisture tension, it was apparent that a method was needed which would not involve handling of the soil during the process of establishing the moisture tension and/or after moisture tension had been established.
MATERIALS AND METHODS

The subsoil studied was of the Moody series. "The Moody soils are well drained Chernozem soils of silty clay loam texture, formed under grassland in a subhumid climate. The parent material was calcareous wind deposited silty material (loess). The major portion of the loess is thought to have been deposited during the Wisconsin glacial periods" (30).

Collection of Field Samples

Bulk samples of subsoil materials belonging to the Moody series were collected in the fall of 1963 from an east facing backslope exposed in the construction of Interstate Highway 29. The site was located in the SW 1/4 sect 24 T103N R50W, Minneha County, South Dakota. The position in the backslope from which the sample was taken was equivalent to 6-8 feet below the original soil surface.

Methods of Soil Analysis

Air dry samples of the soil were studied with routine laboratory analysis to obtain some general information about the soils.

Moisture retention by the soil over the moisture tension range 1/3 to 15 atmospheres was determined with the pressure cooker and pressure membrane apparatus as outlined in U.S.D.A. Agriculture Handbook No. 60 (27).

Particle size distribution analysis followed essentially the method given in U.S.D.A. Agriculture Handbook No. 60 (27) except that the 50μ determination was added and the 20μ determination omitted.
Electrical conductivity of the saturation extract was determined with a conductivity bridge.

Calcium carbonate equivalent was determined by the method outlined in U.S.D.A. Agriculture Handbook No. 60 (27).

The pH of the saturated soil paste was determined by glass electrode.

The cation exchange capacity was characterized according to Russel and Stanford (25) with ammonium acetate.

Total nitrogen determination was made with the Kjeldahl method outlined by Jackson (17). A commercially prepared catalyst (CuSO₄+K₂SO₄) was used.

Environmental Chamber Procedure

First Experiment

Experiment 1 was conducted to study the effect of moisture tension and fertilizer P concentration on the uptake of phosphorus by plants. Oat seedlings were grown on calcareous silt loam subsoil material at five levels of moisture stress: 1/3, 1/2, 1, 3 and 6 atmospheres tension. Three levels of fertilizer phosphorus 0, 50, 100 mg. fertilizer P per 200 g. of air dry soil were studied at each level of moisture stress. Ammonium phosphate fertilizer containing 18, 20, 0 percent elemental N, P, K respectively was used for the source of phosphorus. In previous fertility studies (16) the test soil indicated only nitrogen and phosphorus deficiencies, therefore no other nutrients were added. The fertilizer material was ground to a powder and
mixed with the soil in a V-blender. Enough fertilizer was mixed with soil at one time to satisfy the needs for the entire experiment.

The five moisture tensions were obtained by the following procedure developed by the author.

First, a moisture retention curve was established for the soil with the pressure cooker and pressure membrane apparatuses. From this curve the percent soil moisture was plotted which corresponded to 1/3, 1/2, 1, 3 and 6 atmospheres tension.

Round, 12-ounce waxed cardboard cartons were filled with 200 g. of fertilizer treated air dry soil. (A sample of the air dry soil was also dried at 107°C and the percent moisture calculated for the air dry soil.) A given weight of water was then added to the soil to bring it to the 1/3 atmosphere percentage (field capacity) by carefully pouring it into the container of soil so as to cause a minimum of disturbance to the soil. The container of soil was then placed in an environmental chamber. The temperature was set at 60°F ± 1/2° and the relative humidity at 81% ± 2%. The moisture was allowed to evaporate from the soil under these conditions. The containers were weighed at twenty-four hour intervals. By keeping a record of the water loss from the soil and knowing the original weight of water added, it was possible to calculate the weight of water remaining in the soil. Thus by knowing the oven dry weight of the soil in the container and the amount of water remaining in the soil it was possible to calculate the

1 Isco Model E-1, Instrumentation Specialties Co., Inc., 5624 Seward Ave., Lincoln, Nebr.
percent moisture at any given time. When the soil reached the moisture percentage corresponding to the desired moisture tension (previously determined from the moisture retention curve), the container was sealed with a transparent plastic film (Handy Wrap, manufactured by Dow Chemical Co.) to prevent further evaporation before planting. Along with the preparation of the above soil, a carton with bottom removed was nested in an identical container with bottom intact and filled with 200 g. of unfertilized soil. This soil was also wet to 1/3 atmosphere percentage and treated exactly in the same manner as the container of fertilizer treated soil.

Oat seeds, selected for uniformity of size, were soaked for four hours in deionized water. The bottomless containers containing the unfertilized soil at a given moisture tension were nested in a container of fertilized soil at the same moisture tension. Fifty-three pre-soaked oat seeds were planted about 1 cm. below the surface of the soil in each container. A template was used to evenly distribute the seeds. The container of soil was covered with transparent plastic film and placed in the environmental chamber. A constant temperature of 60° F ± 1/2° was maintained in the chamber and the lights were on sixteen hours a day. See Figure 1.

The containers were opened nine days after planting and the seedling roots were washed free of soil. The roots and shoots were excised from the seeds, oven dried at 65°C and weighed. Roots plus shoots were ground to pass through a 40-mesh screen in a micro-Wiley mill. Phosphorus content of the plant material was then determined.
Figure 1. Upper left: Placement of the unfertilized soil in contact with the fertilized soil. Upper right: Template used to aid in planting of the oat seeds. Lower: Container covered with plastic film after planting to prevent further evaporation of soil moisture.
The experiment was run as a 3x5 factorial (3 levels of fertilizer P and 5 levels of moisture tension) in a randomized complete block design with three replications. Due to the limited space in the growth chamber, replications had to be run at separate times (4, 26).

**Second Experiment**

To measure the effect of wetting and drying of the soil on the availability of fertilizer phosphorus to plants, a second experiment was conducted. One level of fertilizer phosphorus, 50 mg. P per 200 g. of air dry soil, and two moisture tensions, 1/3 and 1 atmosphere, were used.

The same procedure was followed as in experiment 1 except the fertilizer treated soil was put through two wetting and drying cycles. Each cycle consisted of wetting the soil to 1/3 atmosphere tension and allowing it to dry to 15 atmosphere tension. At the end of the second cycle the tensions were adjusted to 1/3 or 1 atmosphere. The comparison treatments were the same except the soil was maintained at a constant moisture tension throughout the course of the experiment. The experiment was run as a $2^2$ factorial in a randomized complete block design with three replications.

**Determination of Phosphorus in Plant Material**

The ground plant material was dried for twenty-four hours at 65°C and 0.10 g. of plant material was used for the analysis. The procedure used was a modified method by Blancher (3) of the Vanadomolybdophosphoric-Yellow Color method given in Jackson (17). The intensity of the color
was read on the Beckman DU spectrophotometer at 470 m\(\mu\). Samples were run in duplicate.
RESULTS

General Soil Analysis

Air dried samples of the soil material were studied with routine laboratory analyses to characterize some of its properties.

Chemical properties of the soil material

Results of chemical determinations made on the soil material are given in Table 1.

Table 1. Some chemical properties of the subsoil under investigation.

<table>
<thead>
<tr>
<th>pH (Saturated Paste)</th>
<th>CaCO₃ Equiv. %</th>
<th>C.E.C. me/100 g.</th>
<th>Electrical Conductivity (ECx10³)</th>
<th>Total Nitrogen %</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>16.24</td>
<td>12.4</td>
<td>0.38</td>
<td>0.025</td>
</tr>
</tbody>
</table>

As indicated by the pH of 7.7 and a calcium carbonate equivalence of 16.24% this soil material is alkaline and contains appreciable quantities of free alkaline earth carbonates.

The soluble salt content, as indicated by the electrical conductivity, does not appear to be excessive for plant growth.

The cation exchange capacity (C.E.C.) of 12.4 me/100 g. was consistent with comparable C.E.C. data reported for the Moody soil series (30).

The total nitrogen content was very low, 0.025%.
Particle size distribution and moisture retention properties of the soil material

Results of the particle size distribution analysis are given in Table 2. The sand fraction was taken as particles greater than 50µ, the silt fraction as particles less than 50µ but greater than 2µ and the clay fraction as those particles less than 2µ. The results indicate the textural class of the soil material to be a silt loam.

Table 2. Mechanical analysis of subsoil under investigation.

<table>
<thead>
<tr>
<th>Depth (feet)</th>
<th>Particle size distribution</th>
<th>Textural Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand 50µ</td>
<td>Silt 50-2µ</td>
</tr>
<tr>
<td>6.8</td>
<td>6.9</td>
<td>68.0</td>
</tr>
</tbody>
</table>

Moisture retention data are given in Table 3. From this data a moisture retention curve was plotted and is shown in Figure 2. The soil material retained 22.7% of the moisture within the available moisture range (1/3 to 15 atmospheres moisture tension).

Table 3. Moisture content of subsoil under investigation at various moisture tensions.

<table>
<thead>
<tr>
<th>Atmospheres Tension</th>
<th>0</th>
<th>1/3</th>
<th>1</th>
<th>3</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Moisture</td>
<td>57.5</td>
<td>32.5</td>
<td>18.0</td>
<td>14.7</td>
<td>9.8</td>
</tr>
</tbody>
</table>
Figure 2. Moisture retention curve for the subsoil under investigation. Bar on right shows available moisture range (1/3 to 15 atm. tension).
Preliminary Investigation of the Environmental Chamber Procedure

Preliminary to the main investigation two questions had to be answered regarding the method of establishing a moisture tension in the soil material. First, could the moisture content of the soil be accurately calculated from water loss data. This calculation had to be reasonably accurate since this was the only way of knowing when the soil in the container had reached the desired moisture content. Second, did a moisture gradient exist vertically through the soil and if so to what extent. This was important since the assumption was made that the roots would absorb phosphorus from a soil at uniform moisture tension. The data in Table 4 give the results of an investigation conducted to answer these questions. The data indicate that moisture distribution through the soil was for all practical purposes constant and that moisture content could be calculated from water loss data.

Table 4. Vertical distribution of soil moisture through soil material that has been brought to selected moisture content by evaporation in the environmental chamber. (Total depth of soil was 3.0 cm.)

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Depth of soil sampled (cm.)</th>
<th>Actual moisture content (%)</th>
<th>Predicted soil moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 1.5</td>
<td>23.6</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td>1.5 - 3.0</td>
<td>23.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0 - 1.5</td>
<td>13.8</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td>1.5 - 3.0</td>
<td>13.9</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0 - 1.5</td>
<td>9.3</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>1.5 - 3.0</td>
<td>10.1</td>
<td></td>
</tr>
</tbody>
</table>
First Experiment - Effect of Moisture Tension and Phosphorus Fertilizer Level on Dry Weight of Plants and Phosphorus Uptake

Effect on dry weight

The dry weights of the plant material were calculated on a 50 plant per culture basis to correct for differences in germination. The data are given in Table 5.

Table 5. Effect of moisture tension and fertilizer phosphorus level on the dry weight per 50 oat seedlings.

<table>
<thead>
<tr>
<th>P fertilizer level</th>
<th>Grams of plant material produced per 50 plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>mg. P per pot</td>
<td>Moisture Tension - atmospheres</td>
</tr>
<tr>
<td></td>
<td>1/3</td>
</tr>
<tr>
<td>0</td>
<td>0.760</td>
</tr>
<tr>
<td>50</td>
<td>0.740</td>
</tr>
<tr>
<td>100</td>
<td>0.740</td>
</tr>
<tr>
<td>mean</td>
<td>0.747</td>
</tr>
</tbody>
</table>

L.S.D. (.05) = .056 g.

There was no significant change in mean dry weight when the moisture tension was increased from 1/3 to 1 atmosphere or from 3 to 6 atmospheres. A significant decrease in mean dry weight did occur when the moisture tension was increased from 1 to 3 atmospheres.
Differences in mean dry weight were nonsignificant between phosphorus fertilizer levels.

Effect on phosphorus uptake

Phosphorus uptake data for the soil material at three phosphorus fertilizer levels and five moisture tension levels are shown in Table 6. The increases in mean phosphorus uptake over that of the control of both the 50 mg. and the 100 mg. levels of phosphorus fertilizer were significantly greater at the 1% level. The increase in mean phosphorus uptake from the 100 mg. level of phosphorus fertilizer over uptake from the 50 mg. level was significant at the 5% level.

Table 6. Uptake of P by oat seedlings as affected by moisture tension and P fertilizer levels.

<table>
<thead>
<tr>
<th>P fertilizer level - mg. P per 200 g. air dry soil</th>
<th>P uptake - mg. P per g. dry weight</th>
<th>Moisture Tension - atmospheres</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.9, 5.8, 5.8, 6.2, 5.8, 5.9</td>
<td>1/3, 1/2, 1, 3, 6, mean*</td>
</tr>
<tr>
<td>50</td>
<td>12.6, 10.0, 7.6, 7.1, 6.4, 8.7</td>
<td>L.S.D. (.05) = 0.8 mg.</td>
</tr>
<tr>
<td>100</td>
<td>13.5, 11.1, 8.6, 7.8, 7.3, 9.7</td>
<td>L.S.D. (.01) = 1.8 mg.</td>
</tr>
<tr>
<td>mean*</td>
<td>10.7, 9.0, 7.3, 7.0, 6.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a, b, c, cd, d</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L.S.D. .05 = 0.6 mg.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L.S.D. .01 = 1.1 mg.</td>
<td></td>
</tr>
</tbody>
</table>

*Any two means not having letters in common are significantly different at the 5% level by L.S.D. comparisons. Any two means with the same letter are not significantly different.
There was a significant decrease in mean phosphorus uptake when the moisture tension was increased from 1/3 to 1/2 atmosphere, 1/2 to 1 atmosphere, and 1 to 6 atmospheres. The differences in mean phosphorus uptake between 1 and 3, and 3 and 6 atmospheres were non-significant.

The data presented in Table 7 are the increases in phosphorus uptake at the 50 and 100 mg. levels of phosphorus fertilizer above the uptake at the 0 mg. level. This increase in phosphorus uptake will be termed "fertilizer P" in this paper.

Table 7. "Fertilizer P" uptake by oat seedlings as affected by moisture tension and P fertilizer level.

<table>
<thead>
<tr>
<th>P fertilizer level -</th>
<th>Fertilizer P uptake - mg. P per g. dry weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>mg. P per 200 g. air dry soil</td>
<td>Moisture Tension - atmospheres</td>
</tr>
<tr>
<td></td>
<td>1/3</td>
</tr>
<tr>
<td>50</td>
<td>6.7</td>
</tr>
<tr>
<td>100</td>
<td>7.6</td>
</tr>
<tr>
<td>mean</td>
<td>7.2</td>
</tr>
</tbody>
</table>

The effect of moisture tension and level of phosphorus fertilizer on the uptake of "fertilizer P" is shown in Figure 3.

The rate of decrease in phosphorus uptake with increasing moisture tensions was much greater at low moisture tensions than at high moisture tensions.
Figure 3. Effect of moisture tension and phosphorus fertilizer level on "fertilizer P" uptake by oat seedlings.
An important observation was the sharp effect on reducing "fertilizer P" uptake due to increasing the soil moisture tension from 1/3 to 1 atmospheres. Using the 50 mg. level of phosphorus fertilizer as an example, uptake of "fertilizer P" decreased from 6.7 to 4.2 mg. as the moisture tension increased from 1/3 atmosphere to 1/2 atmosphere and to 1.8 mg. at 1 atmosphere.

The shapes of the two curves in Figure 3 were similar and closely resembled the moisture desorption curve for soil material. Therefore, absorption of "fertilizer P" must be a linear function of the soil moisture percentage on a dry weight basis. This relation was tested and is shown in Figure 4. The correlation coefficient of 0.99 is significant at the 1% level.

The slopes of the two curves in Figure 4 were equal. This indicates there was no interaction between phosphorus level and moisture tension within the given moisture range and phosphorus fertilizer levels. Therefore, under these conditions, an increase in phosphorus fertilizer level increased the uptake of "fertilizer P" by an equal amount over the given moisture range.

The curves in Figure 4 were extrapolated to zero "fertilizer P" uptake. Uptake ceased at 12.1 and 9.4 percent moisture for 50 and 100 mg. phosphorus fertilizer levels, respectively (15 atmosphere percentage was 9.8%).
Figure 4. Relation of "fertilizer P" uptake by oat seedlings to percent by weight of soil moisture for two levels of phosphorus fertilizer.
Second Experiment - The Effect of Fluctuations in Soil Moisture Tensions During Initial Soil-Fertilizer Reaction Period on Subsequent P Uptake

To measure the effect of wetting and drying of the soil on the availability of phosphorus fertilizer to plants, a second experiment was conducted. The results of this experiment are given in Table 8 and illustrated in Figure 5.

Table 8. Effect of fluctuating moisture tension during the initial soil-fertilizer reaction period on subsequent P uptake by oat seedlings.

<table>
<thead>
<tr>
<th>Moisture Tension (atm.)</th>
<th>P uptake—mg. per culture*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>12.3 a</td>
</tr>
<tr>
<td>1</td>
<td>7.3 b</td>
</tr>
<tr>
<td>Moisture fluctuated</td>
<td>11.6 a</td>
</tr>
<tr>
<td>Moisture constant</td>
<td>6.8 b</td>
</tr>
</tbody>
</table>

*Any two means not having letters in common are significantly different at the 1% level by the F test. Any two means with the same letter are not significantly different.

As in experiment 1, highly significant differences in phosphorus uptake were found between moisture levels. However, no significant differences in phosphorus uptake were found between the fluctuated soil moisture treatment and the constant soil moisture treatments. Fluctuations in soil moisture tension during the initial soil-fertilizer reaction period had no significant effect on phosphorus uptake.
Figure 5. Effect of moisture tension fluctuation during initial soil fertilizer reaction period on P uptake at two moisture tensions.
DISCUSSION

New Method for Establishing a Desired Moisture Tension

A new method was developed for establishing desired moisture tensions in soils for use in short-term, constant-moisture measurements of nutrient absorption by plant roots. Various methods which have been reported in the literature (1, 7) involved handling the soil during the process of establishing the moisture tension and/or after moisture tension has been established when transferring it to the containers to be used in the uptake study.

Handling caused considerable puddling of the soil, especially at the lower moisture tensions. In addition it was impossible to get uniform packing of the soil in the container to which it was transferred.

With the new method of establishing soil moisture tension, the soil was not handled during the entire operation—from the adjustment of the moisture tension to the harvesting of the plants. Since no handling of the soil was involved, puddling of the soil and uniform packing in the containers were not problems.

Consequently, this new method gives a more representative sample. Soil structure is maintained and is more uniform between treatments.

Effect of Moisture Tension and Phosphorus Fertilizer Level on Phosphorus Uptake

Considerable work by previous investigators supplies inconsistent evidence of the relationship between moisture supply and
phosphorus nutrition of various crops. Some workers have found a decrease in phosphorus uptake with a decrease in soil moisture content, while others have found an increase in phosphorus uptake with a decrease in soil moisture content. The new short-term constant moisture uptake procedure used in this work gives a more accurate evaluation of the relationships between soil moisture tension and ion uptake by roots than older methods, because the tension in the entire root zone is maintained relatively constant.

The data in Figure 3 show clearly that "fertilizer P" uptake by oat seedlings decreases as soil moisture tension increases.

Olsen et al. (22), using a technique different from that used in this work, found the same trend for phosphorus uptake by corn seedlings. These observations also agree with results reported for Rb uptake from soil by corn seedlings (7) and also for Rb uptake by broad-beans from sand containing low concentrations of Rb (31).

Moisture stress could be explained to affect phosphorus uptake in two ways. It could affect the growth and physiological activity of the plant, thus the utilization of mineral nutrients by the plant and/or it could affect the physical movement of the phosphorus through the soil to the plant roots.

It does not seem likely that the large decrease in "fertilizer P" uptake with initial increases in moisture tension could be attributed to the effect of moisture stress on the growth and physiological activity of the plants. A large decrease in "fertilizer P" uptake occurred with an increase in moisture tension from 1/3 to 1 atmosphere.
This is only an increase in tension of 2/3 of an atmosphere. There was no significant decrease in plant weight with an increase in soil moisture tension from 1/3 to 1 atmosphere. "Fertilizer P" uptake was a linear function of moisture content of the soil.

Therefore, it appears that the decline in "fertilizer P" uptake with an increase in soil moisture tension was due primarily to a restriction in the physical movement of the phosphorus through the soil to the plant roots. At 1/3 atmosphere moisture tension, the moisture films will be relatively thick and continuous throughout the soil. Under these conditions a root in contact with the films is able to maintain an efficient transfer of phosphate ions from the soil solution to the root. As phosphate ions are depleted from the soil solution in immediate contact with the root, others diffuse in to replace them. Such moisture films permit the maximum exchange of ions demanded by the equilibra conditions existing within and between the soil solution and the root. As the moisture content of the soil approaches the wilting point (15 atm.) the water films exist primarily as thin, isolated wedges. The movement of phosphate ions through the soil under such conditions will be slow, since only a very small area of the pore system is effective in permitting diffusion of ions through the soil. Under these conditions a root will deplete the soil water adjacent to it of its phosphate ions; however, any further transfer of ions from more distant points in the soil will be severely restricted due to the lack of continuous moisture films.
The effect of increasing the phosphorus fertilizer level in the soil was to increase the uptake of "fertilizer P" by an equal amount over the given moisture range. At the high phosphorus fertilizer level, "fertilizer P" uptake per g. of plant material changed from a low of 1.5 to a high of 7.6 mg. with an increase in available water from 6 atmospheres tension to 1/3 atmospheres tension. At low phosphorus levels the uptake of phosphorus per g. of plant material was increased from a low of 0.6 to a high of 6.7 mg. Therefore, for plants subject to alternate periods of low and high amounts of available water, deficiencies might occur at the low P level, whereas the high P levels could supply the P needs of the plants.

Upon extrapolation of the curves in Figure 4 to zero "fertilizer P" uptake it was found that "fertilizer P" uptake became inconsequential when the soil reached the vicinity of the wilting point (15 atmospheres tension). This is consistent with the findings of Beck and Fanning (9) and Boatwright et al. (2).

It was evident from the second experiment that the availability of the phosphorus fertilizer was only affected by the moisture tension during the uptake period and not by the soil moisture treatment during the initial soil fertilizer reaction period previous to phosphorus uptake.

The decrease in "fertilizer P" uptake with increasing soil moisture tensions point to some practical implications in the fertilization of phosphorus deficient subsoils in the Northern Great Plains where the zone of fertilizer placement dries out rapidly and remains dry for
extended periods of time during the growing season. Under such conditions phosphorus uptake from applied phosphorus fertilizers would be greatly limited and plants could undergo phosphorus deficiencies even though there was sufficient moisture below the fertilized zone.

In light of this experiment it seems probable that a more efficient use of P fertilizers may be had in phosphorus deficient subsoils by placing a starter application of fertilizer with the seed to supply the plant during initial stages of establishment with needed phosphorus and placing the bulk of the fertilizer deeper in the profile where it will be in contact with a more uniform moisture supply and thus be more consistently available to the plant.
CONCLUSIONS

1. "Fertilizer P" uptake decreased rapidly with initial increases in soil moisture tension.

2. Uptake of "fertilizer P" was a linear function of the soil moisture content. Thickness of moisture films was a possible factor controlling "fertilizer P" uptake.

3. Uptake of "fertilizer P" became inconsequential when the soil reached the vicinity of the wilting point.

4. Availability of phosphorus fertilizer was only affected by soil moisture tension during the uptake period and not by soil moisture treatment during the initial soil fertilizer reaction period previous to phosphorus uptake.

5. The new technique used to establish moisture tensions in soils for use in short-term, constant moisture measurements of nutrient absorption by plant roots was very satisfactory. Soil structure was not destroyed and it allowed for more uniform and representative treatments.


