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TO PLANT SPECIES DIFFERING IN MINERAL
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Availability of phosphorus in phosphate rock to plant

species differing in mineral composition

by

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I. INTRODUCTION

The availability of the phosphorus in phosphate rock is generally lower than that of phosphorus in superphosphate. Phosphate rock is a better source of phosphorus for plants in acid soils than in neutral or alkaline soils, presumably because its solubility increases with an increase in the acidity. In a given soil, the availability depends on the plant species. For example, buckwheat and lupine are much more efficient in utilizing phosphorus from phosphate rock than are barley or wheat.

There is some evidence (a) that soil acidity may be altered by growth of crops, (b) that the pH of the medium near the roots during the growing season may differ from the pH of the medium at a distance, (c) that the alteration of soil pH by plants depends on the kinds of salts (or fertilizers) supplied, and (d) that differences among plant species in relative uptake of cations and anions may affect the acidity of the medium. From this evidence, it may be inferred that an important factor in determining the differences in availability of the phosphorus of phosphate rock to different plant species is the relative uptake of cations and anions, which affects the ionic environment in the soil and the solubility of the phosphate rock.

The experimental work reported in this thesis was conducted to test the hypothesis that the differences among

plant species in the availability of phosphorus of phosphate
rock are related to the differences in relative uptake of
cations and anions among species and to the associated effects
in the soil.

II. LITERATURE REVIEW

Sand-culture experiments by Balentine (1894), Merrill
(1898), and Truog (1916), soil culture experiments by Fried
(1953), Murdock and Seay (1955), McLean (1956), and Gladkova
(1969), and a field experiment by Ames and Kitsuta (1932) have
demonstrated that the availability of the phosphorus in phos-
phate rock may differ among plant species. Fried (1953),
using P^{32}-labeled phosphate rock and correcting for the effect
of size and extensiveness of the root absorbing surface, re-
ported that the "feeding power" of plants for phosphorus added
in phosphate rock decreased in the following order: buckwheat,
legumes (alfalfa, crotalaria, ladino clover), and grasses
(orchardgrass, bromegrass, perennial ryegrass, millet, and oat).

A. Truog's Theory

Truog (1915, 1916, 1922) used the laws of mass action and
chemical equilibrium to explain the different feeding power of
plant species on phosphate rock. He explained that the reac-
tion making the phosphorus in phosphate rock available to
plants was largely a reaction between carbonic acid and the
tricalcium phosphate in the phosphate rock to form dicalcium
phosphate and calcium bicarbonate. If none of the products
of the reaction were removed from solution, the reaction soon
reached a state of equilibrium. If the dicalcium phosphate
was removed but the calcium bicarbonate was removed only in

part, the reaction would proceed a little further but would soon come to a state of equilibrium due to the accumulation of the calcium bicarbonate. When this point was reached, further solution of the phosphate rock would be prevented. This condition was inferred to prevail with plants low in calcium. In such cases, the plants would soon suffer a deficiency of soluble phosphate. If both the products of the reaction were simultaneously and continually removed in the proportion in which they were produced, between the carbonic acid and the phosphate rock would continue, and the plants would have a continuous supply of soluble phosphate along with soluble calcium bicarbonate. This condition was inferred to prevail, at least in part, with plants containing a high calcium content. Such plants should also be strong "feeders" on phosphate rock.

Chirikov (1916) reported that phosphate rock alone gave up phosphorus to barley but the phosphorus became nonassimilable when calcium salts were added. Peas, buckwheat, and lupine were less sensitive to calcium salts than was barley. He reported also that potassium chloride and ferric chloride increased the feeding power of barley for the phosphorus of phosphate rock. Magnesium sulfate had no effect. Sodium sulfate and sodium chloride had an action similar to that of potassium chloride.

Bauer (1920) grew corn in sand cultures treated with phosphate rock or superphosphate as the source of phosphorus and with sodium nitrate or ammonium nitrate as the source of nitrogen. He leached some of the cultures with the idea that the

leaching should remove the accumulation of calcium bicarbonate postulated by Truog and hence should increase the uptake of phosphorus by the corn. He found that the phosphorus uptake from the phosphate rock was increased by leaching and that a large quantity of soluble calcium had been leached out. Bauer and Haas (1922) added calcium carbonate in different quantities to sand cultures that had been supplied with phosphate rock as a source of phosphorus and then subjected some of the cultures to leaching. They reported that the dry weight of soybeans grown as a test crop was increased by leaching and that it decreased with an increase in the pH of the cultures.

Murdock and Seay (1955) studied the availability of phosphorus and calcium from phosphate rock and superphosphate to red clover and wheat in the greenhouse. They found that red clover was a stronger feeder on the phosphate rock than was wheat. The ratio of P^{32} to Ca^{45} (derived from the phosphate rock) was 4.5 in wheat, 1.2 in clover, and only 0.44 in the phosphate rock, from which they concluded that the plants took up phosphorus more readily than calcium from the phosphate rock.

Bartholomew (1928) grew 11 plant species on the same substrate and nutrient medium used by Truog. He reported very low dry-weight yield of plants on the phosphate-rock cultures. The dry-weight yields obtained with phosphate rock plus calcium chloride were almost equal to those obtained with phosphate rock alone. Only rice, cotton, vetch, and sweet clover yielded enough sample to permit analyses for calcium and phosphorus.

All four species had calcium contents over 1%, which would indicate they were strong feeders on phosphate rock, according to Truog. Only vetch and sweet clover were found experimentally to be strong feeders on phosphate rock. Rice and cotton did not have this capability.

B. Solubility of Phosphate Rock

Teakle (1928) reported that the solubility of precipitated calcium phosphate increased as the pH decreased. From the minimum at pH 10, the solubility increased gradually as the pH was decreased to 6 and then increased rapidly as the pH was decreased below 6. In the presence of excess calcium ion, the trend of solubility of calcium phosphate with pH was the same, but the concentration of phosphate was much depressed. Gaarder (1930) reported that the solubility of phosphate in a calcium phosphate suspension at pH 6.5 was nearly zero and that it increased as pH decreased. The increase in solubility was gradually down to pH 5.5 and then rapid at lower pH values.

Benne, Perkins, and King (1936) reported the minimum solubility of precipitated calcium phosphate of pH 7.5. The trend of the solubility was comparable to the trends reported by Teakle and Gaarder. Stelly and Pierre (1943) equilibrated phosphate rock with solutions of various pH values and reported that the solubility of phosphate rock at about pH 6.5 was nearly zero. The solubility gradually increased from pH 6.5 down to about 5.5 and increased rapidly from about pH 5.5 to about pH 2.

C. Availability of Phosphorus in Phosphate
Rock in Relation to Soil Acidity

In experiments with soils and crops, the availability of phosphorus added in phosphate rock has been found to be greater in acid soils than in neutral or alkaline soils. The exact trend of response with soil pH depends on the soil and the crop.

Slater and Barnes (1935) conducted an experiment to test the efficiency of phosphate rock on unlimed soil (pH 5 to 5.5) and limed soil (pH 7 to 7.5) in Ohio. They reported the response to phosphate rock relative to the response to superphosphate supplying an equal quantity of phosphorus and found that for wheat the value was 40% for acid soil (pH 5 to 5.5) and 0% for limed soil (pH 7 to 7.5).

Bartholomew (1937) grew sudangrass on a silt loam soil, the pH of which had been adjusted to range from 4.3 to 7.1. The soil was supplied with as much as 130 milligrams of phosphorus per culture as phosphate rock or superphosphate. From his data, the ratio of the availability coefficient of phosphorus added as phosphate rock to the availability coefficient of phosphorus added as phosphate rock to the availability coefficient of phosphorus added as superphosphate was found to be highest in soil of pH 4.8 and to decrease as the pH was increased or decreased.

Joos and Black (1951) grew sudangrass in mixtures of bentonite and sand adjusted to various pH values and supplied with

164 milligrams of phosphorus as phosphate rock or up to 44 milligrams of phosphorus as superphosphate per culture. They reported that the availability of phosphorus added as phosphate rock decreased as the pH of the medium was increased from 4.6 to 6.6. Ellis, Quader, and Truog (1955) conducted a similar experiment in which the pH range was 4.9 to 7.4. Their data show that the ratio of the availability coefficient of phosphorus in phosphate rock to that of phosphorus in superphosphate was highest at pH 5.5 and decreased at higher and lower pH values.

In an investigation involving different soils in the pH range from about 5.2 to 8, Peaslee (1960) found that the ratio of the availability coefficient of phosphorus in phosphate rock to that of phosphorus in superphosphate (R) could be expressed to a good approximation ($r^2 = 0.99$) by the equation R/pOH = a + bR, where a and b are constants. The value of R was near zero at pH 8 and approached unity at pH 5.2.

In a field experiment on a fine sandy soil in Florida, Neller (1956) added various quantities of sulfur to lower the pH from 7.4 to 4.6. He reported that uptake of phosphorus by oats from phosphate rock increased from as low as 28.6 g per acre at pH 7.4 to 182.3 g per acre at pH 4.6.

It has been noted that factors other than the hydrogen-ion activity may be involved in the dissolution of phosphate rock. Johnston (1952, 1954a, 1954b) studied the solubilization of "insoluble" phosphate by various organic compounds. He

reported that a large number of organic acids were capable of dissolving tricalcium phosphate but that the pH of the solvent acids and the concentration of dissolved phosphate were not well correlated. The effect of calcium, noted previously, is another factor to which some attention has been given.

D. Differential Acidity of Media in Relation to Plant Species

Hartwell, Pember, and Merkle (1919) found that the quantity of calcium oxide required to neutralize the soils on which different crops had been grown varied from crop to crop. The crops were as follows in order from the highest lime requirement to the lowest: rye, buckwheat, beet, onion, and redtop.

Smith and Robertson (1931) measured the pH of soils that were fallowed and cropped to potato after treatment with sulfur or calcium hydroxide to adjust the pH from 4 to 8. They found that the acidity of the uncropped soils increased by more than one pH unit during the growing season and that the change was less marked in the cropped soils. By the end of the growing season the difference had practically disappeared, and the acidity of the soil approached the value found at the beginning of the season. Aso (1932) found that the pH of soil after cultivation to barley was lower than it was before planting but that for rice the trend was the reverse.

Koslowska (1934) grew 39 species of plants in culture solutions buffered at pH 3 to 8 with Na_2HPO_4 and reported that

the pH changed to different degrees with different species
when the solutions were dilute. The changes in pH were slight
with full strength of Knop's solution and were nonexistent
with solutions 10 times the concentration of Knop's solution.

E. Differential Acidity of Media in Relation to Genetic Make-up of Plant Varieties

Lyness (1936) grew two inbred varieties and four hybrids
of closely inbred lines of yellow dent corn in sand cultures
providing various kinds of nutrient solutions. He found that
when the culture solutions were displaced after 83 days the pH
of the solutions differed among varieties. The differences in
acidity were more pronounced in the dilute solution than in
the more concentrated solution.

Subramoney and Sankaranarayanan (1964) reported that acid-
tolerant varieties of rice seeds during germination increased
the soil pH to 5.0 - 5.5 even from a pH as low as 3.2, but
those varieties not resistant to acid conditions failed to
increase the soil pH, and their germination and growth were
affected. Foy et al. (1965a) found that aluminum-sensitive
wheat and barley varieties had zones of lower pH adjacent to
the roots or else absorbed more aluminum at the same pH than
did less sensitive genotypes. Foy et al. (1965b) planted
aluminum-sensitive and tolerant wheat varieties in culture
solution. They found that the sensitive varieties lowered the
pH of the solution, but the tolerant varieties raised the pH

of the solution, resulting in a difference as large as 0.7 pH
unit in the nutrient solution.

F. Differential Acidity of Media in Relation to Root Excretions

Russell and Appleyard (1915) studied the composition of
soil air. They reported no significant differences in the
carbon dioxide content of soil air in which different species
of plant were grown. Dustman (1925) found that the amounts of
CO_2 evolved from plant roots in soil cultures in 6 weeks were
380, 251, 158, 143, 133, and 112 mg with corn, soybean, buck-
wheat, field pea, rye, and barley, respectively. In sand cul-
ture, the amounts of CO_2 evolved in 4 weeks were 3826, 2761,
1477, 3048, 2230, and 2642 mg per culture of corn, soybean,
buckwheat, field pea, rye, and barley, respectively.·

Washuttl (1970) found that when excised roots of three
plant species were placed in various solutions the greatest
drop in pH occurred within the first 30 minutes. Changes were
smaller in aerated solutions than in nonaerated solutions and
were smaller in Hoagland's solution than in water or KNO_3
solution, which suggested that in a short period of contact
the respired CO_2 had more influence on changes in the pH than
did other metabolic processes. The differences in pH of solu-
tions among species were marked at 30 minutes but almost zero
after 2 hours. The differences in pH were greater in KNO_3 and
water than in Hoagland solution.

Prjanischnikow (1934) conducted various experiments in an attempt to determine why the capability to use the phosphorus of phosphate rock was so much more pronounced in lupines than in oats. He found that the pH of the nutrient medium in sand cultures was much lower and the concentration of phosphorus in solution was accordingly much higher in cultures planted to lupines than in those planted to oats. When oats were grown in competition with lupines, the oats made much better growth and had a much higher phosphorus percentage than when grown alone.

Peterburgskii and Tarabrin (1960) split plant roots between a chamber containing exchange resin treated with mineral salts and a chamber of quartz sand moistened with distilled water or nutrient solutions. They found that the resin became more acid with growth of the plants, and they considered that the increase in acidity of the resin was due to hydrogen ions excreted from the plant roots. They also reported that the quantity of acidity increased with the adsorption capacity of the exchange resin and not with the weight of the root mass.

Vancura (1964) grew barley and wheat for 10 days in sand after sterilizing the seed with mercuric chloride. The root excretions were then extracted from the sand with water. The exudate measured amounted to about 0.5 mg per barley plant and included 19% ash, 9% reducing sugar, 0.3% volatile acids, 17% nonvolatile acids, and 1% nitrogen. Similar results were obtained with wheat.

G. Differential Acidity of the Media in Relation
to Microbial Activity in the Rhizosphere

By the plate-count technique, Louw and Webley (1959a)
demonstrated that the numbers of acid-producing and dicalcium
phosphate-dissolving bacteria both increased in the root
region of oat. These bacteria produced lactic acid and 2-
keto-gluconic acid from glucose (Louw and Webley, 1959b). Soil
microorganisms capable of producing organic acids (citric,
glycollic, succinic, gluconic, oxalic, lactic) have been iden-
tified as Aspergillus niger, Penicillium sp., Nocardia sp.,
Bacterium sp., Escherichia coli and E. freundii (Sperber,
1958; Meyer and Konig, 1960; Konig, 1961). Hirte (1970) in-
cubated soil high in organic matter or soil with heavy dressing
of mineral nitrogen and found that during the phase of inten-
sive decomposition there was a marked increase in soil pH
associated with increased microbial development.

There has not been work on soil pH in the rhizosphere of
various plant species in relation to numbers of acid-producing
and phosphate-dissolving microorganisms. The aspect of
microbial effects on differential soil acidity by plant species
is not yet known.

H. Differential Acidity of Media in Relation to
Differential Uptake of Cations and Anions from Media

Fudge (1928) analyzed soil samples from the Alabama,
Rhode Island, and New Jersey Experiment Stations which had been

fertilized and cropped for 16 years. He found that sodium nitrate and calcium cyanamide increased soil pH, and ammonium sulfate decreased soil pH. His results suggested that the alteration of soil pH was due partially to the differential uptake of cations and anions from fertilizers by plants. But he explained his results by the physiological effect of fertilizers and base saturation of soil colloids.

Nightingale (1934) conducted a sand culture experiment using one-year-old apple trees as the test plant. He flushed the cultures with complete solutions containing ammonium sulfate or calcium nitrate and with minus-nitrogen solution at the rate of 36 liters per 24 hours for 16 days. The change in pH of the solution due to passage through the cultures was less than ± 0.1 pH unit. He found that the pH of sand immediately adjacent to the roots differed from the initial pH of the solution in accordance with the source of nitrogen in the solution. The pH of sand at 1 to 2 cm from the root was the same as that of the initial solution. The pH of sand adjacent to roots supplied with ammonium sulfate decreased from 6.0 to 4.0-4.5 and that supplied with calcium nitrate increased from 4.5 to 5.6.

Hoagland (1923) grew barley in culture solutions of various single salts and combination of salts for 1 to 4 days and then measured the absorbed quantities of cations and anions along with the pH of initial and final solutions (without addition of water to bring the solutions to volume and without aspiration

to expel respired carbon dioxide). His data were not consistent. In general, however, the final pH of the solutions was higher than the initial pH when anion absorption exceeded cation absorption, and the final pH was lower than the initial pH when cation absorption exceeded anion absorption.

Adams and Pearson (1970) placed cotton and peanut seedlings in various culture solutions of single salts and combination of salts for 24 hours. Aeration was provided in this experiment. The solution was brought to volume after harvesting. They reported that the pH of the solutions varied with the ratio of total cation uptake to total anion uptake. Their results were not consistent but suggested that if the ratio of cation uptake to anion uptake was over 1.0 the final pH of the solution was lower than the initial pE of the solution. If the ratio was less than 1.0, the final pH was higher than the initial pH. In addition, they reported that cotton created a more acid root environment than did peanut.

I. Differential Acidity of Media in Relation to Excess Base Content of Plants

Odland, Smith, and Damon (1934) observed that individual crops had different effects on the yield of crops which followed. They found that different plant species altered the soil acidity to different degrees. But the removal of soil bases was not significantly correlated with the soil pH or with lime requirements. They measured soil pH by the quinhy-

drone electrode and the removal of soil bases by the alka-
linity of the plant ash by the method of Frear (1930). The
soils were not uniformly fertilized before this experiment was
begun. Their poor correlation between the removal of soil
base and the pH of the soil or the lime requirement thus may
have been due mainly to the heterogeneity of the soil. The
methods of measurement of pH and the removal of soil base also
may be questioned.

Pierre, Meisinger and Birchett (1970) studied the effect
of nitrogen fertilizers on soil acidity. They found that in
fallowed soil the acidity developed from ammonium nitrate was
almost equal to the theoretical amount that should be developed
by nitrification. When oats were grown, the increase in
acidity due to ammonium nitrate was lower than theoretical
value in the absence of a crop by 27%. With buckwheat, the
increase in acidity was higher than theoretical value by 87%.
The deviation from the theoretical increase in soil acidity
from ammonium nitrate fertilizer was in quantitative agreement
with that calculated from the composition of the crop.

III. MATERIALS AND METHODS

A. Materials

1. Soil

A layer of Buckner loamy sand 30 to 50 cm in depth was taken from Polk County, 100 ft south and 510 ft east of the NW$\frac{1}{4}$, NE$\frac{1}{4}$, Section 30, T81N, R22W, 0-2% slope. The pH of the soil (1:1 soil to water) was 5.0, and the extractable P by the Bray I method (Bray and Kurtz, 1945) was 13 μg per gram.

2. Phosphate rock

The sample was sold by the American Agricultural Chemical Co., Fulton, Illinois, and was supplied through the courtesy of Dr. J. R. Webb. The sample was treated with Silverman's solutions (Silverman et al., 1952) to eliminate alkaline-earth carbonates and was passed through a 200-mesh sieve. It contained 13.79% P.

3. Superphosphate

A sample of concentrated superphosphate containing 20.3% P was ground to pass a 200-mesh sieve.

4. Nutrient solutions

a. Experiment 1

1) Minus-phosphorus starting nutrient solution.
In 24 liters, the solution contained 156.11 g of $Ca(NO_3)_2 \cdot 4H_2O$, 81.86 g of $MgSO_4$, 99.52 g of KNO_3, and 160 ml of micro-

nutrient solution.

2) <u>Micronutrient solution</u> (Hoagland and Arnon, 1950)
In 1 liter, the solution contained 2.86 g of H_3BO_3, 1.81 g of
$MnCl_2 \cdot 4H_2O$, 0.22 g of $ZnSO_4 \cdot 7H_2O$, 0.0615 g of $CuSO_4$, 0.0180 g
of H_2MoO_4, and 5.00 g of ferrous tartrate.

3) <u>Nitrogen supplement solution</u>   Potassium nitrate
solution contained 72.143 g of KNO_3 per liter.

b. <u>Experiment 2</u>

1) <u>Minus-phosphorus starting nutrient solution</u>
In 30 liters, the solution contained 177.2 g of $Ca(NO_3)_2 \cdot 4H_2O$,
61.4 g of KNO_3 and 240 ml of micronutrient solution of Hoagland
and Arnon.

2) <u>Supplementary minus-phosphorus nutrient solution</u>
In 20 liters, the solution contained 78.4 g of $Ca(NO_3)_2 \cdot 4H_2O$,
27.2 g of $MgSO_4$, and 51.7 g of KNO_3.

c. <u>Experiment 3</u>   In 8 liters, the solution contained
11.3352 g of $Ca(NO_3)_2 \cdot 4H_2O$, 5.7755 g of $MgSO_4$, and 9.7066 g of
KNO_3, the pH was adjusted to 5.0 by HNO_3 and KOH.

5. <u>Plants</u>

Plant	Source
Spring barley (Larker)	Dr. R. E. Atkins
Oat (X434 II)	Dr. K. J. Frey
Rye (Balbo)	Earl May Seed Co.
Annual ryegrass	Earl May Seed Co.
Sorghum (hybrid R.P. 303)	Earl May Seed Co.
Wheat (Gate)	Dr. K. J. Frey
Buckwheat (Silver Hull)	Earl May Seed Co.
Cabbage (Golden Acre)	Earl May Seed Co.

Plant	Source
Collards	Earl May Seed Co.
Rape	Earl May Seed Co.
Lupine	Earl May Seed Co.
Alsike clover	Earl May Seed Co.
Ladino clover (Merrit)	Dr. I. T. Carlson
Red clover	Earl May Seed Co.
White Dutch clover	Earl May Seed Co.
Tobacco (White Burley)	Earl May Seed Co.
Tomato (Rutgers)	Earl May Seed Co.

B. Methods

1. Laboratory methods for plant material

a. Total phosphorus   The ashing method described by
Black (1957) was followed. A quantity of 0.500 g of ground
plant material was placed in a 50-ml beaker and treated with
5 ml of a solution of magnesium acetate (50 g of magnesium
acetate in 950 ml of distilled water). The solution was
evaporated to dryness on a steam plate. The beakers were then
placed in a cold muffle furnace. The temperature was raised
to about 200°C and maintained at that temperature until the
sample was charred. Then the temperature was raised to 500°C
and maintained at that value for 2 hours. After the furnace
had cooled, the beaker was removed, and the ash was moistened
with 5 ml of 1N nitric acid. After about 5 minutes, the acid
was neutralized with 5 ml of 1N ammonium hydroxide. The solu-
tion was evaporated to dryness on a steam plate. Then the
beaker was reheated in a muffle furnace for an hour at 500°C.
After the beaker had cooled, it was placed on a steam plate,
and 7.5 ml of 1N nitric acid were added. After 15 minutes,

the contents of the beaker were transferred quantitatively to a 50-ml volumetric flask. When the volumetric flask was at room temperature, distilled water was added to produce a volume of 50 ml. A set of beakers containing standard phosphorus solutions in quantitites of 0, 25, 50, 100, 175, 250 micrograms of P was run along in the same manner as the samples.

Colorimetric measurements of phosphorus were made by the metavanadomolybdate-nitric acid method as described by Black (1957). A 5-ml aliquot of the solution prepared as described in the preceding paragraph was pipetted into a test tube of approximately 50-ml capacity. A 25-ml volume of the molybdate-vanadate solution (Solution A was prepared by dissolving 97 g of ammonium molybdate in 400 ml of distilled water. Solution B was prepared by adding 2.52 g of ammonium metavanadate to 250 ml of boiling water, allowing the solution to cool, adding 1012 ml of concentrated nitric acid, and diluting the resulting solution to 5 liters with distilled water. Solution A was poured into solution B, and the resulting solution was diluted to 9 liters with distilled water and mixed thoroughly.) was added, mixed with the aliquot of the test solution, and allowed to stand for 1 hour. Then the transmission was measured with an Evelyn photoelectric colorimeter fitted with a 420 millimicron filter.

b. Total nitrogen including nitrate   The total nitrogen content of the plant samples (including nitrate) was determined by the modified Kjeldahl method described by

Bremner (1965a).

    c. Ash alkalinity   The ashing procedure by Frear
(1930) as modified by Banwart (1972) was followed. A 0.5000 g
sample of dry, finely ground plant material was weighted into
a 100 ml beaker and moistened with 10 ml of distilled water,
followed by a quantitative addition of 5 ml of a 10% solution
of $Mg(NO_3)_2 \cdot 6H_2O$. The beaker was placed on a steam plate until
nearly dry, and then transferred to a desiccator containing
water for several hours or overnight. As an added means of
obtaining sufficient moisture content for slow ashing, the
surface of the sample was sprayed with a fine mist of water.
The beaker was then placed in the front of a muffle furnace
set at approximately $400^{\circ}C$, with the leading edge of the beaker
about flush with the edge of the furnace, where the temperature
was about $120^{\circ}C$. As the sample started ashing in the side of
the beaker nearest the furnace, the beaker was gradually moved
into the furnace until the ashing front had moved across the
beaker. The beaker was left in the furnace for continued slow
ashing while the next sample was placed at the mouth of the
furnace for the initial ashing. When the fourth sample was
put in place for the initial ashing, the first beaker was re-
moved from the furnace. After all the samples had undergone
the preliminary ashing, all beakers were returned to the fur-
nace, and the temperature was raised to $500^{\circ}C$ for 30 minutes.
The samples were then removed, returned to the furnace in a new
location, and heated for an additional 30 minutes at $500^{\circ}C$.

With each group of samples, two beakers containing 0.25 g of Carbon Black G were treated the same as samples. After the beakers were allowed to cool to room temperature, 10 ml of distilled water was added slowly, to prevent mechanical loss, followed by exactly 20 ml of standard 0.5 $\underline{N}$ HCl. The beakers were covered with watch glasses, placed on a steam plate, and kept at a temperature just below boiling point for about 20 minutes. After cooling, the samples were titrated with standard 0.5 $\underline{N}$ NaOH using methyl red (0.2 g of methyl red in 100 ml of distilled water) as an indicator. The end-point was at a dull yellowish orange color, which was obtained at approximately pH 5.3.

The milliequivalents of base required for titration of the Carbon Black G, minus the milliequivalents for titration of the plant sample, gave the ash alkalinity of the sample.

The total milliequivalents of ash alkalinity minus the total mill_. quivalents of nitrogen in the plants per culture, after correction for the corresponding values in control plants grown without nutrients in sand, represents an estimate of the difference between the sum of the cations and the sum of the anions derived from the soil in the production of the plants. This is so because (a) the organic sulfur is converted to sulfate in the ash alkalinity determination, (b) the nitrogen is lost from the plant material in the ash alkalinity determination, and (c) essentially all the organic nitrogen present in the plant material was absorbed as nitrate because the

subsoil used as substrate contained little native nitrogen, and all the nitrogen added in the nutrient solutions was in the nitrate form. Positive values of the difference indicate that the plants absorbed more equivalents of cations than anions. Negative values indicate that the plants absorbed more equivalents of anions than of cations.

In this work, the roots were not collected for analysis. Only the plant tops were analyzed. The total milliequivalents of ash alkalinity minus the total milliequivalents of nitrogen in the plant tops, after correction for the corresponding values in control plants grown without nutrients in sand, represents most, but not all, of the difference between the total cations and total anions absorbed from the soil. The quantity just described is indicated by A_c for brevity. It represents an index of the quantity described in the preceding paragraph. Certain use will be made of the difference between the ash alkalinity and the total nitrogen in the plant tops without correction for the corresponding values in the control plants grown in sand without nutrients. This quantity is indicated by $\underline{A}$. It also represents an index of the quantity described in the preceding paragraph.

2. Laboratory methods for culture solutions

Potassium, calcium, and magnesium in the culture solutions were determined by atomic absorption with the aid of a Perkin-Elmer Atomic Absorption Spectrophotometer, Model 303, as

described by the Perkin-Elmer Staff (1971).

Nitrate nitrogen was determined by distillation with Devarda's alloy as described by Bremner (1965b).

Sulfate was determined by the turbidimetric method described by Chesnin and Yien (1951).

3. Laboratory methods for soils

a. pH measurement of wet or dry soil mass   A suspension of 20 g (air-dry weight basis) of soil in 20 ml of distilled water was prepared and allowed to stand for an hour. The pH was then measured by a Beckman Model G pH meter.

The samples of the wet soil mass for calibration purposes were taken from the soil layer in the phosphate-rock cultures after removal of roots and after mixing. The samples of the dry soil mass were the air-dried portions of the samples of the wet soil mass.

The redox potential of the soil (plus quinhydrone) adjacent to plant roots was measured in the following way. The waxed paper plug was removed from the 2.5 x 7.5-cm opening that had been cut in the side of the waxed paper culture vessel at the level of the soil layer. A newly developed root distant from other roots was selected for the measurement. Quinhydrone powder was sieved onto the root and surrounding soil and was allowed to stand 5 minutes. Then a sleeve-type, saturated calomel electrode was placed in contact with the soil surface that had received the quinhydrone, and the clean tip of the

bright platinum wire that constituted the platinum electrode was inserted into the soil surface to a depth of 1 to 2 mm at a location 0 to 2 mm to the side of the root and 5 to 7 mm back from the root tip. A Beckman Model G pH meter was used to record the redox potential. The temperature was measured also.

The pH of the soil near the root was then found by interpolation in a calibration curve obtained from a plot of redox potentials against pH values measured on a sample of the wet soil mass that had been mixed after removal of the roots. The Eh was measured in the manner described in the preceding paragraph. The pH was measured on a 1:1 suspension of soil (air-dry basis) in water with the aid of a glass electrode and a Beckman Model G pH meter. The calibration curve used in Experiment 2 (Main Experiment) was a regression of Eh on the pH of all samples of the wet soil mass regardless of plant species. The calibration curve used in Experiment 1 (Preliminary Experiment) was a regression of Eh on the pH of five selected samples of the wet soil mass.

This technique of measuring pH by the quinhydrone electrode was tested with quantities of Okoboji soil that had been incubated with various quantities of calcium carbonate. There was a high correlation ($r = -0.914**$) between the pH of air-dry soils and the Eh of 50% saturated moist soils by quinhydrone technique as described. The equation obtained was:

$$Eh(mv, 25^{\circ}C) = 701.5 - 58.9 \ pH,$$

which was comparable to theoretical equation proposed by

Biilmann and Tovborg-Jensen (1927),

$$Eh(mv, 25^{\circ}C) = 704-59 \ pH.$$

A special experiment was conducted to determine whether the calibration curve could be used to determine the pH of soil near the roots where the results could conceivably be influenced by the electrical field around the roots.

To attack this problem, sorghum was grown on cultures in which phosphate rock was added to Buckner soil. The container, soil, sand, and nutrients were similar to those of Experiment 1 and 2 (Preliminary and Main Experiment). After the sorghum had grown for 3 weeks, the Eh at various locations near the root was measured by this technique on one side of a selected root. On the opposite side of the root, the soil was leached with the nutrient solution used in the experiment and then allowed to drain, after which the same technique of measuring Eh was used. The results are shown in Table 1.

In normal measurements made without leaching, there was a trend of decreasing Eh with increasing distance from the root, but after leaching the values of Eh were essentially unaffected by the location of the electrode. The implication of these results is that the Eh values measured near the roots are not appreciably influenced by the electrical field around the roots. The differences in Eh values among cultures after leaching are probably a consequence of contamination with $CaCO_3$ which splashed into the cultures from the roof of the greenhouse.

While measurements of the Eh of samples in the greenhouse

Table 1. Redox potential (Eh) measured at various distances
perpendicular to sorghum roots, with and without
prior leaching of soil treated with quinhydrone

Cul- ture no.	Treatment	Eh value of soil with quinhydrone at the indicated distance (mm) perpendicular to the root, mv					
		0	5	10	15	20	25
1	Normal	140	136	118	112	110	104
	Leached	102	98	100	100	98	98
2	Normal	136	130	124	97	98	92
	Leached	122	122	126	122	126	120
3	Normal	126	102	92	94	98	93
	Leached	112	111	110	108	110	108
4	Normal	120	122	112	101	100	100
	Leached	105	105	108	105	105	104
5	Normal	137	138	135	128	103	105
	Leached	143	143	141	140	138	139

were being made, the temperature ranged from 22 to 27°C. Eh

values are affected by temperature. The temperature effect

is given by the following equation by Biilmann and Krarup (1924)

and Collins (1931):

$$Eh(mv, 25°C) = Eh(t°C) + 0.009(t-25) + 246.4.$$

The magnitude of the temperature effect between 20 and 30°C is

only 0.45 mv, which is beyond the sensitivity of the pH meter

used in this work. Therefore, none of the observed Eh values

were corrected for temperature.

4. Greenhouse procedure

a. Soil sample preparation   Soil samples were air dried and sieved through a 2-mm sieve. Calcium hydroxide solution of 0.02 N̲ was sprayed on the soil samples to bring them to the desired pH by trial and error. The samples were air dried, sieved through a 2-mm sieve, and thoroughly mixed. One-third of each sample was mixed with finely ground super-phosphate at the rate of 0.04 g of P per kg of soil. Another third of each sample was mixed with finely ground phosphate rock at the rate of 0.10 g of P per kg of soil. The last portion was kept as it was. The pH of soils used in Experiment 1 (Preliminary Experiment) was 5.6, and in Experiment 2 (Main Experiment) was 5.8.

b. Preparation of cultures   Seven hundred g of silica sand was weighed directly into a heavy, waxed-paper container in Experiment 1. In Experiment 2, a polyethylene bag was inserted inside the waxed container, and the sand was put in-side this bag. The container was tapped to smooth the surface of the sand. A 300-g quantity of soil was then spread smoothly over the sand surface. In Experiment 1 (Preliminary Experiment) only, 50 ml of minus-phosphorus starting solution was carefully poured over the soil surface, and enough deionized distilled water was added to bring the cultures to 50% water saturation. The samples were kept at this water content for at least 2 weeks until planting. At the date of planting, 300 g of silica sand was spread over the soil surface. The seeds were planted

in this sand portion then water was added to bring to total volume to 50% of saturation.

For Experiment 2 (Main Experiment) a layer of 300 g of soil was placed on the sand, and 300 g of silica sand was placed on the soil. Then 50 ml of minus-phosphorus starting solution was added, and enough deionized distilled water was added to bring the water content of the sand and soil to 50% of saturation. This water content was maintained until the seeds were planted or until the seedlings were transplanted, as the case might be.

For those cultures assigned for measurement of soil pH near the roots, the waxed paper container had been cut by a razor blade to have three open portions of 2.5 x 7.5 cm around the wall located at the soil layer. These cut portions were replaced in the container, and the container with the soil and sand was inserted in a similar empty container to hold the cut portions in their normal position.

c. Experiment 1 (Preliminary Experiment) Ten plant species (barley, oat, rye, ryegrass, sorghum, alsike clover, buckwheat, rape, tobacco, and lupine) were grown with treatments of

(a) Buckner loamy sand, pH 5.6,

(b) Same as (a) but with 12 mg of P as superphosphate,

(c) Same as (a) but with 30 mg of P as phosphate rock, and

(c) Silica sand (1300 g).

Ten replicates were used for phosphorus availability and

A_c measurements. Three replicates of the phosphate-rock treatment were simultaneously assigned for measurement of soil pH near the roots at harvest. The cultures were arranged as a split-plot design with plant species as main plots and the four treatments as subplots. In addition, three replicates of the ten plant species were grown on cultures of the phosphate-rock treatment to provide for measurements of soil pH at the early growth stage. These cultures were arranged as a randomized complete block and were mixed in with the other ten replicates.

The ratio of the availability of coefficient of phosphorus in phosphate rock to that of phosphorus in superphosphate, denoted by R, was calculated from the expression,

$$R = (\frac{U_r - U_s}{U_{std} - U_s})(\frac{X_{std}}{X_r})$$

where

U_r = total phosphorus in plants grown on phosphate-rock treated soil,

U_{std} = total phosphorus in plants grown on superphosphate-treated soil,

U_s = total phosphorus uptake in plants grown on soil,

X_r = milligrams of phosphorus added in phosphate rock, and

X_{std} = milligrams of phosphorus added in superphosphate. This method of calculating the availability-coefficient ratio involves the assumption that the yield of phosphorus in the

plants increased linearly with the supply of phosphorus added
as phosphate rock and superphosphate within the range of addi-
tions used in the experiments.

The timing of the operations in the greenhouse was as
follows. Soil samples were treated with minus-phosphorus
starting solution on September 18, 1971. On October 3, 30
seeds of tobacco were planted at a depth of 5 mm in the sand
in the tobacco cultures; on October 24, 30 seeds of alsike
clover were planted at a depth of 1 cm in the sand in alsike
clover cultures; on October 31, 20 seeds of barley, oat, rye,
sorghum, and rape and 50 seeds of ryegrass were planted at a
depth of 1 cm in the sand; and on November 7, 15 seeds of
buckwheat and lupine were planted at a depth of 1 cm in the
sand. All the seeds were treated before planting with Arasan,
a fungicide (Dupont Semesan Company Inc., 101 West Tenth Street,
Wilmington 98, Delaware). The water content of the cultures
was kept at 50% of saturation by daily weighing of the cultures
and addition of the water needed. Thinning of the plants was
done 3 weeks after planting, except for tobacco, which was
thinned 5 weeks after planting. The numbers of plant per cul-
ture after thinning were 15 for barley, oat, rye, and sorghum;
10 for buckwheat, tobacco, rape, and lupine; 20 for alsike
clover; and 30 for ryegrass.

Measurements of soil pH near the roots of plants on the
three supplemental replicates of the phosphate rock cultures
were made November 22 on the barley, oat, rye, ryegrass,

sorghum, and rape cultures; November 28 on the buckwheat cultures; and December 5 on the alsike clover, lupine, and tobacco cultures. An addition of 50 mg of N per pot as 5 ml of KNO_3 nitrogen supplement solution was made on December 12. The barley, oat, rye, ryegrass, and buckwheat cultures were harvested December 18 and 19; and the alsike clover, rape, sorghum, and tobacco cultures were harvested December 26. Measurements of soil pH were made at the time of harvest. The lupine was not harvested in this experiment because all the plants made very poor growth.

No nutrients were added to the sand cultures at any time.

Only the above-ground parts of the plants were harvested. These parts were cut off at the surface of the sand, rinsed with distilled water, put in a paper bag, and dried at 60°C for 48 hours. The dry weight was determined; and the samples were ground to pass a 20-mesh sieve and were placed in glass bottles for subsequent analyses for total N, P, and ash alkalinity.

The roots were removed from the soil in the phosphate-rock cultures, and the soil was air dried, sieved through a 2-mm screen, and mixed. The pH was measured after addition of water to the soil as described previously in connection with pH measurements.

d. Experiment 2 (Main Experiment)   Sixteen plant species (barley, oat, rye, ryegrass, wheat, sorghum, alsike clover, ladino clover, red clover, white clover, cabbage,

collards, rape, buckwheat, tobacco, and tomato, were grown
on cultures of:

    (a) Buckner loam sand, pH 5.8,

    (b) Same as (a) but with 12 mg of P as superphosphate,

    (c) Same as (a) but with 30 mg of P as phosphate rock, and

    (d) Silica sand (1300 g).

Ten replicates were used for phosphorus availability and
A_c measurements. Three replicates of the phosphate-rock treat-
ment were simultaneously assigned for measurements of soil pH
near the roots at harvest. The cultures were arranged as a
split-plot design with plant species as the main plots and the
four types of cultures as subplots. Three additional repli-
cates of the phosphate-rock cultures were carried along to pro-
vide for measurements of soil pH near the roots at the early
growth stage. These cultures were arranged in a randomized
complete block design and were mixed in with the other ten
replicates.

The timing of the various operations was as follows.
Tobacco seed was planted in a complete-nutrient sand culture
on February 8, 1972. Soil samples were treated with 50 ml of
minus-phosphorus starting solution and enough deionized dis-
tilled water to bring them to 50% of saturation on February 5,
1972. On February 19, the first group of plants was planted:
15 tobacco seedlings per culture, 48 alsike clover, ladino
clover, red clover, and white clover seeds per culture, and
20 tomato, collards, and rape seeds per culture. On February

26, the second group of plants was planted: 25 seeds of oat, 30 seeds of barley, rye, wheat, and sorghum, 20 seeds of buckwheat and cabbage, and 80 seeds of ryegrass. Plants were thinned on March 11 to leave the following numbers of plants per culture: 10 for buckwheat, 15 for cabbage, collards, and rape, 20 for oat, 25 for barley, rye, sorghum, and wheat, 36 for alsike clover, ladino clover, red clover, and white clover, and 50 for ryegrass. Supplementary minus-phosphorus nutrient solution was added at 25 ml per culture on March 11, March 25, and April 1. Insecticide, plants were sprayed with 1% suspensions of Chlordane on March 11 and 17, Kentane on March 22, and D.D.T. on April 1, 3, 7, and 13. The soil pH near the root for the early growth stage of all plant species was measured on March 25 and for the harvesting time on April 22 for the second group and on April 29 for the first group.

The water content of the cultures was kept at 50% of saturation by daily weighing of the cultures and additions of water. No nutrients were added to the sand cultures.

Only the above-ground portion of the plants was harvested. The plants were cut off at the soil level, rinsed with distilled water, put in a paper bag, and dried at 60°C for 48 hours. The dry weight was determined, and the plant material was ground to pass a 20-mesh sieve and was kept in glass bottles for determination of total N, P, and ash alkalinity. The roots were removed from the soil in the phosphate-rock cultures, and a sample of the wet soil was removed and used

for making the calibration curve of Eh versus pH. The remainder of the soil was air dried and sieved to pass a 2-mm screen. The pH was measured on these samples after addition of water to the air-dried soil as described previously in connection with pH measurements.

e. Experiment 3 (Solution Culture Experiment)   The same 16 plant species as in Experiment 2 (Main Experiment) were grown on sand in waxed-paper container provided with a complete nutrient solution for 5 weeks. Then a plant or plants were carefully taken from the container, and the sand was washed from the roots. Enough plants to give 15 to 20 g of fresh weight were used for each species. The plants were held upright in bottles containing nutrient solution by wrapping cotton around the stems and inserting the wrapped stem or stems into the hole of a rubber stopper. The plants were kept in a complete solution for a week before the trial was started.

The experiment included 18 one-liter bottles, each wrapped with aluminum foil. An outlet from a compressed air line was attached to each bottle. One bottle, without plants, was connected at the head of the air line and another at the end. The remaining 16 bottles, with plants, were assigned to plant species at random for each trial. The compressed air was bubbled through a set of three 8-liter bottles of concentrated sodium hydroxide solution before it entered the air line.

The culture solution for each bottle was prepared by pipetting 200 ml of stock nutrient solution (see page 18)

into a bottle along with 500 ml of boiled, deionized, distilled water. All water used in this experiment, including that used in nutrient solution preparation, was boiled, deionized, distilled water.

Nineteen bottles of culture solution were prepared for each replicate. Three bottles contained no plants. Two of these bottles, located at the beginning and end of the aspiration line, were used to determine the concentration of ions in the absence of plants. One was used to determine the initial pH. This measurement was made immediately, and the bottle was not attached to the aspiration line with the others. The 16 plant species were assigned at random to the remaining locations in the aspiration line. The plants were kept in the solutions for 12 daylight hours, during which the cultures were aspirated continuously with CO_2-free air. Then the plants were removed, and the roots were rinsed with a fine spray of water to wash the adhering nutrient solution back into the bulk solution. Then the solution was transferred to a 1-liter volumetric flask, made to volume with water, mixed thoroughly, and retained for determination of potassium, calcium, magnesium, nitrate, and sulfate. The ion content of the two bottles without plants was taken as the content of the solution before absorption. The difference between the content of these solutions and the solutions in which the plants had been for 12 hours was taken as the quantity of ions absorbed by the plants. The pH values of the solutions in which the plants

had been placed for 12 hours were measured immediately after the solutions were brought to volume.

Three trials were made, one on April 19, one on April 25, and one on April 28. The same plant material was used in all three trials (replicates). In the intervals between trials, the plants were treated with a complete nutrient solution and were rinsed with water and kept in aspirated water at least 1 day before the next trial was started.

IV. RESULTS AND DISCUSSION

A. Experiment 1 (Preliminary Experiment)

The growth of all plant species in this experiment was poor because of the low light intensity and use of too high a concentration of nutrients (18 meq of salt per culture in 160 ml of water). Salt injury symptoms were observed on alsike clover during early growth, but the plants recovered after growing for 4 weeks. Lupine made very poor growth and was not harvested.

Tables 9 through 18 give the basic data on (a) the Eh of the soil near the roots in the presence of quinhydrone at the early growth stage and the estimated pH of soil, (b) the Eh of the wet soil mass in the presence of quinhydrone and the pH of the soil suspension derived from the wet soil mass at the early growth stage for the calibration curves, (c) the Eh of the soil near the roots at harvest in the presence of quinhydrone and the estimated pH, (d) the Eh of the wet soil mass in the presence of quinhydrone and the pH of the soil suspension derived from the wet soil mass at harvest for the calibration curve, (e) the pH of the air-dried soil mass at harvest, (f) the dry-weight yield of plant tops, (g) the yield of phosphorus in the plant tops, (h) the total nitrogen content of plant tops in the phosphate rock and sand cultures, (i) the ash alkalinity of the plant tops in the phosphate rock and sand cultures, (j) the ratio of the availability coefficient

of the phosphorus in phosphate rock to that of phosphorus in superphosphate, and (k) the A_c present in the plant tops.

The phosphorus availability-coefficient ratio, the means of soil pH near the roots at the early growth stage and at harvest, the means of the soil mass pH values at harvest, and the A_c values for the plants are summarized in Table 2. Statistical analyses of the relationships among the variables in Table 2 are shown in Table 3.

The A_c values were negatively correlated with the pH of the soil near the roots of both growth stages at the 5% level of significance and with the pH of the soil mass at harvest at the 1% level of significance (Table 3). These trends are in accordance with the theory. The higher correlation of A_c with the pH of the soil mass than with the pH of the soil near the roots may be a consequence of a relatively large experimental error in obtaining the pH values of the soil near the roots. Sources of error in values of the pH of soil near the roots may be (a) the calibration curve, which was the best fit of measurements on only five selected soil samples, (b) the fact that the pH of the soil near the roots at the early growth stage was measured on only three replicates that were not included in the group of replicates used for determination of the A_c values, and (c) the presence of microbial products from the waxed container in the immediately adjacent soil where the platinum electrode was inserted for Eh measurements. During measurement of values of Eh of soil near the roots,

Table 2. Summary of data obtained in Experiment 1 (Preliminary Experiment)

Plant	R^b	pH of soil near the roots		pH of soil mass after harvest	A_c^a meq/ culture
		Early growth	Harvest		
Barley	0.504	6.16	6.75	6.72	0.134
Oat	0.294	6.23	6.79	6.59	-1.067
Rye	0.289	6.17	6.00	6.75	-0.107
Ryegrass	0.205	6.06	6.66	6.74	-0.153
Sorghum	0.179	6.38	6.03	6.46	1.323
Alsike cl.	0.389	6.08	5.64	6.59	0.737
Buckwheat	0.468	5.28	5.91	5.51	4.566
Rape	0.565	6.02	5.37	5.62	6.789
Tobacco	0.587	6.04	5.24	5.87	4.543

[a](total milliequivalents of ash alkalinity - total milliequivalents of nitrogen in tops of plants per culture of soil treated with phosphate rock) - (total milliequivalents of ash alkalinity - total milliequivalents of nitrogen in tops of plants per culture of sand without added nutrients).

[b]Ratio of availability coefficient of phosphorus in phosphate rock to that of phosphorus in superphosphate.

gummy substances were observed on the soil. These were removed from the soil before the Eh measurements were made, but some portion of these substances may have penetrated into the soil and caused an error in the reading of the Eh value.

The regression coefficient, b, of the pH of soil near the

Table 3. Relationship of variables in Experiment 1 (Preliminary Experiment)

No.	Independent variable X	Dependent variable Y	Correlation coefficient r	Estimated regression coefficient $b \pm s.e._b$ [a]	Regression equation
1	A_c [b]	pH of soil near roots, early growth	-0.687*	-0.078 ± 0.037	$Y = 6.19 - 0.078X$
2	A_c	pH of soil near roots, harvest	-0.779*	-0.166 ± 0.017	$Y = 6.35 - 0.166X$
3	A_c	pH of soil mass, harvest	-0.942**	-0.174 ± 0.023	$Y = 6.64 - 0.174X$
4	A_c	R [c]	+0.789*	0.044 ± 0.013	$Y = 0.305 + 0.044X$

[a] $s.e._b$ = standard error of regression coefficient $\underline{b}$.

[b] See footnotes in Table 2 for definition

[c] Ratio of availability coefficient of phosphorus in phosphate rock to that of phosphorus in superphosphate.

*Significant at 5% level.

**Significant at 1% level.

Table 3. (Continued)

No.	Independent variable X	Dependent variable Y	Correlation coefficient r	Estimated regression coefficient $b \pm s.e._b$	Regression equation
5	pH of soil near roots, early growth	R	-0.413	-0.204 ± 0.151	$Y = 1.620 - 0.204X$
6	pH of soil near roots, harvest	R	-0.539	-0.143 ± 0.078	$Y = 1.239 - 0.143X$
7	pH of soil mass, harvest	R	-0.658	-0.199 ± 0.086	$Y = 1.644 - 0.199X$

roots on A_c was unexpectedly lower at the early growth stage than at harvest. If uptake of unequal numbers of equivalents of cations and anions by the plants is the cause of the alteration of the acidity of the soil near the roots, the changes of soil pH near newly developed roots should be similar at both growth stages for a given change in A_c. Perhaps the explanation is that the excess of salts present at the early growth stage inhibited to some extent the differential uptake of cations and anions that influences soil acidity.

The regression coefficient, b, of the regression of the pH of the soil near the roots at harvest on A_c was almost equal to that of the regression of the pH of the soil mass at harvest on A_c. This observation may be accounted for on the basis that the soil was sandy and had a low buffer capacity plus the fact that, by harvest, the soil was penetrated extensively by roots.

The phosphorus availability-coefficient ratio was negatively correlated with all three sets of soil pH measurements, as expected from theory, but the correlations were not statistically significant. The lower correlation of the availability-coefficient ratio with the pH of the soil near the roots at the early growth stage than at harvest may be a consequence of the salt damage mentioned previously. The lower correlation of the availability-coefficient ratio with the pH of the soil near the roots at harvest than with the pH of the soil mass at harvest may be a consequence of the greater experimental errors of pH estimation from Eh values measured near the roots than of

direct pH measurement on the soil mass.

The phosphorus availability-coefficient ratio was positively correlated with A_c at the 5% level of significance. This observation is in accordance with expectations from the theory that, if uptake of more equivalents of cations than anions causes a decrease in the pH of the soil and a decrease in the concentration of calcium (both of which would increase the dissolution of phosphate rock), the phosphorus availability-coefficient ratio should increase with an increase in A_c.

The over-all results of this experiment verified the theory to be tested, but the levels of statistical significance were not as high as desired, and there were some minor discrepancies. The growing conditions were poor, due to insufficient light, and the plants did not make good growth.

B. Experiment 2 (Main Experiment)

The basic data obtained in Experiment 2 are recorded in Tables 19 through 31. The data include (a) the Eh of the soil near the roots in the presence of quinhydrone at the early growth stage and the estimated pH of the soil, (b) the Eh of the wet soil mass in the presence of quinhydrone and the pH of the suspension derived from the wet soil mass at the early growth stage for the calibration curve, (c) the Eh of the soil near the roots at harvest in the presence of quinhydrone and the estimated pH, (d) the Eh of the wet soil mass in the presence of quinhydrone and the pH of the soil suspension

derived from the wet soil mass at harvest for the calibration curve, (e) the pH of the air-dried soil mass at the early growth stage, (f) the pH of the air-dried soil mass at harvest, (g) the dry-weight yield of plant tops, (h) the yield of phosphorus in the plant tops, (i) the ash alkalinity, (j) the total nitrogen, (k) the $\underline{A}$ values of plant tops in the phosphate rock cultures and in the sand cultures, (l) the A_c values, and (m) the calcium content of plant tops in the phosphate rock cultures.

Table 4 summarizes values for the ratio of the availability coefficient of the phosphorus in the phosphate rock to that of phosphorus in superphosphate, the A_c values, the A values and calcium content of plant tops from the phosphate-rock cultures, and the four different measurements of soil pH. Relationships among the variables in Table 4 are given in Tables 5 and 6 and in Figures 1 to 7.

The conditions for plant growth were considerably more favorable during this experiment than during the preliminary experiment, and the growth was correspondingly better. The general results verified those obtained in the preliminary experiment, but the statistical relationships were more highly significant. Additional observations made possible additional interpretations.

The calcium content of the plants increased significantly with the $\underline{A}$ values. Such a relationship would be expected on the basis that calcium makes up a substantial proportion of

Table 4. Summary of data obtained in Experiment 2 (Main Experiment)

Plant	A^a/ culture, meq	A_c^b/ culture, meq	Ca content of above-ground parts of plants/ culture, meq	pH of soil near the roots		pH of soil mass		R^c
				Early growth	Harvest	Early growth	Harvest	
Barley	-1.948	-0.591	1.76	6.47	7.29	6.46	6.72	0.195
Oat	-2.635	-0.865	1.90	6.32	6.48	6.29	6.37	0.231
Rye	-0.749	-0.045	0.88	7.21	7.37	6.61	6.33	0.053
Ryegrass	-0.451	0.049	1.79	6.13	6.13	6.46	6.15	0.213
Sorghum	-0.686	0.242	1.15	5.90	6.71	6.31	6.23	0.090
Wheat	-1.736	-0.560	0.68	6.44	6.94	6.15	6.35	0.116
Buckwheat	3.744	4.873	7.77	5.02	4.93	5.68	4.98	0.665

[a]A = Milliequivalents of ash alkalinity minus milliequivalents of total nitrogen in above-ground parts of plants per phosphate rock culture.

[b](Milliequivalents of ash alkalinity minus milliequivalents of total nitrogen in above-ground parts of plants per phosphate rock cultures) minus (milliequivalents of ash alkalinity minus milliequivalents of total nitrogen in above-ground parts of plants per sand culture).

[c]R = Ratio of availability coefficient of phosphorus in phosphate rock to that of phosphorus in superphosphate.

Table 4. (Continued)

Plant	A/ culture, meq	A$_c$/ culture, meq	Ca content of above-ground parts of plants/ culture, meq	pH of soil near the roots		pH of soil mass		R
				Early growth	Harvest	Early growth	Harvest	
Cabbage	3.660	4.819	8.63	4.98	5.79	5.99	5.47	0.827
Collards	3.445	3.945	7.70	5.16	5.82	6.10	5.53	0.829
Rape	2.879	3.334	6.72	4.88	5.98	5.97	5.51	0.797
Alsike cl.	-0.188	0.173	3.76	5.95	5.68	6.20	5.75	0.447
Ladino cl.	-0.019	0.404	3.38	5.33	6.09	5.93	5.84	0.323
Red clover	-0.530	-0.036	3.12	5.48	5.86	6.20	5.97	0.238
White cl.	0.218	0.725	3.95	5.54	6.00	6.24	5.76	0.402
Tobacco	3.184	3.165	5.89	4.67	5.69	5.88	5.18	0.529
Tomato	1.408	1.651	4.72	4.92	5.72	5.81	5.46	0.514

Table 5. Linear correlations and linear regressions among variables in Experiment 2 (Main Experiment)

No.	Independent variable X	Dependent variable Y	Correlation coefficient r	Regression coefficient $b \pm s.e._b$ [a]	Regression equation
1	A[b]	Calcium content of plants	0.803**	0.989 ± 0.194	$Y = 3.394 + 0.989X$
2	A_c[b]	pH of soil near roots, early growth	-0.769**	-0.278 ± 0.062	$Y = 6.02 - 0.278X$
3	A_c	pH of soil near roots, harvest	-0.684**	-0.221 ± 0.063	$Y = 6.45 - 0.221X$
4	A_c	pH of soil mass, early growth	-0.703**	-0.090 ± 0.027	$Y = 6.26 - 0.090X$
5	A_c	pH of soil mass, harvest	-0.851**	-0.205 ± 0.034	$Y = 6.12 - 0.205X$
6	Calcium content	R[b]	0.974**	0.098 ± 0.007	$Y = 0.013 + 0.098X$

[a] $s.e._b$ = standard error of regression coefficient, b.

[b] See footnotes to Table 4 for definitions.

**Significant at 1% level.

Table 5. (Continued)

No.	Independent variable X	Dependent variable Y	Correlation coefficient r	Regression coefficient b ± s.e.$_b$	Regression equation
7	pH of soil near roots, early growth	R	-0.805**	-0.295 ± 0.058	Y = 2.071 - 0.295X
8	pH of soil near roots, harvest	R	-0.723**	-0.296 ± 0.076	Y = 2.226 - 0.296X
9	pH of soil mass, early growth	R	-0.689**	-0.717 ± 0.187	Y = 4.807 - 0.717X
10	pH of soil mass, harvest	R	-0.815**	-0.499 ± 0.085	Y = 3.081 - 0.449X
11	A_c	R	0.902**	0.120 ± 0.015	Y = 0.245 + 0.120X
12	Calcium content	pH of soil near roots, early growth	-0.833**	-0.228 ± 0.040	Y = 6.56 - 0.228X
13	Calcium content	pH of soil near roots, harvest	-0.773**	-0.190 ± 0.041	Y = 6.91 - 0.190X
14	Calcium content	pH of soil mass, early growth	-0.732**	-0.071 ± 0.017	Y = 6.43 - 0.071X
15	Calcium content	pH of soil mass, harvest	-0.871**	-0.159 ± 0.024	Y = 6.48 - 0.159X

Table 6. Multiple linear regression equations and standard multiple regression equations representing relationships among certain variables in Experiment 2 (Main Experiment)

| No. | Independent variables | | Dependent variable Y | Multiple correlation coefficient |
	X_1	X_2		
16	Calcium content	pH of soil near roots, early growth	R^c	0.974**
17	Calcium content	pH of soil near roots, harvest	R	0.975**
18	Calcium content	pH of soil mass, early growth	R	0.975**
19	Calcium content	pH of soil mass, harvest	R	0.976**

[a]b'_1 and b'_2 are independent of the original units of measurement (Steel and Torrie, 1960).

[b]Standard error of b' independent of the original units of measurement.

[c]See footnote to Table 4 for definition.

**Significant at 1% level.

Multiple linear regression equation	Standard multiple linear regression equation[a]	s.e.$_b$.[b]
$Y=-0.030+0.099X_1+0.007X_2$	$Y'=-0.113+0.992X'_1+0.021X'_2$	0.113
$Y=-0.191+0.103X_1+0.030X_2$	$Y'=-0.718+1.031X'_1+0.074X'_2$	0.098
$Y=-0.334+0.102X_1+0.054X_2$	$Y'=-1.257+1.013X'_1+0.053X'_2$	0.085
$Y=-0.485+0.110X_1+0.077X_2$	$Y'=-1.823+1.097X'_1+0.141X'_2$	0.118

Figure 1.   Calcium content versus $\underline{A}$ values in tops of 16
            species of plants grown on phosphate rock cultures,
            where A = milliequivalents of ash alkalinity minus
            milliequivalents of total nitrogen in plant tops
            per culture

CALCIUM IN PLANT TOPS PER CULTURE, meq.

A VALUES PER CULTURE, meq.

$Y = 3.394 + 0.989X$, $r = 0.809$**

52b
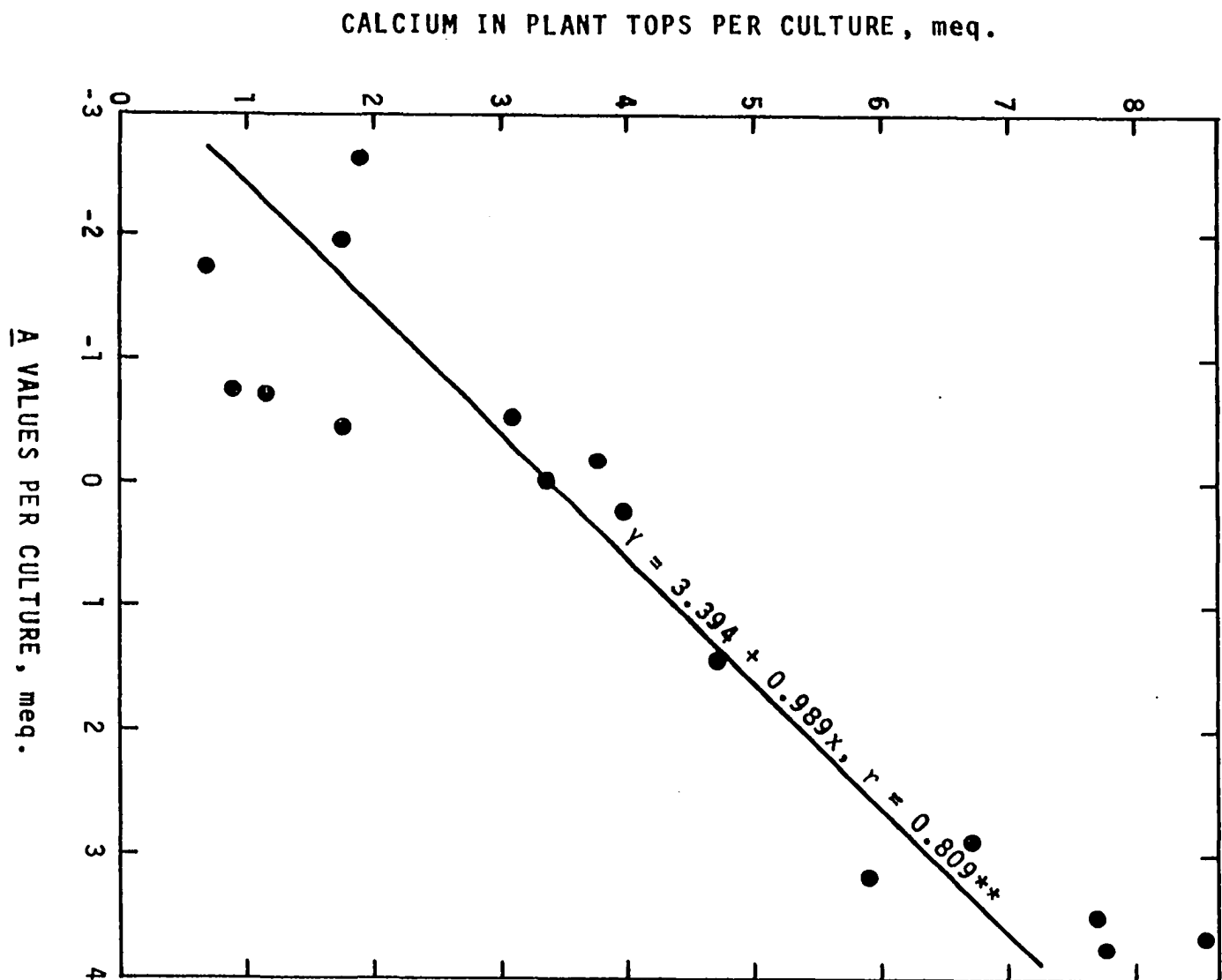
Figure 2. The pH of the soil near the roots of 16 plant
species in the phosphate rock cultures versus
the A_C values, where A_C = (milliequivalents of
ash alkalinity minus milliequivalents of total
nitrogen in plant tops per phosphate culture)
minus (milliequivalents of ash alkalinity minus
milliequivalents of total nitrogen in plant tops
per sand culture)

Figure showing pH of soil near roots versus A_c values per culture (meq).

Legend:
● pH OF SOIL NEAR ROOTS AT EARLY GROWTH STAGE
△ pH OF SOIL NEAR ROOTS AT HARVEST

$Y = 6.45 - 0.221x, \; r = -0.684^{**}$

$Y = 6.02 - 0.278x, \; r = -0.769^{**}$

Y-axis: pH OF SOIL NEAR ROOTS

X-axis: A_c VALUES PER CULTURE, meq.
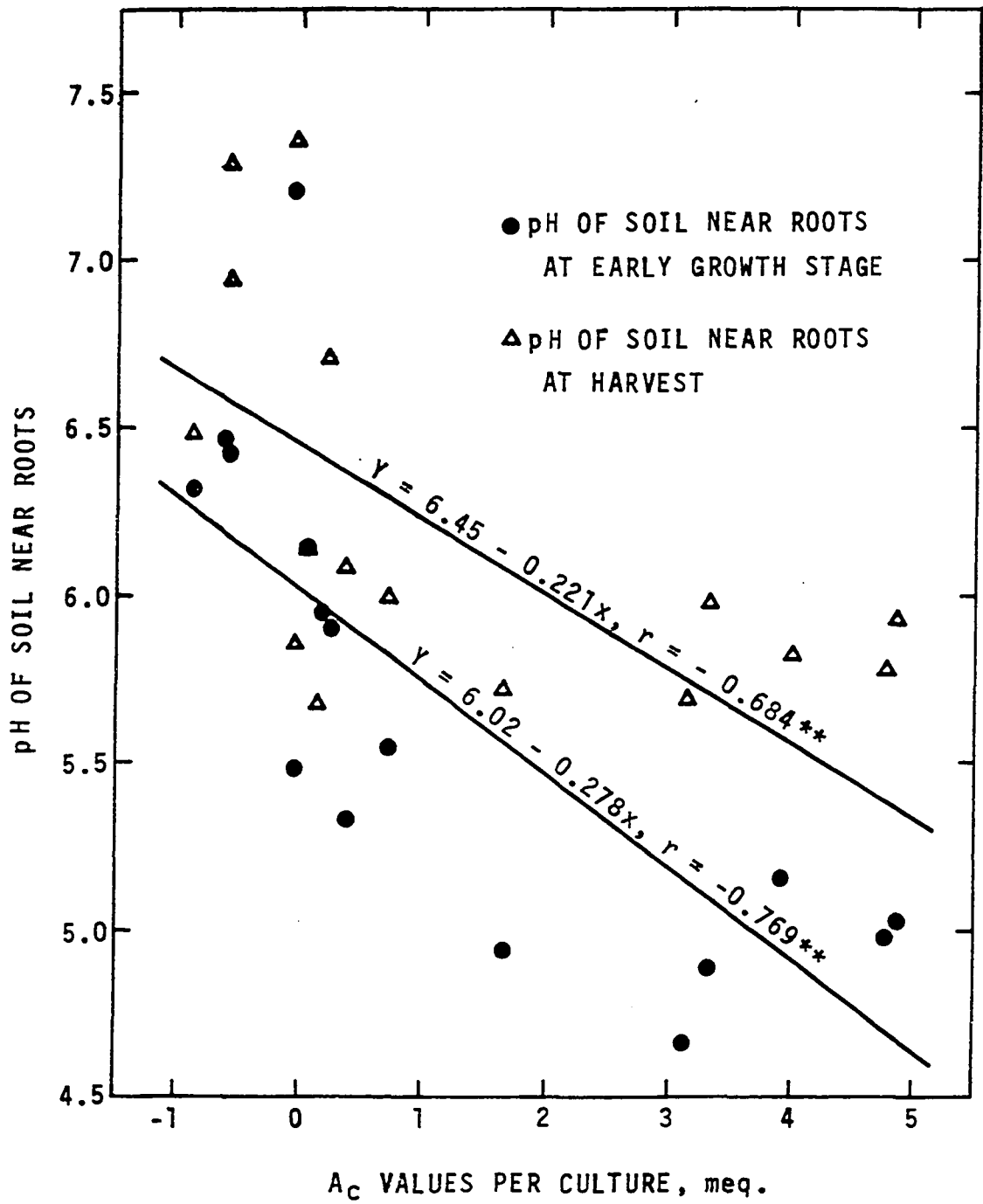
Figure 3. The pH of the soil mass after growth of 16 plant species versus the A_c values, where A_c = (milliequivalents of ash alkalinity minus milliequivalents of nitrogen in plant tops per phosphate rock culture) minus (milliequivalents of ash alkalinity minus milliequivalents of total nitrogen in plant tops per sand culture)

$Y = 6.26 - 0.090 X, r = -0.703**$

$Y = 6.12 - 0.205x, r = -0.851**$

● pH OF SOIL MASS AT EARLY
GROWTH STAGE

△ pH OF SOIL MASS AT HARVEST

pH OF SOIL MASS

A$_C$ VALUES PER CULTURE, meq.
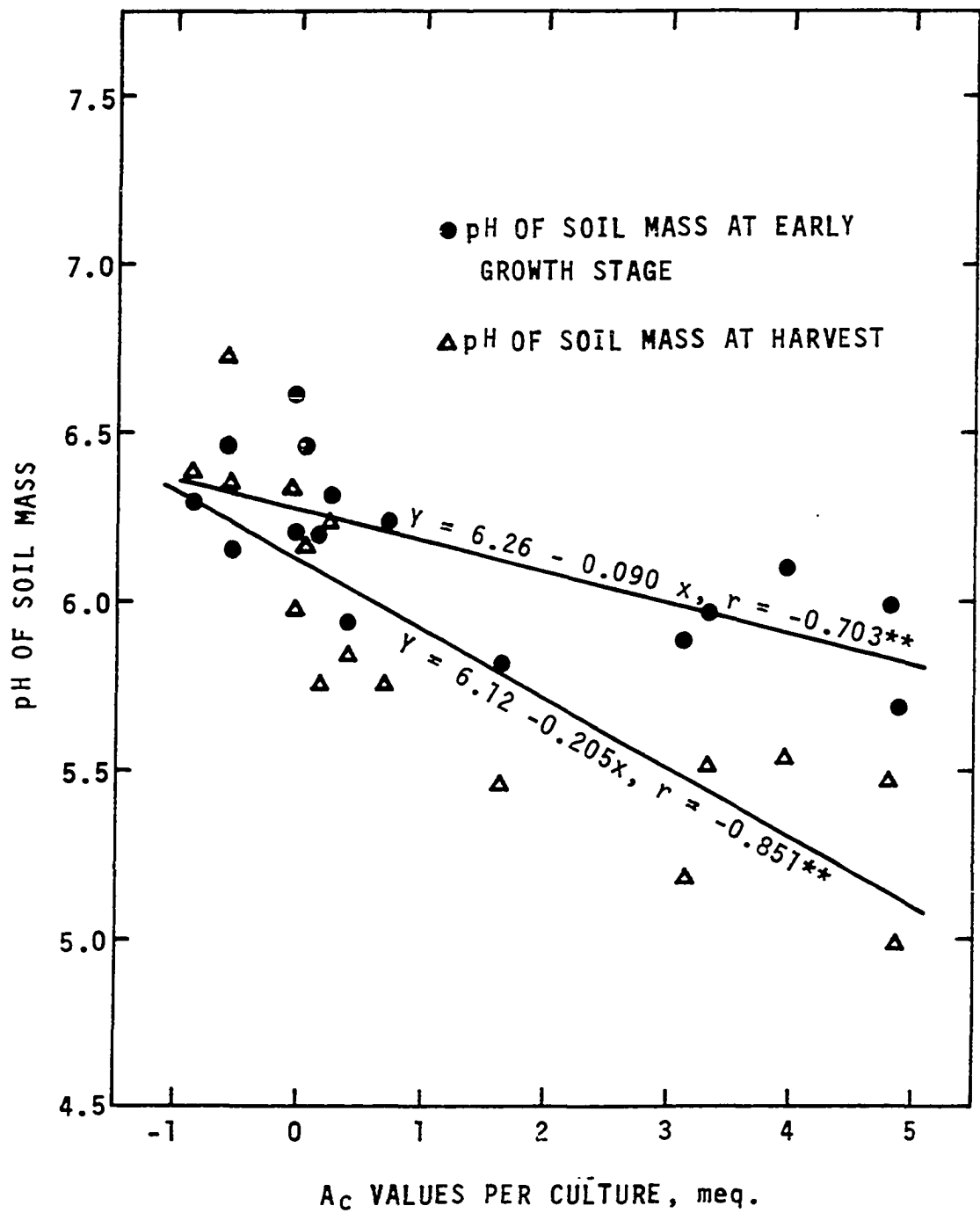
Figure 4. Ratio of availability-coefficient of phosphorus in
          phosphate rock to that of phosphorus in superphos-
          phate for 16 plant species versus the calcium
          content of the plant tops per phosphate rock culture

PHOSPHOROS AVAILABILITY COEFFICIENT RATIO

CALCIUM CONTENT OF PLANT TOPS PER CULTURE, meq.

$Y = 0.013 + 0.098X, r = 0.974**$

55b
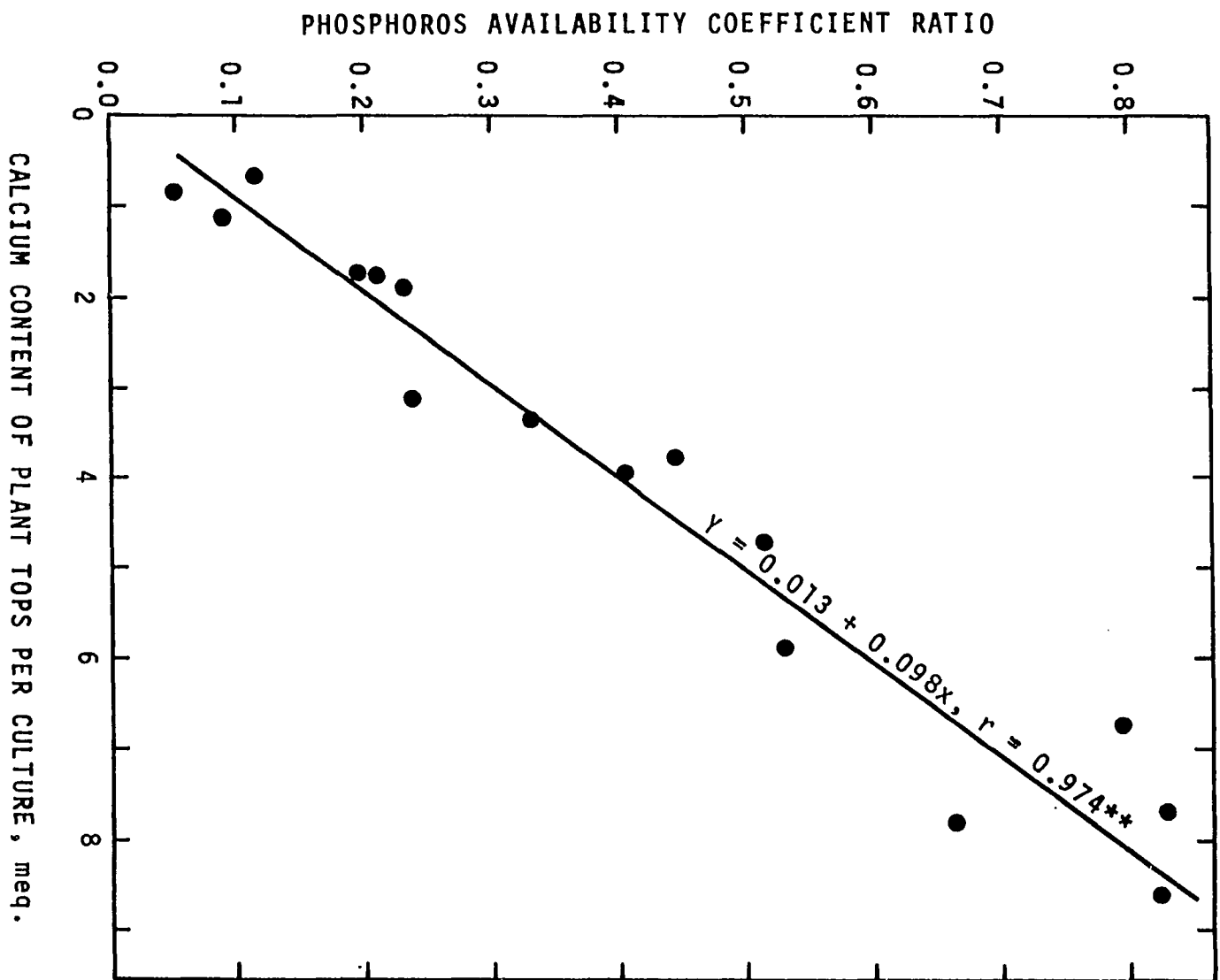
Figure 5.   Ratio of availability coefficient of phosphorus in
            phosphate rock to that of phosphorus in superphos-
            phate for 16 plant species versus the pH of the
            soil near the roots
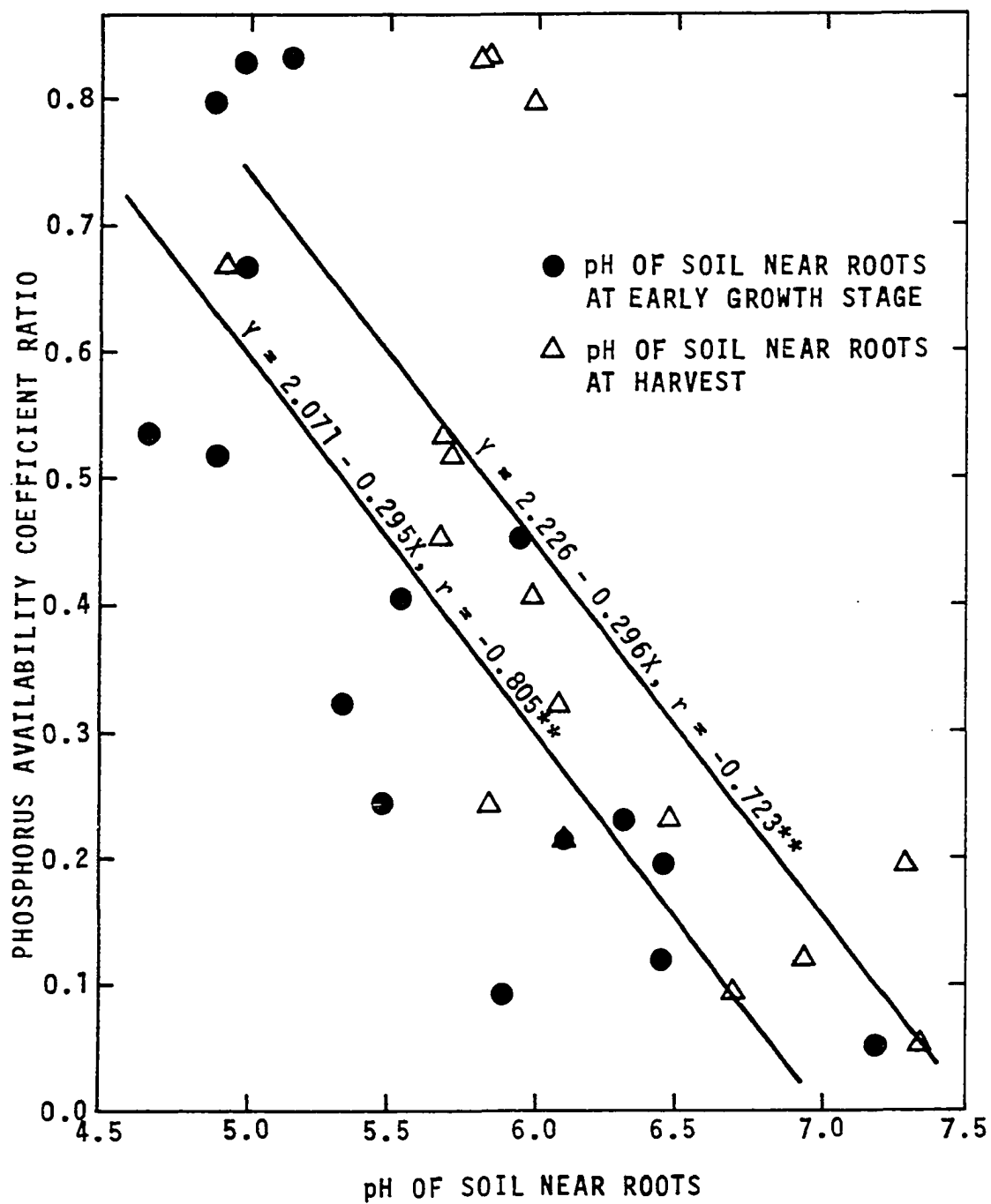
Figure 6. Ratio of availability coefficient of phosphorus
in phosphate rock to that of phosphorus in super-
phosphate for 16 plant species versus the pH of
the soil mass
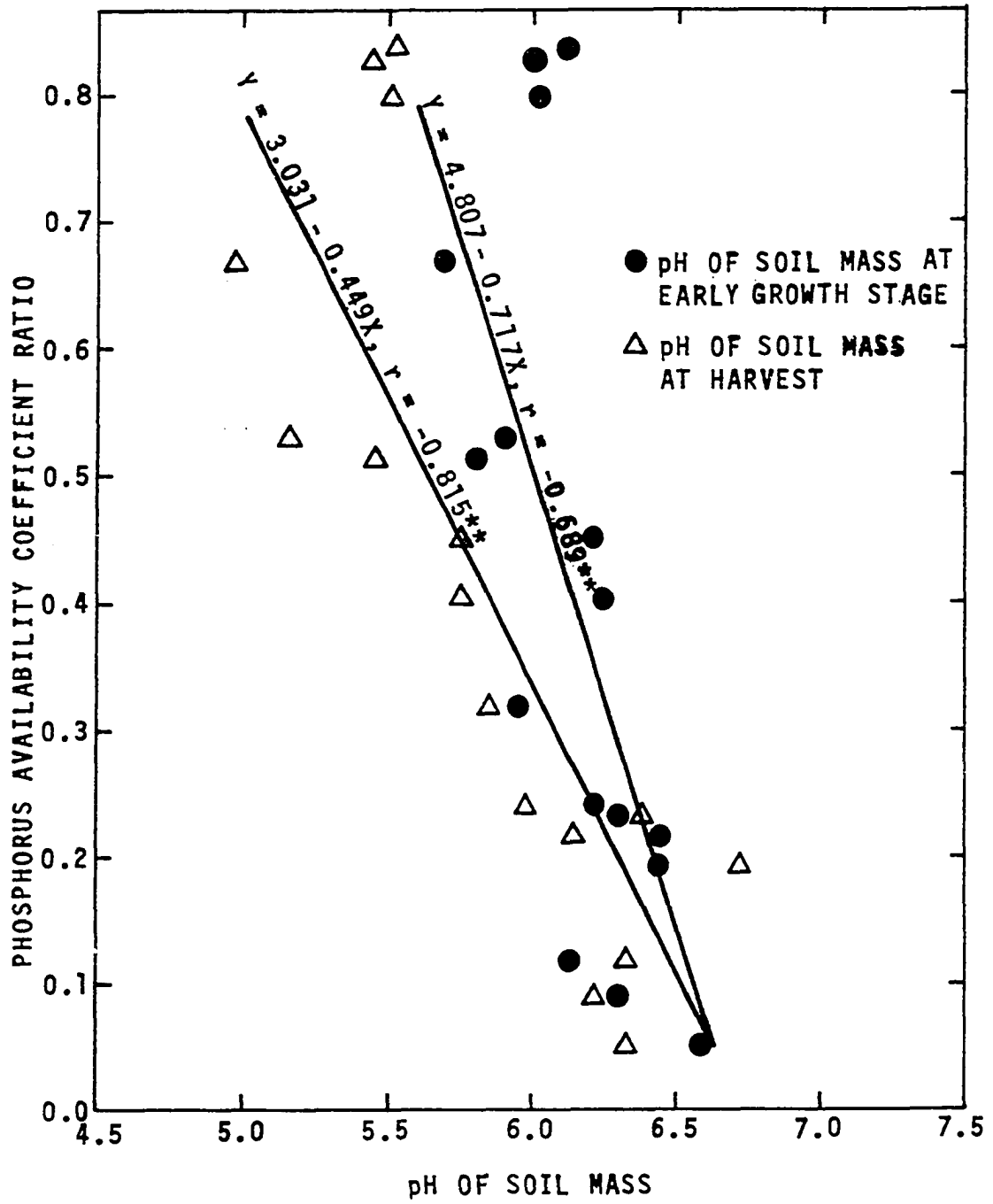
Figure 7. Ratio of availability coefficient of phosphorus in phosphate rock to that of phosphorus in super-phosphate for 16 plant species versus the A_c values, where A_c = (milliequivalents of ash alkalinity minus milliequivalents of total nitrogen in plant tops per phosphate rock culture) minus (milliequivalents of ash alkalinity minus milliequivalents of total nitrogen in plant tops per sand culture)

PHOSPHORUS AVAILABILITY COEFFICIENT RATIO

A_C VALUES PER CULTURE, meq.

$Y = 0.245 + 0.120x$, $r = 0.902**$
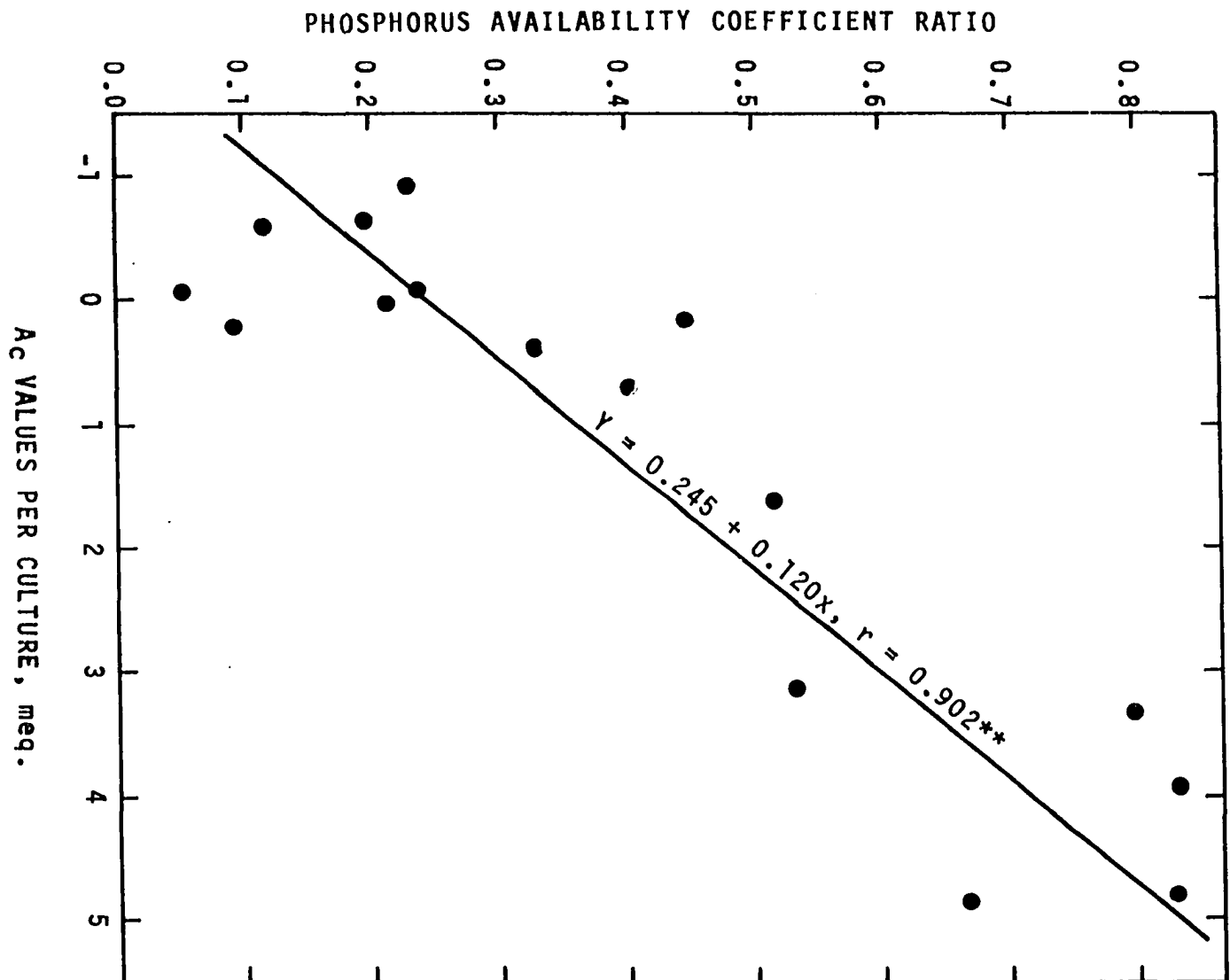
the total bases absorbed by plants. Along with the development of acidity in the soil, therefore, an increase in $\underline{A}$ value in the plants is associated with uptake of more calcium. Both the production of acidity in, and the removal of calcium from, the root medium modify the ionic environment in such a way as to increase the solubility of phosphate rock.

With all four sets of pH measurements, the soil pH decreased significantly as the A_c values of the plants increased. These results support the theory that the differential uptake of cations and anions alters the acidity of the medium. The coefficient of regression of the pH of the soil mass on the A_c value was greater in absolute terms at harvest than at the early growth stage, as seems reasonable from the cumulative effects of differential ion absorption during growth. Moreover, the absolute values of the coefficient of regression of the pH of the soil on the A_c values were greater in the case of measurements of pH of soil near the roots than in the case of measurements of pH of the soil mass, as would be expected if the cause of the pH changes in the soil originated at the surface of the roots.

The phosphorus availability coefficient ratio, $\underline{R}$, was correlated with the calcium content of the plants at the 1% level of significance. The correlation coefficient (0.974) was the highest one obtained in the experiment. This observation supports Truog's theory that plants that take up relatively large amounts of calcium displace the chemical

equilibrium between the phosphate rock and the soil solution, and this causes more phosphate rock to dissolve and produces a higher concentration of phosphorus in the solution; the plants then take up more phosphorus from phosphate rock.

The phosphorus availability coefficient ratio increased as the pH decreased in all four sets of pH measurements. All correlations were significant at the 1% level. The solubility of phosphate rock increases as the pH decreases. Hence, the increase in soil acidity associated with uptake of cations in excess of anions should theoretically increase the ratio of the availability coefficient of the phosphorus in phosphate rock to that of the phosphorus in superphosphate. The regressions of R on the pH of the soil near the roots were similar at the early growth stage and at harvest, which suggests that R was a function of the pH of the soil near the roots.

The absolute values of the coefficients of regression of R on the pH of the soil mass at both growth stages are larger than the corresponding coefficients of regression of R on the pH of the soil near the roots at both growth stages, reflecting the greater effect of unequal cation and anion uptake by the plants on the pH of the soil near the roots than on the pH of the soil mass.

The phosphorus availability coefficient ratio, R, was correlated with A_c ($r = 0.902$), as would be expected from the fact that both R and A_c were correlated with soil pH and with the calcium content of the plants. Soil pH was negatively

correlated with the calcium content of the plants, presumably because the calcium content of the plants were correlated with R.

The multiple regressions of the phosphorus availability coefficient ratio, R, on the calcium content of the plants and on soil pH are given in Table 6. The multiple correlation coefficients are not appreciably higher than the simple correlation of R with calcium content ($r = 0.974$, Table 5), which suggests that the uptake of calcium by the plants was the primary responsible factor for the differences in R and that soil pH was not. Further evidence is provided by the standard multiple linear regression equations in Table 6, in which the partial regression coefficients, b'_1 and b'_2, are independent of the original units of measurement. In all the four standard multiple regression equations, the partial regression coefficient associated with calcium uptake, b'_1, is much greater than the partial regression coefficient associated with soil pH, b'_2. Moreover, one may note that the sign of b'_2 is positive in every instance, whereas theoretically it should be negative. This observation provides further evidence that when the calcium content of the plants was known, the soil pH was of little or no independent value in estimating the phosphorus availability coefficient ratio, R.

Theoretical calculations by Peaslee et al. (1962) indicate that soil pH has a greater effect than does the concentration of calcium in solution on the concentration of phosphate in

solution in equilibrium with phosphate rock. If one considers $\underline{R}$ an index of the solubility of phosphate rock and the calcium content of the plants an index of calcium uptake from the soil solution, it would thus be supposed that a statistical associa- tion of $\underline{R}$ with soil pH should be found more easily than a statistical association of $\underline{R}$ with calcium content of the plants.

Perhaps a partial explanation for the results obtained may be found in the comparative experimental errors of mea- surement. The experimental errors of calcium measurement were relatively small. The coefficient of variation of calcium determinations within plant samples was only 0.9%, and calcium analyses were made on all ten of the replicate plant samples from the phosphate rock cultures used in calculating $\underline{R}$. In contrast, the pH values of soil near the roots were estimated from calibration curves, the correlations of which were r = -0.59 and r = -0.93. These two sets of measurements and the measurements of pH of the soil mass at the early growth stage were made on only three replicates that were not included in the replicates used for determination of $\underline{R}$ and calcium con- tent. Only the measurements of pH of the soil mass at harvest were made on the ten replicates used in calculating $\underline{R}$. The correlation between $\underline{R}$ and the measurements of pH of the soil mass at harvest was the highest of the group of four correla- tions involving soil pH, as would be expected from the descrip- tion of the method. The coefficient of variation of the pH measurements of the soil mass at harvest over all ten

replicates was 3.9%, which compares with an analogous figure
of 12.3% for the calcium content of the plants over the same
ten replicates. The experimental error associated with the
measurements of pH of the soil mass at harvest is thus
small. Most of the 12.3% figure for calcium arises from dif-
ferences in yield of the plants on the replicate cultures.

The calculations made by Peaslee et al. (1962) had to do
with the rate of change of concentration of phosphorus in
solution with respect to the hydrogen ion concentration at a
constant calcium-ion concentration and with respect to the
calcium-ion concentration at a constant hydrogen-ion concen-
tration. They found that a given change in hydrogen-ion
concentration had many times more effect on the concentration
of phosphate in solution than did an equal change in molar
concentration of calcium. In the experiment under considera-
tion here the pH range was from 5.0 to 6.7, and the range in
calcium content of the plants was from 0.9 to 8.6 meq per
culture. If the pH values are delogarized, one may see that
the range of hydrogen-ion concentration exceeded the range of
calcium content in the plants, which suggests that soil pH
should have been a more significant factor than the calcium
content of the plants. One does not know, however, the range
in concentration of calcium in solution in the soil associated
with the range in content of calcium in the plants.

Another way to look at the results is to use the A_c values
as an index of the change in soil acidity associated with the

growth of the different plant species because, according to theory, the differential uptake of cations and anions by plants from the soil causes the soil acidity to change. The correlation between R and A_c was higher than the highest correlation of R and soil pH ($r = 0.902$ vs. $r = -0.815$), but still lower than the correlation between R and the calcium content of the plants ($r = 0.902$ vs. $r = 0.974$). The poorer correlation in the case of A_c may be due to the relatively high experimental errors associated with the determination of A_c. The coefficient of variation of determinations of A was 27.24% and the coefficient of variation of determination of A_c would be even greater because of the additional sources of error in A_c (a comparable coefficient of variation for A_c could not be correlated because of insufficient plant material to make the replicate analyses needed), but the coefficient of variation of determinations of calcium content was only 0.92%. Thus, if the A_c values could be determined in such a way that this error of the mean was comparable to the error of the mean of the determinations of calcium content, the correlation between the A_c value and R might be as great as, or greater than, the correlation between the calcium content and R. Thus, as a consequence, it might be inferred that the correlation between the soil acidity and R is as great as, or greater than, the correlation between calcium uptake and R.

In summary, the results of this experiment support the theory that the differential uptake of cations and anions

from the soil by plants affects the acidity of the soil and the calcium concentration in the soil solution around the roots and that these factors affect the solubility of phosphate rock and the availability coefficient of the phosphorus it contains. Plants that acidify the soil and absorb much calcium increase the availability coefficient of the phosphorus. Plants that raise the pH of the soil and absorb little calcium decrease the availability coefficient of the phosphorus. The results suggest that differences in calcium uptake had a more significant effect than differences in soil acidity on the availability coefficient of the phosphorus of phosphate rock.

C. Experiment 3 (Solution Culture Experiment)

The initial and final calcium, magnesium, potassium, nitrate, and sulfate contents of the culture solutions, the A_s values (milliequivalents of cations absorbed minus milliequivalents of anions absorbed by the plants), and the pH of the solutions after the absorption period are given in Appendix Tables 32 to 36. The means of the A_s values, pH values, and calcium uptake values are given in Table 7. Certain relationships among the variables in Table 7 are summarized in Table 8 and Figure 8.

The pH values of the solutions after absorption of ions by the plants were correlated negatively with the A_s values, as expected from theory and as indicated also by the measurements made on plants and soils in the preceding experiment.

Table 7. Summary of data obtained in Experiment 3 (Solution
Culture Experiment)

Plant	A_s[a] values per culture, meq	pH of solution after ion uptake by plants	Calcium uptake per culture, meq
None	0.0	5.43	0.0
Barley	-1.482	7.26	0.216
Oat	-0.935	7.03	0.178
Rye	-1.021	7.50	0.249
Ryegrass	-2.112	7.72	0.493
Sorghum	-2.294	7.51	0.380
Wheat	-2.982	7.64	0.627
Buckwheat	-0.624	4.96	0.204
Cabbage	-0.987	7.00	0.226
Collards	-1.602	7.31	0.456
Rape	-1.910	7.22	0.608
Alsike clover	-1.411	7.34	0.391
Ladino clover	-2.404	7.46	0.449
Red clover	-0.985	6.66	0.278
White clover	-1.326	7.29	0.307
Tobacco	-1.659	7.26	0.519
Tomato	-0.985	6.80	0.289

[a]A_s = milliequivalents of cations absorbed minus milli-
equivalents of anions absorbed per solution culture.

Table 8. Linear correlations and linear regressions among variables in Experiment 3 (Solution Culture Experiment)

Independent variable X	Dependent variable Y	Correlation coefficient r	Regression coefficient $b \pm s.e._b$[a]	Regression equation
A_s[b]	pH of solution after ion uptake by plants	-0.639**	-0.632 ± 0.203	Y = 6.144 - 0.632X
Calcium uptake	pH of solution after ion uptake by plants	0.261	2.258 ± 1.016	Y = 6.294 + 2.258X

[a]$s.e._b$ = standard error of the regression coefficient, b.

[b]A_s = milliequivalents of cations absorbed minus milliequivalents of anions absorbed per solution culture.

**Significant at 1% level.

Figure 8. The pH of the culture solution after ion absorp-
tion by 16 plant species versus the $\underline{A}$ values, where
A_s = milliequivalents of cations absorbed minus
milliequivalents of anions absorbed per solution
culture

pH OF SOLUTION AFTER ION UPTAKE BY PLANTS

As VALUES PER CULTURE, meq.

Y = 6.14 - 0.632x

Y = -0.639x
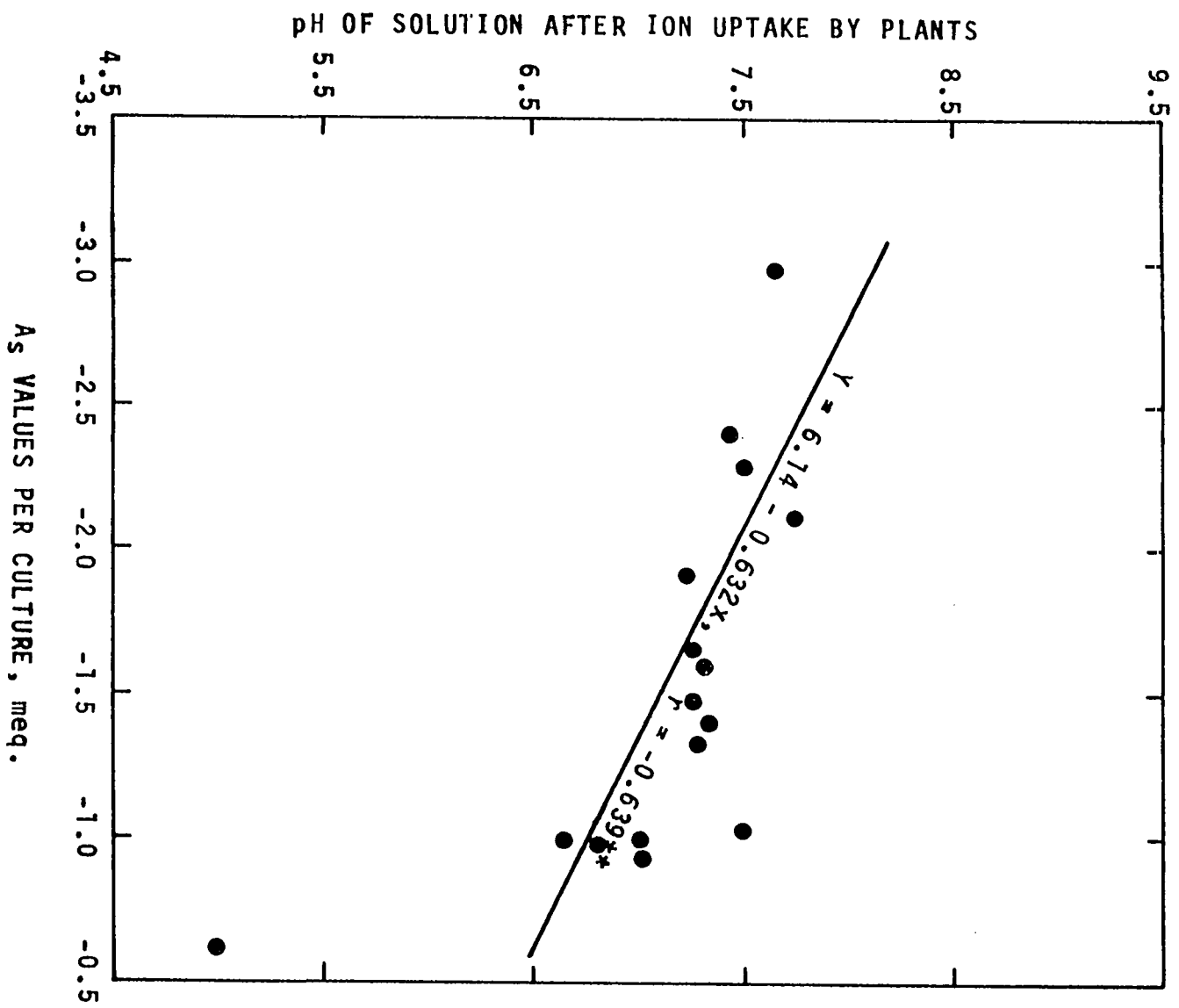
The solutions were aerated continuously with CO_2-free air during the absorption period. It was found experimentally that an artifically carbonated nutrient solution of pH 4.88 had a pH of 6.68 after bubbling with CO_2-free air for 30 minutes, a pH value that compares closely with the initial value of 6.70 before carbonation. Thus, the pH values of the solutions after the absorption period should be little influenced by free carbonic acid derived from the roots.

There was no significant correlation between the calcium uptake and the pH of the solutions. The trend was for the pH of the solutions to increase as the calcium uptake increased, which is the reverse of the observation in the preceding experiment. This result indicates that calcium uptake was not the principal cause of changes in pH of the solutions.

The results of this experiment confirm the inference made from the main experiment that the differential uptake of cations and anions by plants produces changes in the pH of the nutrient medium. The higher is the A_s value, the greater is the acidity of the nutrient medium. In contrast to the findings in the main experiment, however, the solution culture experiment provided no indication of a close association of calcium uptake with the pH of the nutrient medium.

V. SUMMARY AND CONCLUSIONS

Soil- and solution-culture experiments were conducted under greenhouse conditions to investigate associations between the mineral composition of different plant species and ratio of the availability coefficient of the phosphorus in phosphate rock to that of the phosphorus in superphosphate. In particular, attention was directed to two aspects of the mineral composition: (1) The difference between the content of chemical equivalents of mineral elements absorbed through the roots as cations and the content of chemical equivalents of mineral elements absorbed through the roots as anions. Uptake of cations in excess of anions should make the nutrient medium more acid. Because the solubility of phosphate rock increases with the acidity, the phosphorus availability-coefficient ratio observed with the various plant species should increase with the excess of mineral elements absorbed as cations over mineral elements absorbed as anions in the plants and with an increase in soil acidity resulting therefrom. (2) The calcium content of the plants. Calcium is one of the ionic components of the apatite mineral that contains the phosphorus in phosphate rock. Therefore, on the basis of the solubility-product principle, the availability coefficient of the phosphorus in phosphate rock should increase with the calcium content of the various plant species because increasing calcium absorption will lower the activity of calcium in the

soil solution and will increase the dissolution of the apatite.

Two experiments were done in which various plant species were grown on a single soil. The results showed that, with an increase in the excess of mineral elements absorbed as cations over the mineral elements absorbed as anions found by analysis in the various plant species, the soil pH decreased and the ratio of the availability coefficient of the phosphorus in phosphate rock to that of the phosphorus in superphosphate increased. Similarly, with an increase in the calcium content of the various plant species, the phosphorus availability-coefficient ratio increased. The calcium content of the plants was correlated negatively with the pH of the soil and positively with the excess of mineral elements absorbed as cations over the mineral elements absorbed as anions in the various plant species.

The statistical association of the phosphorus availability-coefficient ratio with the calcium content of the plants was greater than it was with the soil pH or the excess of mineral elements absorbed as cations over the mineral elements absorbed as anions. Although this result implies that, of the three factors mentioned, calcium uptake had the greatest influence on the availability coefficient of the phosphorus in phosphate rock, the inference is not as straightforward as desirable for two reasons. First, the experimental errors were far greater in the case of the measurement of the

excess of mineral elements absorbed as cations over the mineral elements absorbed as anions than was the experimental error of measurement of the calcium content of the plants. Second, in an experiment in which the same plant species were grown in solution cultures, the uptake of calcium had a low positive but statistically nonsignificant correlation with the pH value of the solutions after absorption of ions by the plants.

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VIII: APPENDIX

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Table 9. Eh and estimated pH of soil near the roots at the early growth stage in the preliminary experiment

Plant	Culture no.	Eh, mv (22-27°C)[a] Individual measurements	Mean	Estimated pH Individual values	Mean
Barley	108	52,58	55	6.21	
	118	52,64,62	59	6.15	
	124	63,60	61	6.12	6.16
Oat	105	57,52	55	6.21	
	112	52,54	53	6.24	
	123	52,52,60,52,54	54	6.23	6.23
Sorghum	106	72,74	73	5.93	
	120	62,84,87,100,72,80	77	5.87	
	125	70,80,80,85	79	5.84	5.88
Rye	102	60,56,63	60	6.14	
	113	60,62,55,52	57	6.18	
	126	56,60,53,52	57	6.18	6.17
Ryegrass	109	62,62	62	6.10	
	111	68,68,68	68	6.01	
	123	68,60	64	6.07	6.06
Buckwheat	104	108,108,108	108	5.38	
	116	108,108	108	5.38	
	124	112,112,110,105	110	5.55	5.37
Rape	110	62,70,66,74,72	69	6.20	
	119	68,65,67,77,75	70	5.98	
	121	57,58,75	63	6.09	6.02
Alsike clover	107	60,60,60,60	60	6.14	
	115	60,60,58	59	6.12	
	130	62,62	62	6.10	6.43
Tobacco	103	60,60	60	6.14	
	107	55,58,54	55	6.21	
	122	50,50,54	51	6.26	6.49
Lupine	101	112,112	112	5.51	
	114	102,102	102	5.47	
	129	102,102	102	5.47	5.67

[a]Against a saturated calomel electrode in the presence of quinhydrone.

Table 10. Eh of wet soil mass in the presence of quinhydrone, and pH of suspension of wet soil mass at the early growth stage for the calibration curve in the preliminary experiment

Culture no.	Eh, mv (24°C)[a]	pH[b]
125	82	5.78
105	80	5.82
106	70	6.00
118	59	6.16
119	55	6.21

[a]Against saturated calomel electrode in the presence of quinhydrone.

[b]Equal parts of soil (air-dry basis) and water by weight. Measurements were made with a glass electrode pH meter.

Table 11. Eh and estimated pH of soil near the roots at harvest in the preliminary experiment

Plant	Culture no.	Eh, mv $(22-27^\circ C)$ [a] Individual measurements		Mean	Estimated pH Individual values	Mean
Barley	8	48, 27		38	6.74	
	18	28, 12, 35		32	6.83	
	24	48, 45, 49		47	6.61	
	50	32, 32		32	6.83	6.75
Oat	5	44, 38, 33, 22		34	6.80	
	12	32, 27, 38		32	6.83	
	23	33, 37		35	6.78	
	45	32, 35, 40		37	6.75	6.79
Sorghum	6	69, 70, 68, 73		70	6.13	
	20	82, 82		82	5.97	
	25	80, 80, 80		80	6.00	
	44	78, 79, 80		79	6.01	6.07
Rye	2	98, 98		98	5.83	
	13	88, 86, 89		88	5.98	
	26	69, 70, 73		71	6.12	
	41	80, 87. 73		80	6.00	5.98
Ryegrass	9	37, 45, 56		46	6.62	
	11	38, 42		40	6.70	
	35	52, 38		45	6.63	
	49	32, 37, 45, 48		42	6.68	6.66
Buckwheat	4	80, 90, 100, 84		92	5.92	
	16	90, 98,		94	5.89	
	27	93, 91		92	5.92	
	47	90, 94		92	5.92	5.91
Rape	10	125, 122, 127		125	5.38	
	19	122, 125		124	5.39	
	21	125, 127		126	5.37	
	44	122, 138, 124		128	5.34	5.37
Alsike clover	7	110, 115, 105		110	5.58	
	15	115, 90		103	5.68	
	30	108, 106, 110		108	5.61	
	46	102, 99, 101		101	5.71	5.64
Tobacco	3	132, 140		136	5.24	
	17	140, 122		131	5.30	
	22	138, 140		139	5.20	
	42	115, 158		137	5.22	5.24

[a]Against a saturated calomel electrode in the presence of quinhydrone.

Table 12. Eh of wet soil mass in the presence of quinhydrone and pH of suspension of wet soil mass at harvest for the calibration curve in the preliminary experiment

Culture no.	Eh, mv (22-27°C)[a]	pH[b]
7	100	5.83
44	76	6.00
49	64	6.21
45	41	6.42
35	52	6.28

[a]Against a saturated calomel electrode.

[b]Equal parts of soil (air-dry basis) and water by weight. Measurements were made with a glass electrode pH meter.

Table 13. pH of air-dried soil mass at harvest in the preliminary experiment

Plant	pH values[a]				
	Rep. 1[b]	Rep. 2	Rep. 3	Rep. 4	Mean
Barley	6.70	6.83	6.62	6.72	6.72
Oat	6.55	6.53	6.82	6.47	6.59
Sorghum	6.45	6.32	6.35	6.74	6.46
Rye	6.72	6.75	6.60	6.85	6.75
Ryegrass	6.80	6.50	6.82	6.83	6.74
Buckwheat	5.92	5.42	5.40	5.31	5.51
Rape	5.39	5.35	5.55	6.18	5.62
Alsike clover	5.98	6.68	6.80	6.92	6.59
Tobacco	6.10	6.05	5.62	5.72	5.87

[a]Equal parts of soil (air-dry basis) and water by weight. Measurements were made with a glass electrode pH meter.

[b]Measurements on replicate cultures.

Table 14. Yield of dry matter in above-ground parts of plants in the preliminary experiment

| Plant | Yield of dry matter per | | | | |
	1	2	3	4	5
	Sand cultures				
Barley	0.650	0.660	0.645	0.870	0.810
Oat	0.980	1.070	1.095	1.070	1.060
Rye	0.440	0.435	0.415	0.360	0.475
Ryegrass	0.170	0.212	0.180	0.170	0.235
Sorghum	0.450	0.700	0.495	0.580	0.430
Alsike clover	0.030	0.050	0.080	0.050	0.010
Buckwheat	0.100	0.080	0.060	0.155	0.168
Rape	0.010	0.040	0.020	0.080	0.030
Tobacco	0	0	0	0	0
	Soil cultures without added phosphorus				
Barley	1.995	1.710	2.000	1.230	1.680
Oat	2.850	2.780	3.110	3.040	3.240
Rye	1.380	0.730	1.540	0.690	1.220
Ryegrass	1.070	1.415	1.560	0.880	1.240
Sorghum	0.900	1.120	1.460	1.190	1.180
Alsike clover	0.350	0.400	0.670	0.390	0.930
Buckwheat	0.840	1.120	1.220	1.500	1.780
Rape	4.130	2.860	2.260	2.320	2.703
Tobacco	0.245	0.730	0.480	0.630	0.355
	Soil cultures treated with superphosphate				
Barley	2.670	2.170	2.345	2.715	2.625
Oat	4.765	3.785	3.730	4.980	3.795
Rye	1.480	1.480	1.670	1.445	1.690
Ryegrass	1.305	2.210	1.615	1.625	1.820
Sorghum	1.630	2.870	2.280	3.390	2.000
Alsike clover	1.810	0.965	0.660	0.840	1.035
Buckwheat	1.995	1.970	1.560	1.850	2.170
Rape	3.270	3.590	3.545	4.890	2.920
Tobacco	1.705	1.730	1.070	1.800	2.325
	Soil cultures treated with phosphate rock				
Barley	2.800	2.340	2.855	1.670	2.800
Oat	3.965	3.980	4.150	3.723	3.900
Rye	1.760	1.283	1.720	1.825	2.455
Ryegrass	1.510	2.340	2.435	1.325	1.810
Sorghum	1.830	1.590	2.135	1.240	1.520
Alsike clover	1.010	1.260	1.345	1.315	1.280
Buckwheat	1.655	1.660	2.180	2.165	1.940
Rape	2.075	4.410	3.470	3.630	3.190
Tobacco	1.475	1.130	2.300	2.520	2.000

culture in indicated replicate, g

6	7	8	9	10	Mean
0.760	0.850	0.790	0.810	0.755	0.760
1.245	0.990	1.085	1.120	1.160	1.087
0.450	0.340	0.405	0.420	0.500	0.424
0.230	0.225	0.185	0.260	0.170	0.204
0.520	0.440	0.520	0.630	0.610	0.539
0.050	0.060	0.060	0.005	0.040	0.043
0.150	0.850	0.060	0.060	0.050	0.175
0.030	0.010	0.080	0.140	0.015	0.047
0	0	0	0	0	0
1.710	1.680	2.200	1.810	2.460	1.908
2.830	3.130	3.220	3.080	3.060	3.034
1.045	1.000	1.420	1.490	1.460	1.301
0.930	1.315	1.630	0.630	1.130	1.243
1.015	1.040	0.840	1.130	0.900	1.087
0.715	0.140	0.530	0.600	0.660	0.540
1.010	0.810	1.380	1.070	0.645	1.238
4.255	2.980	3.260	4.380	3.720	3.287
0.350	0.550	0.190	0.095	0.430	0.405
2.720	1.845	2.473	2.490	2.670	2.426
4.795	3.882	3.410	3.470	3.355	3.915
1.450	2.220	1.470	1.825	1.840	1.572
1.920	2.240	1.640	2.440	2.260	1.907
1.590	2.890	1.520	0.890	2.350	2.150
1.060	0.645	1.520	0.950	1.560	1.104
1.870	1.820	1.780	2.520	1.900	1.804
3.110	2.070	2.690	3.470	9.020	3.355
1.540	2.265	3.100	1.370	1.470	1.837
3.160	2.800	2.410	2.840	2.600	2.583
3.740	3.745	4.100	3.220	4.270	3.884
1.385	1.850	1.660	1.700	2.620	1.809
1.020	1.620	2.560	1.170	1.550	1.671
1.730	1.040	1.510	1.840	1.565	1.600
0.330	0.540	1.225	1.035	1.290	1.068
1.495	1.550	2.070	1.505	2.310	1.749
3.265	4.950	4.285	4.370	4.580	3.875
1.780	1.590	2.260	1.740	1.600	1.839

Table 15. Yield of phosphorus in above-ground parts of plants in the preliminary experiment

Plant	Yield of phosphorus per				
	1	2	3	4	5
Soil cultures without added phosphorus					
Barley	2.127	1.789	2.248	1.004	1.277
Oat	3.004	2.602	2.811	2.426	2.929
Rye	2.089	0.737	1.857	0.640	1.425
Ryegrass	0.942	1.296	1.429	0.942	2.114
Sorghum	0.502	0.685	0.929	0.666	0.689
Alsike clover	0.687	0.785	1.070	0.714	1.934
Buckwheat	2.898	2.424	5.395	5.180	1.559
Rape	4.560	2.768	1.889	2.144	2.240
Tobacco	0.210	0.619	0.368	0.475	0.615
Soil cultures treated with superphosphate					
Barley	5.057	3.602	4.939	4.632	4.100
Oat	6.061	4.708	5.435	6.468	7.829
Rye	3.596	3.963	3.724	2.876	2.626
Ryegrass	1.976	3.474	2.584	3.302	3.425
Sorghum	1.252	2.175	1.860	2.570	1.364
Alsike clover	4.330	1.421	1.591	1.907	1.728
Buckwheat	3.356	7.671	3.522	10.228	11.050
Rape	4.680	9.269	6.063	9.780	5.408
Tobacco	1.756	2.477	1.002	1.757	2.776
Soil cultures treated with phosphate rock					
Barley	5.813	4.306	3.889	1.466	4.077
Oat	5.400	5.317	5.901	4.321	5.381
Rye	3.260	2.346	2.380	2.793	4.650
Ryegrass	2.633	3.664	2.075	1.497	3.276
Sorghum	1.182	1.205	1.618	0.980	1.021
Alsike clover	1.723	2.901	2.690	1.956	2.642
Buckwheat	6.620	8.532	6.806	11.257	5.397
Rape	5.498	7.885	8.342	10.534	9.996
Tobacco	1.985	1.214	4.094	3.740	2.403

culture in indicated replicate, mg

6	7	8	9	10	Mean
1.580	1.781	2.732	1.962	2.273	1.877
2.773	2.867	3.078	3.142	2.497	2.813
1.122	0.936	2.002	1.874	1.837	1.452
0.595	k,228	1.444	0.762	0.967	1.172
0.552	0.607	0.517	0.574	0.495	0.622
1.619	0.317	0.546	1.162	1.241	1.008
2.384	2.223	2.572	2.529	1.512	2.868
4.519	3.010	2.914	4.468	3.633	3.219
0.351	0.361	0.567	0.634	0.149	0.435
3.672	2.018	3.767	3.478	3.668	3.893
6.429	4.584	4.256	5.018	4.737	5.652
2.996	4.205	1.973	4.811	4.939	3.571
3.387	3.420	3.382	3.523	4.457	3.338
1.088	2.705	1.040	0.670	1.805	1.653
1.929	1.073	2.572	1.740	1.685	2.008
5.311	4.732	6.073	6.108	4.123	6.217
7.769	4.482	7.376	9.820	6.850	7.254
1.546	2.377	4.483	1.173	1.885	2.173
5.852	4.096	3.258	5.682	4.748	4.416
3.777	4.698	5.510	3.761	4.987	4.902
2.252	3.108	2.898	1.612	4.506	2.980
0.904	2.569	3.548	0.737	1.900	2.280
1.166	0.564	0.078	1.192	0.926	1.083
0.605	1.081	2.325	1.979	1.876	1.981
4.683	4.758	8.177	5.021	6.616	6.787
9.240	10.667	8.156	8.315	11.679	8.921
2.617	2.401	7.453	1.740	2.218	2.987

Table 16. Total nitrogen in above-ground parts of plants in the preliminary experiment

| Plant | Nitrogen in plants per gram of dry matter, meq | | | | | |
| | Phosphate rock cultures | | | | | |
	Reps. 1 & 2	Reps. 3 & 4	Reps. 5 & 6	Reps. 7 & 8	Reps. 9 & 10	Sand cultures
Barley	2.145	2.145	1.988	2.059	2.095	1.165
Oat	1.380	1.394	1.358	1.644	1.523	0.772
Rye	2.467	2.431	1.909	2.317	2.152	0.479
Ryegrass	2.295	2.059	2.152	2.452	2.753	2.259
Sorghum	1.244	1.258	1.279	1.258	1.258	2 974
Alsike clover	2.896	3.110	3.067	2.330	2.258	-[a]
Buckwheat	1.916	1.487	1.773	1.945	1.945	2.318
Rape	1.230	0.858	1.087	1.230	1.144	-[a]
Tobacco	2.480	2.159	2.016	2.002	2.216	-[b]

[a]Too little sample to analyze.

[b]No sample.

Table 17. Ash alkalinity of above-ground parts of plants in the preliminary experiment

Plant	Phosphate rock cultures					Sand cultures
	Reps. 1 & 2	Reps. 3 & 4	Reps. 5 & 6	Reps. 7 & 8	Reps. 9 & 10	
Barley	2.369	2.124	2.267	2.450	1.572	1.777
Oat	1.062	0.674	1.327	1.225	1.103	0.388
Rye	1.960	2.185	2.471	2.185	2.430	0.347
Ryegrass	1.021	1.776	1.919	2.491	2.614	0.756
Sorghum	1.082	1.695	1.593	1.613	1.225	1.041
Alsike clover	3.186	2.573	3.390	3.349	2.614	-[a]
Buckwheat	3.778	4.207	4.390	4.227	4.370	1.914
Rape	2.573	2.736	3.165	2.736	3.022	-[a]
Tobacco	3.961	4.880	4.513	4.901	4.942	-[b]

[a]Too little sample to analyze.

[b]No sample.

Table 18. Ratio of availability coefficient of phosphorus in
phosphate rock to that of phosphorus in superphos-
phate (R), and the A_c values in the preliminary
experiment

Plant	R	A_c [a]
Barley	0.414	0.134
Oat	0.310	-1.067
Rye	0.344	-0.107
Ryegrass	0.500	-0.153
Sorghum	0.231	1.323
Alsike clover	0.474	0.737
Buckwheat	0.348	4.566
Rape	0.692	6.780
Tobacco	0.508	4.543

[a] A_c = (milliequivalents of ash alkalinity minus milli-
equivalents of total nitrogen in plant tops per phosphate
rock culture) minus (milliequivalents of ash alkalinity minus
milliequivalents of total nitrogen in plant tops per sand
culture). Values are milliequivalents per culture.

Table 19. Eh and estimated pH of soil near the roots at the early growth stage in the main experiment

	Eh, mv[a]			Estimated pH[b]			
Plant	Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3	Mean
Barley	73	79	80	6.58	6.42	6.40	6.47
Oat	81	83	85	6.38	6.32	6.27	6.32
Rye	58	49	40	6.98	7.20	7.44	7.21
Ryegrass	88	91	92	6.18	6.12	6.09	6.13
Sorghum	102	98	98	5.82	5.94	5.94	5.90
Wheat	81	71	83	6.37	6.62	6.32	6.44
Buckwheat	134	125	141	4.99	5.26	4.82	5.02
Cabbage	133	136	134	5.02	4.94	4.99	4.98
Collards	127	129	126	5.17	5.12	5.20	5.16
Rape	136	135	140	4.94	4.96	4.76	4.88
Alsike cl.	100	98	93	5.87	5.93	6.06	5.95
Ladino cl.	120	120	123	5.35	5.35	5.28	5.33
Red clover	111	118	116	5.58	5.40	5.46	5.48
White cl.	113	112	113	5.52	5.56	5.53	5.54
Tobacco	141	149	149	4.81	4.60	4.60	4.67
Tomato	138	135	137	4.88	4.96	4.91	4.92

[a]Against a saturated calomel electrode in the presence of quinhydrone.

[b]Estimated from a calibration curve of pH versus Eh.

Table 20. Eh of the wet soil mass in the presence of quin-
hydrone and pH of a suspension prepared from the
wet soil mass at the early growth stage used in
preparation of the calibration curve in the main
experiment

Soil sample	Eh, mv[a]	pH[b]	Soil sample	Eh, mv	pH
1	87	6.24	25	115	5.91
2	122	5.63	26	58	6.50
3	88	6.12	27	72	6.45
4	110	5.81	28	98	5.88
5	100	6.05	29	60	6.66
6	75	6.52	30	64	6.59
7	85	5.98	31	61	6.80
8	105	5.90	32	101	5.89
9	78	6.50	33	109	5.94
10	87	6.28	34	62	6.82
11	62	6.65	35	88	5.87
12	118	5.96	36	99	5.97
13	103	6.23	37	93	6.54
14	98	6.43	38	110	5.88
15	93	6.59	39	98	6.05
16	82	6.62	40	40	6.30
17	75	6.31	41	88	6.14
18	70	6.48	42	82	6.12
19	87	5.89	43	58	6.34
20	62	6.01	44	76	6.38
21	118	6.02	45	72	6.40
22	93	6.58	46	62	6.62
23	70	6.42	47	124	5.72
24	85	6.32	48	90	6.08

Eh (mv) = 326 - 38.45 pH, r = -0.594*

[a]Against a saturated calomel electrode.

[b]Equal parts of soil (air-dry basis) and water by weight.
Measurements were made with a glass electrode pH meter.

*Significant at the 5% level.

Table 21. Eh and estimated pH of soil near the roots at harvest in the main experiment

Plant	Eh, mv[a]			Estimated pH[b]			
	Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3	Mean
Barley	55	66	43	7.29	7.12	7.47	7.29
Oat	118	108	99	6.33	6.48	6.62	6.48
Rye	46	51	52	7.43	7.35	7.33	7.37
Ryegrass	134	130	130	6.09	6.15	6.15	6.13
Sorghum	97	97	85	6.65	6.65	6.83	6.71
Wheat	83	81	69	6.86	6.89	7.08	6.94
Buckwheat	224	206	201	4.72	4.99	5.07	4.93
Cabbage	156	157	147	5.75	5.74	5.89	5.79
Collards	146	147	158	5.84	5.89	5.72	5.82
Rape	124	155	145	6.24	5.77	5.92	5.98
Alsike cl.	163	159	161	5.65	5.71	5.69	5.68
Ladino cl.	135	138	129	6.07	6.03	6.16	6.09
Red clover	147	152	149	5.89	5.81	5.89	5.86
White cl.	146	138	135	5.91	6.03	6.07	6.00
Tobacco	157	157	166	5.74	5.74	5.60	5.69
Tomato	162	157	156	5.66	5.74	5.75	5.72

[a]Against a saturated calomel electrode in the presence of quinhydrone.

[b]Estimated from a calibration curve of pH versus Eh.

Table 22. Eh of the wet soil mass in the presence of quin-
-hydrone and pH of a suspension prepared from the
wet soil mass at harvest used in preparation of
the calibration curve in the main experiment

Soil sample	Eh, mv[a]	pH[b]	Soil sample	Eh, mv	pH
1	104	6.54	25	126	6.18
2	124	6.20	26	79	6.88
3	94	6.62	27	181	5.30
4	89	6.88	28	118	6.28
5	142	5.94	29	143	5.82
6	185	5.42	30	143	5.97
7	159	5.62	31	160	5.68
8	93	6.62	32	167	5.72
9	142	5.96	33	62	7.01
10	72	7.20	34	171	5.45
11	151	5.87	35	86	6.82
12	82	6.75	36	106	6.49
13	162	5.62	37	193	4.92
14	158	5.79	38	81	6.62
15	141	5.91	39	131	6.05
16	169	5.52	40	63	7.01
17	89	6.68	41	157	5.58
18	73	7.20	42	135	6.02
19	226	4.91	43	142	5.95
20	94	6.68	44	127	6.12
21	155	5.72	45	119	6.18
22	159	5.69	46	151	5.93
23	171	5.42	47	184	5.25
24	106	6.58	48	192	5.12

$$\text{Eh (mv)} = 534.6 - 65.8 \text{ pH}, \quad r = -0.925**$$

[a]Against a saturated calomel electrode in the presence of quinhydrone.

[b]Equal parts of soil (air-dry basis) and water by weight.
Measurements were made with a glass electrode pH meter.

**Significant at the 1% level.

Table 23. pH of the air-dried soil mass at the early growth stage in the main experiment

| Plant | pH[a] | | | |
	Rep. 1	Rep. 2	Rep. 3	Mean
Barley	6.53	6.52	6.34	6.46
Oat	6.30	6.22	6.34	6.29
Rye	6.62	6.60	6.62	6.61
Ryegrass	6.58	6.29	6.52	6.46
Sorghum	6.32	6.33	6.27	6.31
Wheat	6.26	6.26	5.94	6.15
Buckwheat	5.65	5.78	5.60	5.68
Cabbage	6.08	5.67	6.22	5.99
Collards	5.96	6.17	6.16	6.10
Rape	5.86	6.01	6.03	5.97
Alsike clover	6.18	6.30	6.12	6.20
Ladino clover	6.00	6.03	5.76	5.93
Red clover	6.21	6.20	6.20	6.20
White clover	6.26	6.20	6.27	6.24
Tobacco	5.90	5.76	6.02	5.88
Tomato	5.64	5.90	5.90	5.81

[a]Equal parts of air-dry soil and water by weight. Measurements made by a glass electrode pH meter.

Table 24. pH of the air-dried soil mass at harvest in the main experiment

| Plant | pH[a] (replications) | | | | | | | | | | |
	1	2	3	4	5	6	7	8	9	10	Mean
Barley	6.90	7.20	6.48	6.68	6.40	6.72	6.56	6.60	6.82	6.83	6.72
Oat	6.32	6.58	6.45	6.40	6.16	6.31	6.60	6.12	6.41	6.40	6.37
Rye	6.58	6.03	6.70	6.32	6.18	6.30	6.20	6.32	6.62	6.10	6.33
Ryegrass	6.22	6.22	6.10	6.21	6.08	6.14	6.01	6.13	6.18	6.18	6.15
Sorghum	6.45	6.68	6.22	6.05	6.30	6.02	6.36	6.18	6.02	6.05	6.23
Wheat	6.10	6.50	6.38	6.36	6.22	5.88	6.62	6.30	6.65	6.52	6.35
Buckwheat	5.78	4.82	4.55	4.93	4.65	5.38	5.08	4.93	4.58	5.12	4.98
Cabbage	5.50	5.10	5.40	5.32	5.22	5.40	5.92	5.80	5.40	5.63	5.47
Collards	5.58	5.74	5.38	5.50	5.62	5.75	5.38	5.56	5.41	5.40	5.53
Rape	5.80	5.38	5.30	5.30	5.58	5.52	5.50	5.62	5.54	5.52	5.51
Alsike cl.	5.68	5.82	5.50	5.58	5.68	6.08	5.58	5.65	5.76	6.21	5.75
Ladino cl.	5.75	5.75	5.71	5.64	5.55	5.78	5.72	5.68	5.96	6.86	5.84
Red clover	5.58	6.15	6.36	5.96	5.92	6.08	6.48	5.68	5.56	5.48	5.97
White cl.	5.72	6.00	5.92	5.70	6.00	5.68	5.76	5.50	5.61	5.68	5.76
Tobacco	5.43	5.18	5.35	5.00	4.96	5.08	5.10	5.15	5.52	5.45	5.18
Tomato	5.60	5.52	5.50	5.38	5.52	5.58	5.00	5.54	5.35	5.48	5.46

[a]Equal parts of air-dry soil and water by weight. Measurements made by glass electrode pH meter.

Table 25. Yield of dry matter in the above-ground portions
of the plants in the main experiment

Plant	Yield of dry matter per				
	1	2	3	4	5

Sand cultures

Plant	1	2	3	4	5
Barley	0.76	0.90	0.90	0.81	0.86
Oat	1.41	1.62	1.52	1.50	1.65
Rye	0.40	0.47	0.49	0.63	0.53
Ryegrass	0.25	0.29	0.24	0.36	0.30
Sorghum	0.85	0.62	0.87	0.78	0.91
Wheat	1.02	1.03	1.02	1.12	0.91
Buckwheat	0.49	0.69	0.84	0.58	1.02
Cabbage	0.68	0.62	0.76	0.66	0.74
Collards	0.30	0.30	0.16	0.44	0.54
Rape	0.11	0.30	0.25	0.43	0.29
Alsike clover	0.09	0.06	0.12	0.09	0.12
Ladino clover	0.09	0.12	0.08	0.08	1.05
Red clover	0.21	0.27	0.28	0.37	0.32
White clover	0.29	0.17	0.12	0.15	0.04
Tobacco	0.03	0.01	0.01	0.03	0.02
Tomato	0.06	0.07	0.06	0.10	0.10

Soil cultures without added phosphorus

Plant	1	2	3	4	5
Barley	4.51	5.11	4.49	4.03	5.73
Oat	8.58	8.73	8.46	8.35	8.72
Rye	1.99	2.21	1.88	1.62	2.28
Ryegrass	2.81	3.50	3.26	2.99	3.11
Sorghum	3.12	2.80	2.82	2.30	2.92
Wheat	2.97	2.47	2.55	3.44	2.70
Buckwheat	5.61	5.83	6.76	6.38	6.94
Cabbage	5.39	6.92	6.75	7.35	7.37
Collards	6.57	6.14	6.80	7.52	7.50
Rape	3.33	6.64	6.77	6.79	7.17
Alsike clover	3.16	3.64	3.32	2.83	3.83
Ladino clover	2.43	2.65	2.28	2.64	2.51
Red clover	3.23	3.43	3.19	3.74	2.77
White clover	3.11	2.91	2.99	3.34	3.96
Tobacco	2.44	1.49	2.94	2.69	3.38
Tomato	1.05	1.56	1.06	1.63	2.03

culture in indicated replicate, g

6	7	8	9	10	Mean
1.13	1.08	1.03	0.76	0.89	0.412
1.63	1.66	1.56	1.14	1.48	1.517
0.45	0.50	0.51	0.61	0.62	0.521
0.13	0.28	0.22	0.30	0.41	0.278
0.70	0.79	0.82	0.87	0.87	0.808
0.91	1.12	1.34	1.32	0.95	1.072
0.93	0.74	0.80	0.96	0.52	0.765
0.64	0.52	0.57	0.71	0.40	0.630
0.42	0.37	0.21	0.43	0.24	0.343
0.35	0.22	0.35	0.35	0.18	0.283
0.08	0.08	0.15	0.02	0.12	0.093
0.09	0.11	0.10	0.20	0.11	0.204
0.23	0.23	0.36	0.30	0.24	0.283
0.01	0.12	0.16	0.15	0.06	0.107
0.61	0.01	0.02	0.03	0.01	0.018
0.06	0.10	0.08	0.09	0.09	0.081
5.09	1.37	4.45	5.01	3.71	4.350
8.96	9.02	8.47	9.21	8.49	8.719
1.84	1.57	1.32	1.61	1.54	1.786
3.29	3.15	2.73	2.75	2.90	3.047
3.03	4.02	3.75	2.84	3.59	3.119
2.34	4.03	3.68	3.03	2.57	2.958
6.77	8.75	7.65	7.23	7.36	6.928
7.66	4.32	6.9^c	4.96	2.83	6.082
7.35	6.91	6.69	7.16	3.28	6.592
6.89	7.24	8.80	5.94	5.33	6.290
3.78	2.87	3.86	3.69	3.30	3.527
3.20	3.71	3.51	2.63	2.85	2.921
3.17	2.68	3.24	1.41	3.60	3.055
3.58	3.17	4.06	3.29	2.86	3.377
3.82	3.10	3.73	3.59	4.06	3.124
1.16	1.18	1.90	0.92	2.27	1.476

Table 25. (Continued)

Plant	Yield of dry matter per				
	1	2	3	4	5

Soil cultures treated with superphosphate

Plant	1	2	3	4	5
Barley	5.97	6.39	5.74	6.24	6.30
Oat	10.59	11.23	11.48	11.20	11.54
Rye	3.18	3.30	2.05	3.00	2.95
Ryegrass	3.86	4.38	4.73	4.38	4.54
Sorghum	6.78	5.53	7.74	4.92	8.32
Wheat	4.47	3.87	3.64	4.46	4.49
Buckwheat	6.92	9.18	7.77	9.44	7.80
Cabbage	7.92	8.72	7.27	7.70	8.34
Collards	7.92	7.93	7.85	8.92	8.18
Rape	7.40	6.85	6.02	7.87	8.05
Alsike clover	5.47	5.66	4.74	5.83	5.24
Ladino clover	4.88	5.44	5.25	5.17	5.55
Red clover	5.87	4.46	4.79	5.45	5.17
White clover	4.50	5.28	4.98	4.92	5.33
Tobacco	5.37	5.73	5.50	6.03	6.22
Tomato	5.94	7.09	3.60	5.00	5.87

Soil cultures treated with phosphate rock

Plant	1	2	3	4	5
Barley	6.71	5.40	6.16	5.17	6.27
Oat	11.98	11.84	12.04	10.63	11.86
Rye	2.55	2.80	2.76	1.96	2.50
Ryegrass	4.09	4.17	4.85	3.74	3.90
Sorghum	3.45	2.95	4.60	3.53	3.73
Wheat	3.91	3.40	3.46	3.65	3.15
Buckwheat	6.91	10.03	10.23	8.82	8.86
Cabbage	9.18	9.48	8.33	7.54	8.12
Collards	7.91	9.24	8.66	7.14	8.01
Rape	8.08	8.12	8.00	7.95	7.44
Alsike clover	4.78	5.53	4.70	4.83	4.55
Ladino clover	4.05	4.70	4.57	4.21	5.14
Red clover	4.27	3.55	4.15	3.89	3.95
White clover	3.88	5.01	4.63	4.50	4.39
Tobacco	4.45	5.90	6.96	5.92	5.86
Tomato	6.37	5.55	5.68	4.10	6.29

6	7	8	9	10	Mean
6.65	6.24	6.25	6.81	6.29	6.338
11.93	11.90	11.56	11.65	11.07	11.445
2.78	2.61	2.57	2.24	2.97	2.765
4.67	4.64	4.69	4.63	4.61	4.518
7.20	6.31	8.54	6.65	6.41	6.841
4.69	3.37	5.16	4.54	4.19	4.285
9.54	10.22	9.85	10.85	9.23	9.050
7.89	8.32	7.79	9.35	8.77	8.257
7.67	7.23	7.33	8.44	6.95	7.847
7.60	7.77	7.92	8.39	8.67	7.854
5.32	4.99	5.56	5.15	5.59	5.355
5.84	6.51	5.56	5.80	5.30	5.530
5.55	5.31	5.53	6.25	5.28	5.406
6.06	4.55	5.38	5.70	6.00	5.270
5.60	5.87	5.95	5.88	5.35	5.780
4.15	4.56	5.31	4.08	4.66	5.026
6.08	5.64	5.82	5.78	4.58	5.761
10.15	11.11	10.71	9.89	11.14	11.115
2.35	1.83	1.60	1.76	1.87	2.098
4.16	3.76	3.87	3.63	4.15	4.032
3.85	5.04	4.94	4.98	3.82	4.089
3.15	4.13	4.48	3.32	3.41	3.685
8.46	9.93	9.48	10.35	8.81	9.188
7.61	8.78	7.90	8.68	7.48	7.310
7.95	7.72	7.23	8.07	6.78	7.871
7.80	7.22	7.44	8.37	8.51	7.393
5.25	4.49	4.76	4.99	4.74	4.837
2.40	4.89	4.21	3.94	3.81	4.392
4.76	4.38	4.30	4.44	3.85	4.154
4.74	4.47	4.46	3.67	4.37	4.412
5.87	5.14	6.01	5.63	5.03	5.677
3.95	4.59	5.57	4.39	5.22	5.171

Table 26. Yield of phosphorus in above-ground portions of plants in the main experiment

Plant	Yield of phosphorus per				
	1	2	3	4	5

Soil cultures without added phosphorus

Plant	1	2	3	4	5
Barley	3.599	4.374	4.221	3.072	5.031
Oat	6.761	6.076	5.993	5.295	5.441
Rye	2.161	3.169	2.621	1.763	2.334
Ryegrass	2.613	2.793	2.667	2.296	2.444
Sorghum	1.928	1.859	1.923	1.343	2.132
Wheat	2.602	2.880	3.228	2.819	3.299
Buckwheat	6.025	6.926	7.341	5.283	5.621
Cabbage	4.641	4.719	5.062	4.645	4.658
Collards	4.928	4.482	5.406	5.023	4.485
Rape	2.791	4.847	5.145	4.060	4.947
Alsike clover	4.329	3.989	4.017	3.022	3.684
Ladino clover	4.044	3.387	3.751	3.448	3.545
Red clover	4.192	4.617	4.523	4.069	3.357
White clover	4.118	3.719	4.324	4.040	3.809
Tobacco	2.494	1.570	2.975	2.163	2.467
Tomato	1.174	1.451	1.028	1.663	1.953

Soil cultures teated with superphosphate

Plant	1	2	3	4	5
Barley	7.092	7.374	6.945	7.323	7.154
Oat	11.587	11.365	11.847	9.990	8.240
Rye	4.509	5.405	3.187	4.980	4.808
Ryegrass	6.060	6.333	6.386	5.238	5.366
Sorghum	5.475	4.037	5.743	3.700	5.881
Wheat	5.972	4.853	5.533	4.852	5.550
Buckwheat	12.641	13.384	13.442	14.047	12.808
Cabbage	10.581	9.557	9.538	7.777	9.300
Collards	10.296	10.198	10.299	11.418	10.470
Rape	9.798	9.069	10.057	8.122	9.048
Alsike clover	7.910	7.098	6.058	6.635	6.550
Ladino clover	6.178	7.203	7.980	7.124	6.105
Red clover	8.993	6.779	7.396	7.510	7.186
White clover	7.123	7.054	7.689	6.426	7.121
Tobacco	7.421	7.587	7.403	5.560	7.651
Tomato	6.700	8.083	4.277	5.160	5.412

culture in indicated replicate, mg					
6	7	8	9	10	Mean
4.052	1.022	3.391	3.597	2.916	3.537
5.716	5.628	6.115	6.079	5.603	5.871
2.068	1.962	1.180	1.439	1.466	2.006
2.474	2.476	1.906	1.963	2.279	2.391
2.163	2.468	2.152	1.573	2.290	1.974
2.387	3.434	3.540	2.794	2.395	2.938
6.310	7.525	7.191	6.883	7.280	6.639
5.176	2.782	4.337	3.656	2.128	4.181
4.645	4.077	4.065	4.181	2.165	4.346
4.603	4.619	4.801	3.920	3.241	4.297
3.636	3.437	3.359	3.550	3.456	3.663
3.366	3.532	3.622	2.683	3.061	3.444
4.368	3.854	4.231	1.647	4.205	3.906
3.766	3.170	3.816	3.533	3.340	3.763
2.934	2.641	2.865	2.678	2.899	2.569
1.406	0.992	1.786	0.875	1.898	1.423
7.953	6.702	6.712	8.322	8.944	7.452
10.164	13.899	14.989	14.236	8.258	11.454
4.288	4.369	3.824	3.333	4.718	4.339
6.099	5.215	4.643	4.723	5.827	5.589
5.141	4.165	5.841	4.642	4.577	4.920
5.337	4.401	5.490	5.167	4.458	5.161
13.413	14.083	17.612	17.338	12.590	14.136
9.862	7.005	8.102	9.163	8.595	8.947
9.925	8.546	8.342	8.794	8.118	9.641
9.500	9.044	8.253	8.742	9.312	9.094
6.948	5.539	5.794	6.293	6.004	6.483
6.821	6.927	6.594	6.102	4.516	6.555
7.892	6.935	7.078	7.415	7.054	7.424
7.405	5.378	6.650	6.487	7.416	6.875
6.843	8.007	7.033	7.609	6.088	7.120
4.963	4.432	4.747	4.121	4.436	5.233

Table 26. (Continued)

| Plant | 1 | 2 | Yield of phosphorus per | | |
			3	4	5

<u>Soil</u> <u>cultures</u> <u>treated</u> <u>with</u> <u>phosphate</u> <u>rock</u>

Plant	1	2	3	4	5
Barley	7.421	5.357	6.493	4.391	5.605
Oat	11.261	10.080	9.367	7.505	9.535
Rye	2.769	3.416	2.873	1.886	2.380
Ryegrass	5.088	5.029	5.762	3.284	4.189
Sorghum	1.946	1.982	3.220	2.111	2.462
Wheat	3.986	3.298	4.069	3.468	3.939
Buckwheat	11.989	19.638	21.524	17.040	18.322
Cabbage	16.946	15.775	13.395	10.722	15.282
Collards	15.029	16.928	16.333	15.608	16.789
Rape	14.689	15.103	13.216	13.849	14.687
Alsike clover	7.897	8.002	7.144	5.662	6.980
Ladino clover	5.808	7.821	7.056	5.204	7.011
Red clover	6.704	5.670	6.308	5.594	5.617
White clover	7.543	8.737	6.454	5.940	6.172
Tobacco	5.233	8.602	10.677	6.038	9.622
Tomato	8.434	7.148	6.555	5.592	7.523

culture in indicated replicate, mg					
6	7	8	9	10	Mean
5.958	4.952	4.435	5.503	4.140	5.445
9.541	7.755	8.761	8.090	9.112	9.101
2.524	2.137	1.632	1.623	1.889	2.313
4.077	3.580	3.259	3.223	3.436	4.093
2.687	2.974	3.527	2.978	2.666	2.655
2.999	3.667	4.310	4.296	2.762	3.680
19.204	20.059	23.491	21.404	18.342	19.101
14.215	9.658	13.367	15.364	15.573	14.030
15.916	14.529	13.274	14.816	14.021	15.324
13.588	13.155	11.692	14.480	14.127	13.859
6.920	5.864	6.486	7.884	5.328	6.813
5.300	6.611	5.692	4.712	4.145	5.956
6.436	5.375	6.330	6.681	5.251	5.997
6.456	6.777	7.189	5.461	8.224	6.895
10.308	10.629	8.198	10.720	5.805	8.583
5.388	4.297	6.428	4.934	5.867	6.317

Table 27. Ash alkalinity of above-ground portions of plants in the main experiment

| Plant | Ash alkalinity per | | | | |
| | | | | Phosphate | |
	Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5
Barley	0.663	0.722	0.644	0.567	0.741
Oat	0.385	0.443	0.391	0.547	0.534
Rye	1.107	1.324	1.064	1.168	1.531
Ryegrass	1.246	1.309	0.929	1.144	1.394
Sorghum	0.920	0.883	0.844	0.613	0.968
Wheat	0.703	1.226	0.832	0.929	1.084
Buckwheat	1.557	1.129	1.039	1.356	1.595
Cabbage	1.013	1.213	1.130	1.453	1.751
Collards	0.877	1.124	1.021	1.395	1.544
Rape	0.773	1.083	0.935	1.164	1.259
Alsike clover	1.491	1.292	1.375	1.408	1.737
Ldino clover	1.511	1.092	1.698	1.473	1.499
Red clover	1.292	1.311	1.376	1.518	1.679
White clover	1.841	1.255	1.518	1.494	1.659
Tobacco	1.776	1.350	1.615	1.418	1.699
Tomato	1.011	1.247	1.194	1.375	1.362

[a]Too little sample to analyze.

gram of dry matter, meq

rock cultures

Rep. 6	Rep. 7	Rep. 8	Rep. 9	Rep. 10	Sand cultures
0.656	0.461	0.449	0.520	0.617	-0.584
0.534	0.507	0.482	0.501	0.358	-0.327
1.349	1.259	1.324	1.194	0.818	0.006
1.262	1.433	0.944	1.064	1.185	-0.148
0.978	0.638	0.593	0.412	0.735	-0.391
0.993	0.635	0.883	0.762	0.757	-0.058
1.341	1.059	1.045	1.215	1.252	-0.302
1.497	1.492	1.173	0.987	1.335	-0.776
1.134	1.104	1.018	1.186	1.072	-0.250
1.207	0.805	1.012	1.083	1.123	-0.340
1.465	1.473	1.451	1.200	1.454	-0.327
1.563	1.279	1.474	1.170	1.260	-0.404
1.615	1.304	1.340	1.335	1.305	-0.135
1.867	1.515	1.311	1.788	1.765	-0.058
1.544	1.512	1.220	1.405	1.421	-[a]
1.786	1.117	0.987	1.481	0.980	-0.289

Table 28. Total nitrogen content of above-ground parts of
plants in the main experiment

| Plant | Total nitrogen per | | | | |
| | | | | Phosphate | |
	Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5
Barley	0.902	1.069	0.997	0.955	0.925
Oat	0.647	0.654	0.649	0.756	0.714
Rye	1.669	1.664	1.669	1.646	1.610
Ryegrass	1.311	1.256	1.165	1.360	1.331
Sorghum	0.986	1.042	0.908	0.957	0.814
Wheat	1.265	1.243	1.425	1.268	1.385
Buckwheat	1.067	0.763	0.751	0.887	0.881
Cabbage	0.674	0.832	0.736	0.822	0.786
Collards	0.637	0.617	0.608	0.743	0.750
Rape	0.670	0.695	0.634	0.684	0.686
Alsike clover	1.479	1.460	1.467	1.440	1.608
Ladino clover	1.429	1.311	1.491	1.425	1.354
Red clover	1.528	1.630	1.452	1.697	1.682
White clover	1.546	1.265	1.617	1.407	1.860
Tobacco	1.294	0.894	0.839	0.968	0.963
Tomato	0.847	0.789	0.965	1.214	0.874

[a]Average of duplicate analysis except for rye which did
not have enough sample to analyze.

[b]Too little sample to analyze.

gram of dry matter, meq[a]

rock cultures

Rep. 6	Rep. 7	Rep. 8	Rep. 9	Rep. 10	Sand cultures
0.945	0.914	0.983	0.934	1.041	1.037
0.717	0.780	0.712	0.693	0.726	0.879
1.551	1.652	1.646	1.539	1.521	1.358
1.355	1.411	1.242	1.331	1.254	1.509
0.914	0.867	0.888	0.780	1.021	0.744
1.357	1.101	1.551	1.504	1.273	1.051
0.847	0.777	0.853	0.741	0.880	1.180
0.910	1.287	0.877	0.744	0.897	1.067
0.752	0.712	0.737	0.715	0.797	1.208
0.712	0.680	0.707	0.755	0.642	1.316
1.458	1.422	1.425	1.523	1.469	3.561
1.441	1.341	1.504	1.177	1.525	3.353
1.586	1.646	1.566	1.554	1.498	2.302
1.479	1.528	1.609	1.618	1.601	3.160
0.938	0.878	0.808	0.793	0.991	-[b]
1.205	0.962	0.885	1.071	0.963	3.289

Table 29. A values of plants in the cultures treated with phosphate rock in the main experiment

Plant	A values of plants per				
	1	2	3	4	5
Barley	-1.604	-1.874	-2.178	-2.006	-1.157
Oat	-3.139	-2.456	-3.106	-2.222	-2.164
Rye	-0.706	-0.868	-1.579	-0.874	-0.128
Ryegrass	-0.268	0.221	-1.145	-0.808	0.246
Sorghum	-0.109	-0.445	-0.295	-1.214	0.196
Wheat	-2.196	-1.134	-2.050	-1.324	-1.091
Buckwheat	3.386	3.671	2.941	4.136	6.321
Cabbage	3.112	3.617	3.282	4.754	7.836
Collards	1.898	3.180	3.072	4.655	6.316
Rape	0.832	3.409	2.408	3.760	4.263
Alsike clover	0.059	-0.937	-0.431	-0.135	0.584
Ladino clover	0.332	-1.032	0.948	0.204	0.745
Red clover	-1.006	-1.132	-0.318	-0.721	-0.010
White clover	1.142	-0.115	-0.459	0.385	-0.097
Tobacco	2.145	2.676	5.397	2.519	4.327
Tomato	2.019	2.856	3.508	1.844	3.590

[a]A = meq of ash alkalinity minus meq of total nitrogen in above-ground parts of plants per culture. Duplicate analyses per replicate except for rye, where the sample size permitted only a single analysis per replicate. Coefficient of variation of determinations = 27.24%.

culture in indicated replicate, meq[a]

6	7	8	9	10	Mean
-1.758	-2.558	-2.014	-2.398	-1.942	-1.948
-2.863	-3.022	-2.372	-1.894	-4.105	-2.635
-0.404	-0.662	-0.467	-0.553	-1.249	-0.749
-0.387	0.082	-1.194	-0.969	-0.285	-0.451
0.052	-1.155	-1.482	-1.833	-0.581	-0.686
-1.148	-1.923	-2.460	-2.462	-1.758	-1.736
4.179	2.796	1.820	4.906	3.282	3.744
4.464	1.805	2.338	2.114	3.275	3.660
2.242	3.030	2.383	3.805	1.865	3.445
3.857	1.187	2.273	2.666	4.088	2.879
0.037	0.276	0.335	-1.534	-0.074	-0.188
0.535	-0.303	-0.595	-0.028	-1.010	-0.019
0.112	0.460	-0.967	-0.973	-0.743	-0.530
1.365	-0.058	-1.331	0.624	0.719	0.218
3.031	3.256	1.875	3.449	2.163	3.184
3.145	2.211	1.107	1.437	0.789	1.408

Table 30. A_c values of plants in the main experiment

Plant	A_c values of plants per				
	1	2	3	4	5
Barley	-0.325	-0.415	-0.719	-0.693	0.237
Oat	-1.439	-0.502	-1.273	-0.413	-0.175
Rye	-0.165	-0.233	-0.917	-0.022	0.589
Ryegrass	0.146	0.702	-0.747	-0.211	0.742
Sorghum	0.856	0.377	0.692	-0.329	1.229
Wheat	-1.066	0.218	-0.919	-0.095	-0.091
Buckwheat	3.932	4.694	4.156	4.952	7.833
Cabbage	3.722	4.937	4.694	5.473	8.291
Collards	2.325	5.117	3.805	5.297	7.103
Rape	1.014	3.956	2.822	4.472	4.743
Alsike clover	0.409	-0.705	0.034	0.205	1.051
Ladino clover	0.671	-0.584	1.249	0.505	1.309
Red clover	-0.493	-0.475	0.292	0.180	0.770
White clover	1.432	0.432	-0.073	0.868	0.033
Tobacco	2.145	2.676	5.397	2.514	2.316
Tomato	1.228	2.749	1.478	0.962	3.369

[a]A_c = (meq of ash alkalinity minus meq of total nitrogen in above-ground parts of plants per phosphate rock culture) minus (meq of ash alkalinity minus meq of total nitrogen in above-ground parts of plants per sand culture). Duplicate analyses per replicate except for rye, where the sample size permitted only a single analysis per replicate.

culture in indicated replicate, meq[a]					
6	7	8	9	10	Mean
0.075	-0.807	-1.440	-1.161	-0.491	-0.591
0.104	-1.025	-0.492	-0.488	-2.320	-0.865
0.204	0.014	0.223	0.272	-0.411	-0.045
-0.172	0.546	-0.439	-0.472	0.395	0.049
0.847	-0.258	-0.551	-0.846	0.407	0.242
-0.139	-0.681	-1.137	-0.998	-0.704	-0.560
5.557	4.041	3.006	6.329	4.033	4.873
4.784	3.696	3.641	3.091	3.763	4.819
2.854	3.599	2.689	4.432	2.214	3.945
4.437	1.415	2.353	3.246	4.383	3.334
0.328	0.537	0.919	-1.437	0.393	0.173
0.873	0.109	-0.219	0.724	-0.497	0.404
0.794	-0.937	-0.615	-0.241	-0.158	-0.036
1.397	0.328	-0.061	1.107	0.962	0.725
3.531	3.256	1.875	3.447	2.163	3.168
2.475	1.013	0.812	2.070	0.359	1.651

Table 31. Calcium content of above-ground portions of plants on the soil cultures treated with phosphate rock in the main experiment

| Plant | Calcium content of plants per culture, meq[a] |
	1	2	3	4	5	6	7	8	9	10	Mean
Barley	1.83	1.82	1.85	1.75	1.93	1.96	1.69	1.79	1.65	1.33	1.76
Oat	2.18	2.04	2.00	1.72	2.11	1.75	1.80	1.73	1.60	1.97	1.90
Rye	0.74	1.06	1.03	0.72	1.33	0.86	0.79	0.88	0.70	0.65	0.88
Ryegrass	1.62	1.93	2.06	1.58	1.79	1.92	1.69	1.72	1.56	1.58	1.79
Sorghum	1.09	1.12	1.15	1.01	0.98	1.03	1.42	1.40	1.18	1.07	1.15
Wheat	0.85	0.74	0.67	0.73	0.65	0.59	0.74	0.71	0.59	0.50	0.68
Buckwheat	6.41	8.82	9.13	7.01	7.78	7.29	7.74	8.22	8.65	6.59	7.99
Cabbage	9.17	9.31	7.46	8.19	9.20	8.06	10.48	6.76	8.85	8.77	8.63
Collards	7.97	8.33	8.31	7.49	8.22	6.89	7.53	7.23	7.80	7.12	7.70
Rape	7.06	7.56	6.06	7.35	6.46	6.66	6.22	6.45	7.06	6.54	6.72
Alsike	4.22	4.25	3.97	3.05	3.69	3.84	3.39	3.76	3.94	3.74	3.76
Ladino	2.89	4.27	3.93	3.17	3.94	3.08	3.75	3.27	3.06	2.44	3.38
Red	3.49	2.89	3.88	2.89	2.99	2.96	2.89	3.14	3.44	2.64	3.12
White	3.94	5.04	3.63	3.43	3.35	4.04	3.94	3.99	3.56	4.65	3.95
Tobacco	4.89	6.06	6.55	6.61	6.27	6.01	5.92	5.23	5.79	5.01	5.89
Tomato	5.03	4.43	5.42	4.58	5.63	4.15	4.29	5.19	4.49	4.53	4.72

[a]Duplicate analyses per replicate except for rye, where the sample size permitted only a single analysis per replicate. Coefficient of variation of determinations = 0.92%.

Table 32. Calcium and magnesium content of solutions after
absorption of ions by plants in the solution cul-
ture experiment

Plant	Calcium per culture in indicated replicate, meq			Magnesium per culture in indicated replicate, meq		
	1	2	3	1	2	3
None	1.853	2.013	2.055	2.423	2.621	2.622
Barley	1.757	1.679	1.837	2.302	2.120	2.400
Oat	1.765	1.795	1.826	2.315	2.422	2.248
Rye	1.579	1.654	1.942	2.308	2.154	2.167
Ryegrass	1.435	1.280	1.726	2.277	2.179	2.246
Sorghum	1.544	1.468	1.768	1.796	1.990	1.967
Wheat	1.488	1.231	1.320	2.120	2.030	1.986
Buckwheat	1.757	1.773	1.783	2.393	2.037	2.360
Cabbage	1.762	1.589	1.891	2.284	1.944	2.052
Collards	1.569	1.573	1.411	2.063	1.938	1.876
Rape	1.216	1.389	1.491	1.944	2.008	1.918
Alsike	1.609	1.407	1.643	2.203	2.037	2.138
Ladino	1.649	1.389	1.537	2.109	2.003	1.937
Red	1.634	1.762	1.700	2.347	2.058	2.240
White	1.716	1.649	1.634	2.224	2.138	2.109
Tobacco	1.430	1.491	1.444	1.918	2.238	1.782
Tomato	1.530	1.815	1.710	1.831	2.197	2.200

Table 33. Potassium content of solutions after absorption of ions by plants in the solution culture experiment

Plant	Potassium per culture in indicated replicate, meq		
	1	2	3
None	2.760	2.701	2.676
Barley	1.897	1.562	2.602
Oat	2.071	2.000	2.395
Rye	1.194	1.355	0.339
Ryegrass	0.581	0.786	2.243
Sorghum	0.475	2.046	2.472
Wheat	0.034	0.935	0.810
Buckwheat	2.388	2.054	2.530
Cabbage	2.057	1.800	2.237
Collards	1.713	1.923	1.944
Rape	1.300	2.022	2.235
Alsike clover	1.959	1.563	2.101
Ladino clover	1.725	1.291	1.768
Red clover	2.105	1.840	2.258
White clover	1.887	1.439	1.800
Tobacco	1.499	1.744	1.741
Tomato	1.804	2.133	2.628

Table 34. Nitrate and sulfate content of solutions after
absorption of ions by plants in the solution
culture experiment

Plant	Nitrate per culture in indicated replicate, meq			Sulfate per culture in indicated replicate, meq		
	1	2	3	1	2	3
None	4.919	4.962	5.277	5.258	5.778	5.778
Barley	4.191	3.175	4.147	4.341	3.603	4.603
Oat	4.819	3.890	4.447	4.216	4.181	4.837
Rye	2.960	2.746	3.346	4.341	4.116	4.469
Ryegrass	1.587	1.001	3.689	4.059	3.634	4.766
Sorghum	1.101	2.288	3.847	3.747	3.634	4.375
Wheat	0.672	0.415	0.744	3.853	3.494	4.181
Buckwheat	4.705	4.533	4.776	4.637	3.959	4.941
Cabbage	4.104	4.004	4.118	4.409	3.959	4.404
Collards	4.061	3.804	2.688	3.928	3.316	3.756
Rape	2.255	3.089	3.222	3.781	3.603	4.181
Alsike	3.732	3.203	3.546	4.216	3.759	4.409
Ladino	3.761	1.888	2.746	4.341	3.728	4.081
Red	4.605	3.489	4.090	4.469	4.081	4.603
White	4.047	2.717	3.403	4.566	3.666	4.566
Tobacco	3.617	2.717	2.560	4.150	3.959	4.375
Tomato	3.532	3.975	4.719	4.409	3.791	4.837

Table 35. A_s values in the solution culture experiment

Plant	A_s[a] value per cultures in indicated in replicate, meq			
	1	2	3	Mean
Barley	-0.506	-1.988	-1.891	-1.482
Oat	-0.247	-1.551	-0.997	-0.935
Rye	-0.921	-1.706	-0.435	-1.021
Ryegrass	-1.758	-3.015	-1.562	-2.112
Sorghum	-2.108	-2.987	-1.787	-2.294
Wheat	-2.258	-3.694	-2.993	-2.986
Buckwheat	-0.337	-0.777	-0.758	-0.624
Cabbage	-0.731	-0.775	-1.456	-0.987
Collards	-0.497	-1.720	-2.589	-1.602
Rape	-1.565	-2.134	-2.033	-1.910
Alsike clover	-1.054	-1.450	-1.729	-1.411
Ladino clover	-0.522	-2.472	-2.217	-2.404
Red clover	-0.153	-1.495	-1.307	-0.985
White clover	-0.355	-2.248	-1.376	-1.326
Tobacco	-1.221	-2.222	-1.534	-1.654
Tomato	-0.385	-1.784	-0.787	-0.985

[a]A_s = milliequivalents of cations absorbed minus milliequivalents of anions absorbed per culture.

Table 36. pH of solutions after absorption of ions by plants
in the solution culture experiment

| Plant | pH of solution in indicated replicate | | | |
	1	2	3	Mean
None	5.62	5.15	5.52	5.43
Barley	7.05	7.68	7.05	7.26
Oat	7.01	7.28	6.80	7.03
Rye	7.23	7.75	7.52	7.50
Ryegrass	7.69	7.81	7.65	7.72
Sorghum	7.69	7.32	7.52	7.51
Wheat	7.68	7.51	7.74	7.64
Buckwheat	4.01	4.58	4.28	4.96
Cabbage	7.01	7.12	6.88	7.00
Collards	6.88	7.42	7.62	7.31
Rape	7.34	7.50	6.82	7.22
Alsike clover	7.08	7.72	7.21	7.34
Ladino clover	7.10	7.82	7.48	7.46
Red clover	6.38	7.38	6.22	6.66
White clover	6.98	7.70	7.18	7.29
Tobacco	7.24	7.52	7.02	7.26
Tomato	7.21	6.92	6.28	6.80