Mechanisms for the Movement of Plant Nutrients from the Soil and Fertilizer to the Plant Root

S. A. BARBER, J. M. WALKER, and E. H. VASEY

Agronomy Department, Purdue University, Lafayette, Ind.

Plant nutrients in the soil reach the root by root extension, mass-flow, and diffusion. Plant roots grow to less than 3% of the available nutrients in the soil. They may grow to much of the plant's calcium and magnesium requirement but very little of the plant's need for nitrogen, phosphorus, and potassium. Mass-flow may supply the root with much of the plant's need for calcium, magnesium, and nitrogen, but this process does not supply much of the requirement for potassium or phosphorus on many soils. Usually most of the phosphorus and potassium must reach the root by diffusion. Nutrient absorption by the root lowers the phosphorus and potassium content in the soil at the root-soil interface, and a concentration gradient is established along which diffusion occurs. Diffusion is very slow in soil as compared to water.

THERE are three principal mechanisms by which plant nutrients in the soil may reach the surface of a growing root: the root may grow to the nutrients; the nutrients may be carried to the root by mass-flow in the water flowing to the root as a result of water absorption by the root; or the nutrients will diffuse from the soil to the root if the first two processes do not supply enough to meet the plant requirement. Nutrient absorption at the root surface will lower the concentration in the soil at the root surface and create the gradient along which the nutrients will diffuse.

The Amount of Nutrients to Which the Plant Root Grows

The maximum amount of nutrients that can come in direct contact with the plant roots as they grow through the soil is the amount in a volume of soil equal to the volume of the roots. The volume of roots in the soil has been investigated by Dittmer (*5*), who found that roots of soybeans, oats, and rye occupied 0.91, 0.55, and 0.85% of the soil volume of the 0- to 6-inch layer of soil. Abbas and Barber (*1*) calculated that the volume of roots of 10 soybean plants growing in 3-liter greenhouse pots occupied from 0.7 to 1.5% of the soil volume after 26 days of growth. Hence, it can be assumed that the roots usually occupy 1% or less of the soil. However, the roots grow through soil pores which may have a higher than average nutrient content. If we assume a soil with one-third pore space, then the concentration in this pore space may be three times that for the soil. Thus, the roots would contact a maximum of 3% of the available nutrients in the soil. The actual amount contacted would undoubtedly be much less because the roots will push soil away from them as they expand.

The amount of the major nutrients in the 0- to 6-inch layer of a fertile, Crosby silt-loam soil in Indiana is shown in Table I. The amounts absorbed by a 125-bushel corn crop are also shown. If we assume the roots can contact 3% of the nutrients in the soil by growing to them, then they will only reach 6 to 10% of their need for nitrogen, phosphorus, and potassium. However, they could reach all the calcium and magnesium requirement. This assumes that the plant roots reach 3% of the available nutrients in the soil and they are able to absorb the total amount of available nutrients in that soil. The exchangeable calcium and magnesium contents would be lower on soils having lower exchange capacities and consequently the roots would grow to a smaller portion of their calcium and magnesium requirement.

The Movement of Nutrients to the Root Surface by Mass-Flow

Plants roots absorb water, and water flows along a concentration gradient to the plant root. This water contains plant nutrients that are transported to the root surface where they become positionally available for nutrient uptake. The amounts of nutrients that are moved to the plant root by this mechanism depend upon the amount of water used by the plant and the concentration of nutrients in the water. The weight of water used per unit increase in plant weight varies with crops and environment. Russell (*10*) reported values of 293 to 905. Harrold *et al.* (*7*) obtained a value of 240 for corn grown in plastic covered lysimeters. Carlson *et al.* (*4*)

Table I. The Relationship between the Nutrient Requirements of Corn and the Maximum Amounts the Roots Would Contact

Nutrient	*Amount Available in a Fertile Soil, Pounds per Acre*	*Amount Roots Would Reach, Pounds per Acre*	*Nutrient Requirement of 125-Bushel Corn Crop, Pounds per Acre*	*Percentage of Needed Nutrients That Roots May Contact*
Nitrogen	300	9	150	6
Phosphorus	100	3	30	10
Potassium	300	9	100	9
Calcium	4000	120	40	300
Magnesium	750	30	30	100

Table II. Significance of Mass-Flow in Providing Nutrients for Corn in North Central United States Soils

Nutrient	*Average Content of Corn, P.P.M.*	*Mode of Saturation Extract, P.P.M.*	*Mode × 500*	*% Supplied by Mass Flow (Column Divided by Column 1 × 100)*
Calcium	3,000	30	15,000	500
Magnesium	2,000	25	12,500	625
Potassium	20,000	4	2,000	10
Phosphorus	2,500	0.05	25	1

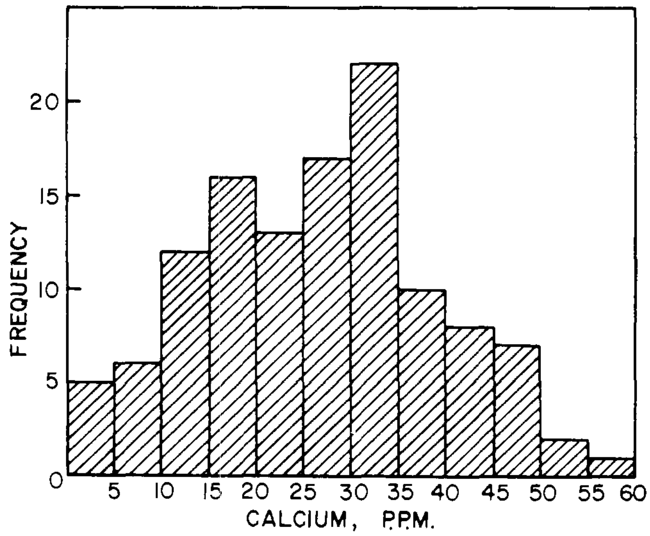

Figure 1. Histogram showing frequency of occurrence of calcium contents of saturation extracts from 135 north central United States soils

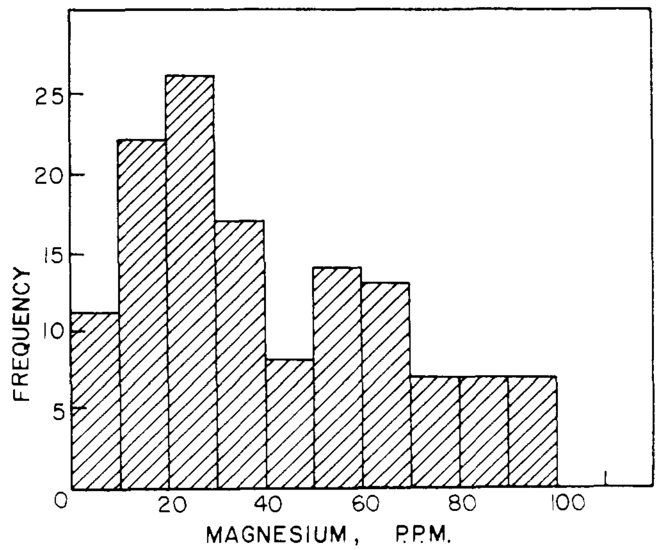

Figure 2. Histogram showing frequency of occurrence of magnesium contents of saturation extracts from 135 north central United States soils

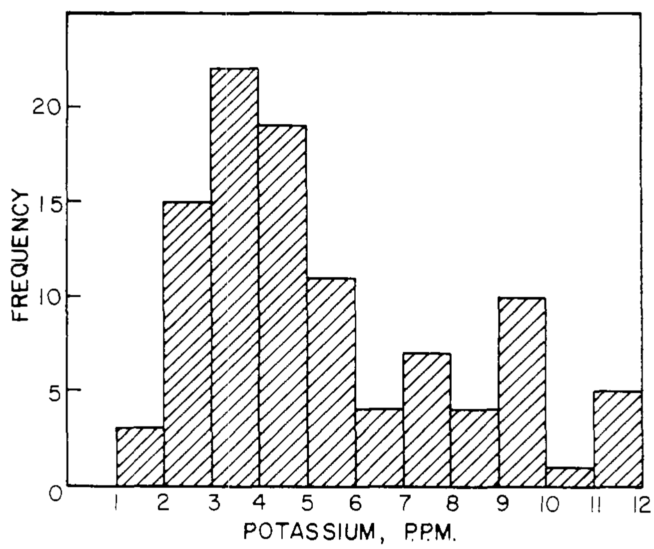

Figure 3. Histogram showing frequency of occurrence of potassium contents of saturation extracts from 135 north central United States soils

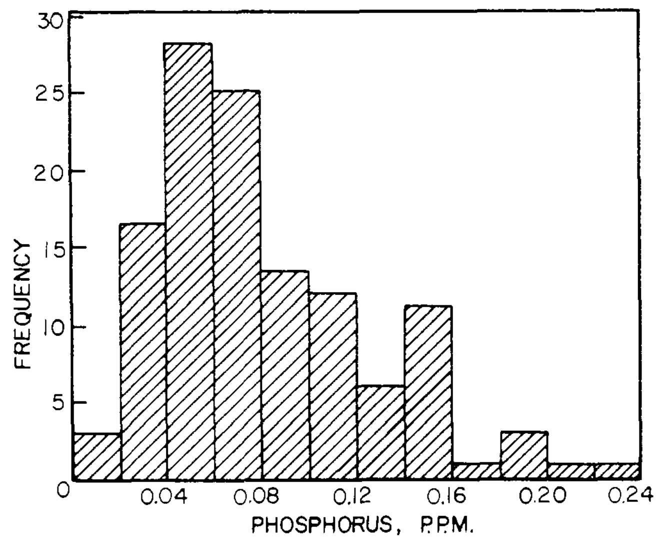

Figure 4. Histogram showing frequency of occurrence of phosphorus contents of saturation extracts from 135 north central United States soils

reported results of evapotranspiration which gave values of 280 to 540 pounds of water per pound of dry matter produced. In the calculations in this paper, the authors have assumed a value of 500 pounds of water used per pound of dry matter produced.

The nutrient content of the soil solution can be estimated from analyses of saturation extracts from the soil and from lysimeter drainage water. Barber (*2*) and Fried and Shapiro (*6*) have reviewed published values. However, most of the values shown in the literature are for saline or arid soils. Recently, Barber *et al.* (*3*) investigated the content of saturation extracts from 135 north central United States soils. The saturation extract was obtained by the method of Richards (*9*). The soil was saturated with water, allowed to equilibrate overnight, and the water extracted with 50 pounds of pressure of nitrogen in a pressure membrane apparatus using filter paper to retain the soil. The extract was analyzed for calcium and potassium with a Coleman flame photometer. Magnesium was determined by the colorimetric method of Young and Gill (*13*), and phosphorus was determined colorimetrically using the stannous chloride molybdic acid procedure as reported by Jackson (*8*).

The values obtained are shown as histograms. The histograms show a distribution of the values about a mode. The histograms for calcium, magnesium, potassium, and phosphorus are shown in Figures 1, 2, 3, and 4, respectively. The values of the mode will be used to indicate the significance of mass-flow in supplying the plant's requirements for these nutrients.

The nutrient content of the plant indicates its need for these nutrients. Table II gives some average compositions for corn and their relationship to the nutrient content of the soil solution and the percentage of the plant's requirement provided by mass-flow. Mass-flow could supply most of the calcium and magnesium requirements of corn but would supply only a small part of the potassium and phosphorus requirement. On many soils, calcium and magnesium would tend to accumulate about the corn root since much more moves by mass-flow than the crop absorbs.

Anions in the soil such as sulfate are very soluble and will move readily with

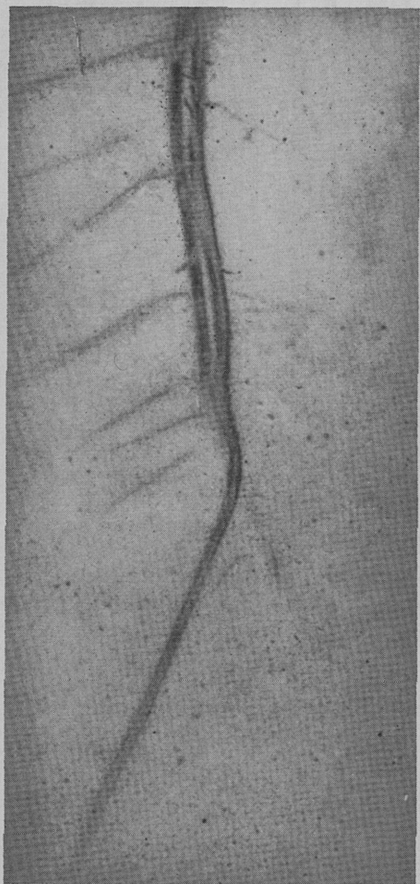

Figure 5. Autoradiograph showing accumulation of sulfate about a corn root as a result of mass-flow

Dark areas represent areas of accumulation of S^{35}

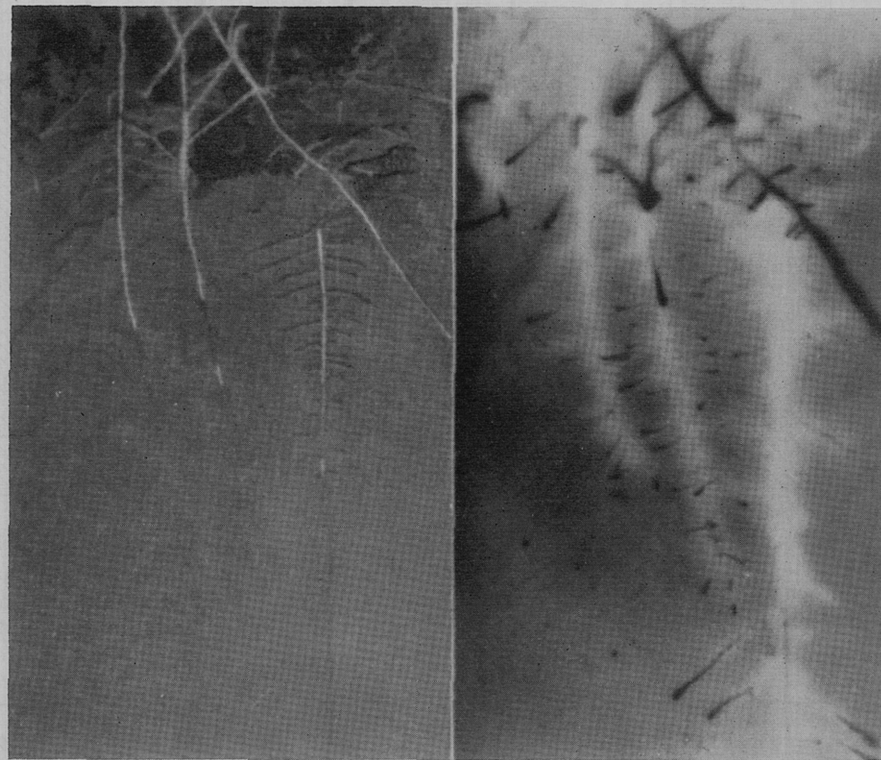

Figure 6. Photograph (left) and autoradiograph (right) showing depleted areas of rubidium about corn roots

Dark areas represent areas of high Rb^{86} content. Light areas represent areas where Rb^{86} has been removed

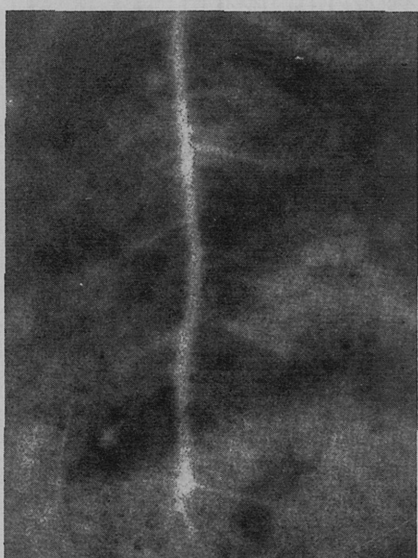

Figure 7. Autoradiograph showing narrow depleted area of P^{32} about a corn root resulting from diffusion of phosphorus to root and uptake

the water to the soil-root interface. A sulfate labeled with S^{35} was mixed uniformly with a soil. The soil was placed in a box similar to that described by Walker and Barber (*12*). The roots were forced to grow through the soil next to a thin plastic film. By placing x-ray film against the plastic film, it was possible to obtain an autoradiograph that showed the effect of corn roots on the sulfate distribution in the soil. The autoradiograph shown in Figure 5 illustrates how much of the sulfur had accumulated about the root as a result of mass-flow.

Movement of Nutrients to the Plant Root by Diffusion

Since neither mass-flow nor root interception can provide the corn plant with its needed phosphorus and potassium, these nutrients must reach the root by diffusion. The root absorbs the phosphorus and potassium at its interface with the soil and develops a concentration gradient. Diffusion occurs along the concentration gradient, and it is the mechanism that supplies most of the phosphorus and potassium on many soils.

Walker and Barber (*12*) were able to show the concentration gradients of rubidium about corn roots that resulted when corn grew in soil. Figure 6 shows a photograph of roots growing in soil and an autoradiograph showing the distribution of rubidium-86 that occurred in the soil after the corn roots had grown into it. The roots were forced to grow through the soil next to a thin plastic film so that autoradiographs and photographs could be taken. A definite diffusion pattern is shown. Vasey and Barber (*11*) obtained a diffusion pattern of P^{32} about a corn root. This is shown in Figure 7. The diffusion band width was much narrower for phosphorus than for rubidium because phosphorus diffuses in soil more slowly.

The rate of diffusion in soil is very slow as compared to the rate in water. The diffusion coefficient for rubidium in water at room temperature is 1.9×10^{-5} cm.^{2} sec^{-1}. The diffusion coefficient of rubidium in a saturated Crosby silt loam was found to be 4×10^{-9} cm.^{2} sec^{-1}. *Phosphorus rates of diffusion* are even smaller; the rate of diffusion of P^{32} in the same Crosby soil was 4×10^{-11} cm.^{2} sec^{-1}. Reaction with the soil caused diffusion to be very slow.

The influence of moisture level and of soil exchange capacity on rubidium diffusion are under study in this laboratory.

The availability of phosphorus and potassium in a soil will be affected by their diffusion coefficient in the soil and upon the concentration gradients that occur. For soils with a similar diffusion rate, the total level of available nutrient, such as exchangeable plus the release of nonexchangeable potassium, should correlate well with uptake. Differences in availability between soils having the same level of available potassium will probably be due to differences in diffusion rates in these soils.

Three processes are involved in getting plant nutrients to the plant root surface: *root extension, mass-flow,* and *diffusion.* The properties of the soil which affect the importance of any one of these processes will affect nutrient availability. Development of soil tests for available nutrients should consider these processes.

Literature Cited

(1) Al-Abbas, H., Barber, S. A., *Soil Sci.* **97,** in press.
(2) Barber, S. A., *Ibid.*, **93,** 39 (1962).
(3) Barber, S. A., Walker, J. M., Vasey, E. H., *New Zealand Intern. Soil Conf. Proc.*, 3 (1962).
(4) Carlson, C. W., Alessi, J., Mickelson, R. H., *Soil Sci. Soc. Am. Proc.* **23,** 242 (1959).
(5) Dittmer, H. J., *Soil Cons.* **6,** 33 (1940).
(6) Fried, M., Shapiro, R. E., *Ann. Rev. Plant Physiol.* **12,** 91 (1961).
(7) Harrold, L. L., Peters, D. B., Dreibelbis, F. R., McGuinness, J. L., *Soil Sci. Soc. Am. Proc.* **23,** 174 (1959).
(8) Jackson, M. L., "Soil Chemical Analysis," Prentice Hall, Englewood Cliffs, N. J., 1958.
(9) Richards, L. A., "Saline and Alkaline Soils." U. S. Dept. Agr. Handbook No. **60** (1954).
(10) Russell, E. W., "Soil Conditions and Plant Growth," 8th ed., Longmans, Green, New York, N. Y., 1950.
(11) Vasey, E. H., Barber, S. A., *Soil Sci. Soc. Am. Proc.* **27,** in press.
(12) Walker, J. M., Barber, S. A., Plant and Soil XVIII, 243 (1962).
(13) Young, H. Y., Gill, R. F., *Anal. Chem.* **23,** 751 (1951).

Received for review October 29, 1962. Accepted March 13, 1963. Division of Fertilizer and Soil Chemistry, 142nd Meeting, ACS, Atlantic City, N. J., September 1962. Journal Paper No. 2040, Purdue University Agricultural Experiment Station, Lafayette, Ind. Contribution from the Department of Agronomy.

End of Symposium

FERTILIZER PARTICLE SIZE

Crop Response to Phosphorus and Potassium in Potassium Phosphates Varying Widely in Particle Size

J. D. DeMENT[1], G. L. TERMAN, and B. N. BRADFORD

Tennessee Valley Authority, Wilson Dam, Ala.

Fusion products approximating the analyses of potassium metaphosphate (KMP) and potassium calcium pyrophosphate (KCP) were produced in pilot plants. KMP was also produced at below-fusion temperatures. Particles of these fertilizers ground rather finely were equal to potassium chloride and concentrated superphosphate as sources of potassium and phosphorus for corn grown in greenhouse cultures. Effectiveness of KMP particles coarser than −6+9 mesh and of KCP coarser than −14+20 mesh decreased markedly with further increase in size. Effectiveness of large particles was greater with surface placement than for mixing with the soil. Solubility in water was a poor index of effectiveness of KMP and KCP for plant growth.

TWO TYPES of fused potassium phosphates have been produced experimentally by the Tennessee Valley Authority: potassium metaphosphate, consisting largely of KPO_3, and potassium calcium pyrophosphate, consisting largely of $K_2CaP_2O_7$. A previous investigation (*2*) showed that potassium in fine (−35 mesh) fused potassium phosphates was equally as available as that in KCl and K_2SO_4, despite wide differences in water solubility of the potassium. Increasing the particle size to −6+9 mesh decreased the availability of the less soluble materials.

Terman and Seatz (*4*) found potassium metaphosphate to be an excellent source of phosphorus for corn, cotton, small grain, and forage crops grown in 175 field experiments on acid to neutral soils in 12 states.

This article reports results with potassium phosphates varying widely in particle size as sources of potassium and phosphorus for crops grown in greenhouse pot tests.

[1] Present address, Esso Research and Engineering Co., Linden, N. J

Materials and Methods

Fertilizers. Chemical analyses of the potassium metaphosphate (KMP), potassium calcium pyrophosphate (KCP), and other fertilizers compared in the various tests are shown in Table I. Potassium phosphates were compared with concentrated superphosphate (CSP) as sources of phosphorus and with muriate of potash (KCl) as sources of potassium.

The fused KMP fertilizers were produced in a pilot plant by burning elemental phosphorus in the presence of KCl at a temperature of about 1800° F. KCP fertilizers were similarly produced by burning elemental phosphorus in the presence of KCl and powdered phosphate rock. The resulting glasses were cooled and crushed to the desired sizes of particles. Petrographic examination indicated small amounts of unreacted KCl in the KMP and of unreacted phosphate rock and beta-$Ca_2P_2O_7$ in the KCP.

KMP glass is largely water soluble. Water solubility (the percentage of phosphorus or potassium that dissolves in a 1-gram sample in 100 ml. of water in 1 hour) of the fused materials, especially of KMP, can be varied by varying the rate of cooling and hence the degree of crystallinity. This also affects the solubility in neutral ammonium citrate (available P_2O_5 by the official A.O.A.C. method). Other studies indicate that KPO_3 is entirely water soluble, but that rate of solution is the important factor in release of potassium and phosphorus.

Three lots of KMP were also made by reacting wet-process H_3PO_4 (67% P_2O_5) with KCl at 850° to 1000° F. This method of production is less expensive than that of burning elemental phosphorus with KCl. These experimental materials consisted largely of crystals of KPO_3 and KH_2PO_4, with minor amounts of KCl and beta-$Ca_2P_2O_7$.

General Procedure in Pot Tests. All experiments were conducted on greenhouse benches at Wilson Dam, Ala. Crops were grown in No. 10 tin food cans lined with polyethylene bags, usually containing 3 kg. of soil, or soil plus sand, per can. Supplemental uniform applications of nitrogen were added as NH_4NO_3, $(NH_4)_2SO_4$, or a mixture