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Characterization of Potassium Uptake and Translocation in Soybeans

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ABSTRACT

Nutrients taken up by plant roots are translocated and distributed to plant parts in order for the plant to carry on its normal functions. To understand these functions better, we developed a five compartment mathematical model which describes K translocation within soybean [*Glycine max* (L.) Merrill] plant parts during vegetative and reproductive growth. The instantaneous rate of change of K contents in the five-compartment soil-soybean system was described using mass balance equations. The seasonal dry matter accumulation, nutrient concentrations, and nutrient contents of the stems, branches, leaves, and pods were used as inputs into the model to determine the effect of growth stage on uptake and translocation parameters. Among the various plant parts, the maximum K fluxes were in the pods (0.257 g m^{-2} d^{-1}) followed by the branches (0.191 g m^{-2} d^{-1}), the stems (0.118 g m^{-2} d^{-1}), and the leaves (0.108 g m^{-2} d^{-1}). The maximum fluxes of K for the stems, branches, and leaves were reached at the same time during vegetative growth. In general, K uptake was higher during vegetative than during reproductive growth. The magnitudes of the transport coefficients were variable during the growing season. During vegetative growth the highest K transport coefficient (15.18 g m^{-2} d^{-1}) was from the stem to the branches indicating that the main transport pathway of K was from the stem to the branch. During reproductive growth the highest transport coefficient (23.26 g m^{-2} d^{-1}) was from the stem to the pods which means that the major movement of K between plant parts during this time was from the stem to the pod. Transport coefficients of K between the branches and pods were low. These results show that the net fluxes of K in soybeans varies with transport pathway within the plant and with plant age.

Additional Index Words: **nutrient transport, compartmental analysis, nutrient mobility, nutrient accumulation, nutrient flux, *Glycine max*.**

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KNOWLEDGE of nutrient uptake and translocation in plants is important for a basic understanding of plant nutrition. Several investigators have published mathematical models that describe movement of nutrients to plant roots (Olsen et al., 1962; Passioura, 1963; Passioura and Frere, 1967; Marriot and Nye, 1968; Baldwin et al., 1973; Baldwin, 1975; Phillips et al., 1976; Cushman, 1979; Bar-Yousef et al., 1980; and Itoh and Barber, 1983). These models outline nutrient transport to plant roots which occurs by mass flow, diffusion, or a combination of both processes. However, few mathematical models have been published that describe nutrient translocation from one plant compartment to the other. Translocation of nutrients in the plant includes the upward movement of nutrients absorbed by the roots, distribution among the plant parts, and redistribution from the initial site of deposition to other parts of the plant (Biddulph, 1959).

Several researchers including Hanway and Weber (1971), Barber (1978), and Batchelor et al. (1984) noted decreases late in the growing season in the concentrations of N and K in all plant parts, except the seeds, even though the nutrients were readily available in the soil. Therefore, during reproductive growth the seeds were considered as sinks for the nutrients, and other plant parts such as leaves, branches, and stems were considered as sources. Thus, depletion of nutrients in the plant parts other than the seed has been attributed to remobilization and subsequent translocation (Scott and Brewer, 1982).

Scott and Brewer (1980) developed a three-compartmental, mathematical model which can be used to describe nutrient transport in plants on a macroscopic scale. Their assumptions were (i) that the soil-plant system was composed of three compartments which simulated the storage and exchange of nutrients by plant parts, (ii) that each plant part was homogeneous, its contents were well mixed, and it interacted with other plant parts by exchanging nutrients, and (iii) that the transfer of nutrients between plant parts occurred in only one direction and at a rate proportional to the concentration of the nutrient in the compartment from which the nutrient flowed. The proportionality parameter was called a transport

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coefficient and was assumed to be constant between the times at which data were collected. Scott and Brewer (1982) expanded their three-compartment system into a four-compartment soil-soybean [*Glycine max* (L.) Merr.] system.

The purpose of this research was to expand the four-compartment system into a five-compartment soil-soybean system by introducing a compartment containing branches which was not considered by the previous systems. This expansion was based upon the data of Scott et al. (1983) who obtained seasonal dry weights and potassium contents of 'Bragg' soybeans grown in well-watered field plots. The seasonal dry weights and K concentrations of the stem, leaf, pod, and branch compartments were used as inputs into the model.

THEORETICAL CONSIDERATIONS

The five-compartment nutrient translocation model assumes that the net direction of nutrient movement during vegetative growth occurs from the soil to the leaves (Fig. 1). The movement of nutrients to the pods during reproductive growth occurs from the stem and branch compartments, since some of the pods are directly attached to the stem while others grow on the lateral branches. The instantaneous rate of change in the amount of a given nutrient in the stem, branch, and leaf compartments during vegetative growth can be described by the following mass balance equations:

$$dQ_s/dt = V - K_{sb}C_s \quad [1]$$

$$dQ_b/dt = K_{sb}C_s - K_{bl}C_b \quad [2]$$

$$dQ_l/dt = K_{bl}C_b \quad [3]$$

where Q_s, Q_b, and Q_l are the quantities of a nutrient (g m^{-2} of land surface) in the stems, branches, and leaves, respectively; V is the whole plant uptake rate (g m^{-2} d^{-1}) during vegetative growth; C_s and C_b are the concentrations of the nutrient (g g^{-1}) in the stem and branch, respectively, K_{sb} and K_{bl} are the nutrient transport coefficients (g m^{-2} d^{-1}) from stem to branch and from branch to leaf, respectively, and t is the time after planting. The nutrient transport coefficient gives a concentration-independent measure of the mobility of the nutrients between plant compartments and is defined as the ratio of the net nutrient flux from the donor compartment to the nutrient concentration in the donor compartment (Scott and Brewer, 1982).

The instantaneous rate of change in the nutrient contents of the plant parts during reproductive growth is characterized by the following mass balance equations:

$$dQ_s/dt = \Theta - (K_{sp} + K_{sb})C_s \quad [4]$$

$$dQ_b/dt = K_{sb}C_s + K_{lb}C_l - K_{bp}C_b \quad [5]$$

$$dQ_l/dt = -K_{lb}C_l \quad [6]$$

$$dQ_p/dt = K_{sp}C_s + K_{bp}C_b \quad [7]$$

where Q_p is the nutrient content of the pods (g m^{-2}), Θ is the whole plant uptake rate (g m^{-2} d^{-1}) during reproductive growth, and K_{lb}, K_{sp}, and K_{bp} are the nutrient transport coefficients (g m^{-2} d^{-1}) from the leaf to the branch, stem to pod, and branch to pod, respectively. These mass balance equations can be solved for the nutrient content of the various plant parts during the growing season.

To solve Eq. [1] through [7], a solution based on seasonal nutrient concentration in the compartments is needed. The mathematical form chosen is the third-order polynomial equation. The relationships between nutrient concentration and time after planting for the stems, branches, and leaves

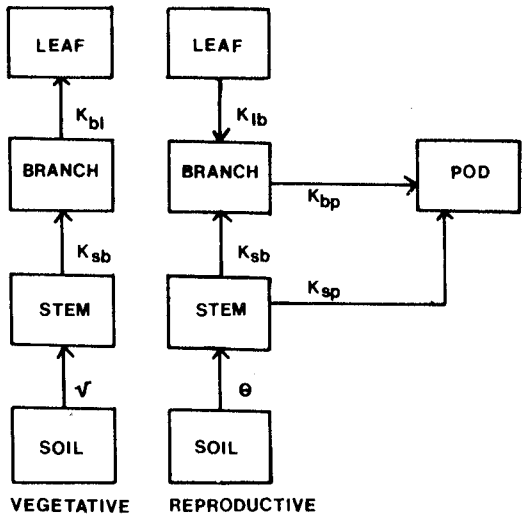

Fig. 1. Transport pathway for K in soybeans during two growth phases. Symbols are explained in the text.

are

$$C_s = a_s + b_s t + c_s t^2 + d_s t^3 \quad [8]$$

$$C_b = a_b + b_b t + c_b t^2 + d_b t^3 \quad [9]$$

$$C_l = a_l + b_l t + c_l t^2 + d_l t^3 \quad [10]$$

where a, b, c, and d are constants and the subscripts s, b, and l designate the stems, branches, and leaves, respectively.

Vegetative Growth

The cumulative amount of a nutrient contained in a given plant compartment during vegetative growth can be obtained by substituting Eq. [8] into Eq. [1], Eq. [8] and [9] into Eq. [2], and Eq. [9] into Eq. [3] and integrating:

$$Q_s(t) = Q_s(t_0) + Q_{Tv} - Q_{Tv}(t_0) - K_{sb}T_{s8} \quad [11]$$

$$Q_b(t) = Q_b(t_0) + K_{sb}T_{s8} - K_{bl}T_{b9} \quad [12]$$

$$Q_l(t) = Q_l(t_0) + K_{bl}T_{b9} \quad [13]$$

where Q_{Tv} is the total amount of the nutrient (g m^{-2}) accumulated by the plant during vegetative growth, and T_{s8} and T_{b9} are the time-integrated forms of Eq. [8] and [9], respectively, from t_0 to t and t_0 is the first sampling date. During vegetative growth,

$$Q_{Tv} = Q_s + Q_b + Q_l \quad [14]$$

and the slope of a plot of Q_{Tv} vs. t gives the uptake rate. The value of the transport coefficient K_{sb} can be determined from Eq. [11] since $Q_s(t)$, $Q_s(t_0)$, $Q_{Tv}(t)$, $Q_{Tv}(t_0)$, and T_{s8} are known. From eq. [13] the value of the transport coefficient K_{bl} is determined since $Q_l(t)$ and $Q_l(t_0)$ are known.

Reproductive Growth

The cumulative amount of the nutrient contained in the four plant compartments during reproductive growth can be obtained by substituting Eq. [8], [9], and [10] into eq. [4], [5], [6], and [7] and integrating:

$$Q_s(t) = Q_s(t_0) + Q_{Tr}(t) - Q_{Tr}(t_0) - (K_{sp} + K_{sb})T_{s8} \quad [15]$$

$$Q_b(t) = Q_b(t_0) + K_{sb}T_{s8} + K_{lb}T_{110} + K_{bp}T_{b9} \quad [16]$$

$$Q_l(t) = Q_l(t_0) - K_{lb}T_{110} \quad [17]$$

$$Q_p(t) = Q_p(t_0) + K_{sp}T_{s8} + K_{bp}T_{b9} \quad [18]$$

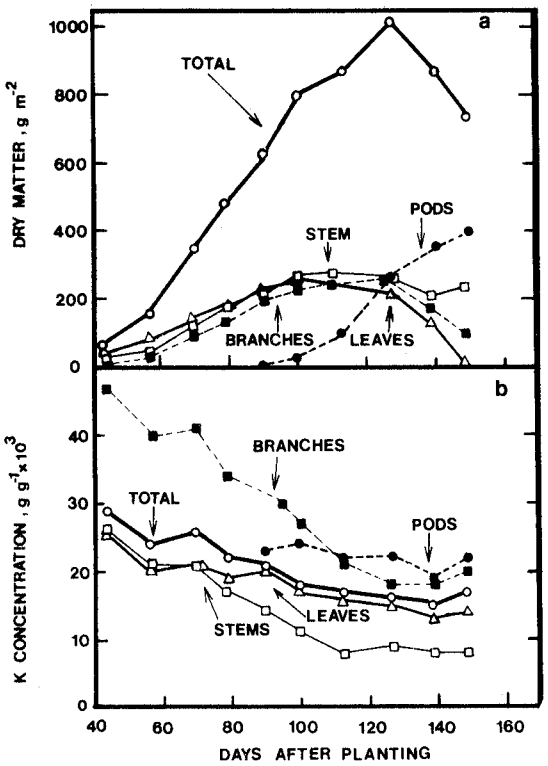

Fig. 2. Seasonal accumulation of dry matter (*a*) and K concentration (*b*) in the different plant compartments.

where T_{110} is the time-integrated form of Eq. [10] from t_0 to t and t_0 is the first sampling date. During reproductive growth,

$$Q_{Tr} = Q_s + Q_b + Q_l + Q_p \qquad [19]$$

Where Q_{Tr} is the total amount of nutrient (g m^{-2}) accumulated by the plant during reproductive growth. The slope of Q_{Tr} vs. t gives the uptake rate Θ. The value of the transport coefficient K_{lb} can be determined from Eq. (17) since $Q_l(t)$, $Q_l(t_0)$ and T_{110} are known. Then the transport coefficient K_{sb} can be derived in terms of the transport coefficient K_{sp} in equation [15]. After substituting the values of K_{lb} and K_{sb} into equation [16] only two unknowns will remain, K_{bp} and K_{sp}, the values of which can be obtained by solving Eq. [16] and [18] simultaneously. The value of the transport coefficient K_{sb} can be determined from the relationship between K_{sb} and K_{sp} obtained from Eq. [15] since the value of K_{sp} is known.

METHODS AND MATERIALS

Equations [1] through [19] can describe the movement of any plant nutrient from one plant part to the other, however, the model was used only with K data which were obtained from a field investigation conducted by Scott et al. (1983) on a Goldsboro loamy sand (Aquic Paleudults, fine, loamy, siliceous, thermic) in which 'Bragg' soybean, a determinate cultivar in maturity group VII, was grown. The soybean was planted conventionally to a stand of 220 000 plants ha^{-1} on 23 May in rows 1-m wide and 75-m long in a field of approximately 1 ha. The experimental design was a nested factorial at four locations with four replications at each location for a total of 16 composite samples, each having an area of 0.30 m^2.

Soil moisture status was monitored with tensiometers at 15, 30, 46, 61, 76, 91, 122, and 152 cm in the ridges and furrows at four locations in the field with four tensiometer banks per location. Soil test before planting and before fertilization showed values of 117.6 kg K ha^{-1} for the surface horizon and 161.3 kg K ha^{-1} for the subsoil. These K values were within the medium to medium plus range according to the South Carolina Soil Test Recommendations (1982). Afterwards, a broadcast fertilization was applied at a rate of 37 kg K ha^{-1}. Chemical weed control was by preplant incorporation of trifluralin (α, α, α-triflouro -2, 6 dinitro-*N*, *N*-dipropyl-*p* toludine) at 1.75 L of material ha^{-1} and application of alachlor [3-(3, 4-dichlorophenyl)-1, 1-dimethyl urea] at 4.94 L of material ha^{-1} at planting. Subsequent weed control was maintained by timely cultivation twice during the growing season. Insects were controlled by aerial application of lannate (*S*-methyl-*N*[(methyl carbamoyi) oxy] thioacetinidate) at 1.75 L of material ha^{-1} at midseason.

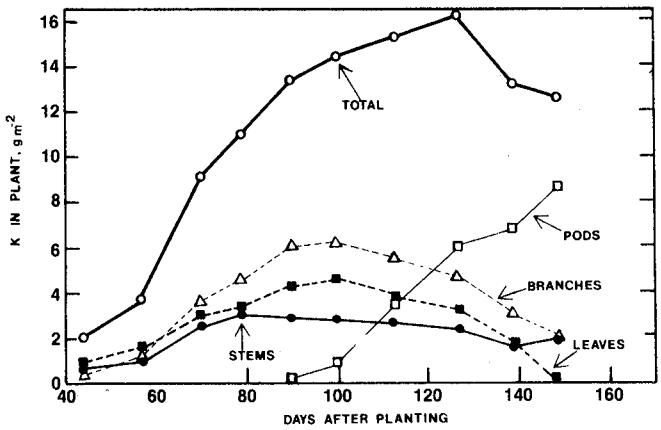

Fig. 3. Seasonal accumulation of K in the plant compartments.

The plants in a 0.3 m^2 area in each of the 16 replications were counted and severed at the soil surface on a total of 10 sampling dates at 10- to 14-d intervals from 7 July to 7 October. Four representative plants were chosen and separated into component parts of stems (main stem only), leaves (leaf blade only), branches (including petioles), and pods. The growth stages were identified according to the conventions and nomenclature presented by Fehr and Caviness (1977). Plant parts were oven dried at 60°C, weighed and ground for K analysis. Potassium was extracted by nitric Perchloric acid digestion and content of K in each plant part was determined by atomic adsorption techniques. The data reported are averages of the 16 replications.

For every sampling interval fluxes of K and crop growth rates (CGR) were calculated from K concentrations and the dry weights for the various plant parts and for the whole plant. The K transport coefficients were calculated from the K contents of the plant parts at the different sampling times.

The seasonal dry matter accumulation, K concentrations, and K contents of the stems, branches, leaves, and pods and of the plant were used as inputs into the model to determine the effects of plant age and transport pathway on the uptake and translocation model parameters.

RESULTS AND DISCUSSION

Dry Matter Accumulation

The accumulation of dry matter during the growing season was typical of well-watered determinate soybeans grown in the field (Fig. 2a). The total plant dry matter accumulation was linear with plant age during most of the growing season. This growth pattern indicates that the soybeans were not stressed. The maximum dry matter accumulated by the total plant was 977.0 g m^{-2} and was found on 27 September. The maximum dry matter accumulations of the leaves, branches, and stems were 263.0, 253.5, and 276.2 g m^{-2} which were found on 31 August, 27 September,

and 13 September, respectively. The decrease in leaf and branch dry weight late in the season can be attributed to abscission as well as to loss of metabolites to the pods. Dry weight of the branches did not decrease to a value as low as that of the leaves because the first order branches remained on the plant during senescence. Changes in stem dry weight were small after 13 September. The dry matter of the pods continued to increase throughout reproductive growth as a result of the continued accumulation of nutrients and metabolites from the other plant components.

Potassium Concentration

The concentration of K in the plant was highest during vegetative growth and generally declined as the season progressed (Fig. 2b). Similar observations were made by Henderson and Kamprath (1970), Harper (1971), and Batchelor et al. (1984). This decline in K concentration can be attributed to dilution brought about by the greater rates of dry matter accumulation as compared with K uptake rates. K concentrations of the leaves, branches, and stems also declined during the season. On a given sampling date during vegetative growth, the highest K concentrations were found in the branches and the lowest concentrations were found in the stems. The relatively steep decline in the K concentration in the branches can be attributed to the production of numerous lateral branches during vegetative and early reproductive growth. As shown by Scott et al. (1983), dry matter accumulation of the stems, branches, and leaves continued in the upper one-third of the canopy until midreproductive growth. During this time there was considerable lateral branching in the middle of the canopy.

These K concentrations in the four plant parts indicate that on a macroscopic scale transport is not dominated by diffusion. This results from the higher K concentrations in the branches than (i) in the leaves during vegetative growth and (ii) in the pods during the early reproductive growth.

Potassium Contents

The accumulation of K by the plant and its component parts during the growing season is shown in Fig. 3. The shapes of these curves are similar to those of the dry weight accumulation with the exception that for the stems, branches, and leaves the highest K accumulations usually were found earlier than the dry matter accumulation. The decrease in the slopes of the curves during the later portion of the growing season indicates that K uptake declined with plant age. The highest K contents during the early portion of the growing season were in the leaves, and the highest K contents after the midreproductive growth were in the pods. As with dry weight, the accumulation of K by the branches reached a high during late vegetative growth and remained at that level until midreproductive growth. Generally accumulation of K in the vegetative parts increased until 100-d after planting. This was followed by a decline of K in these vegetative parts of the plant. However, when the total plant (stems, branches, leaves, and pods) were considered, K accumulation continued to increase until 127-d after planting, when a plateauing of the accumulation occurred. The decrease in K content of branches and leaves could be attributed to shedding of these parts late in the season and to translocation of the nutrient from these parts to the pods. Hamond et al. (1951) have shown that translocation of K to the seed increased rapidly after leaf fall began and that most of it came from the leaves, stems, and roots. They found that the longer leaves remained on the plants, the more thoroughly they were depleted of K. The decrease in the total K content is also due to the shedding of branches and leaves late in the season.

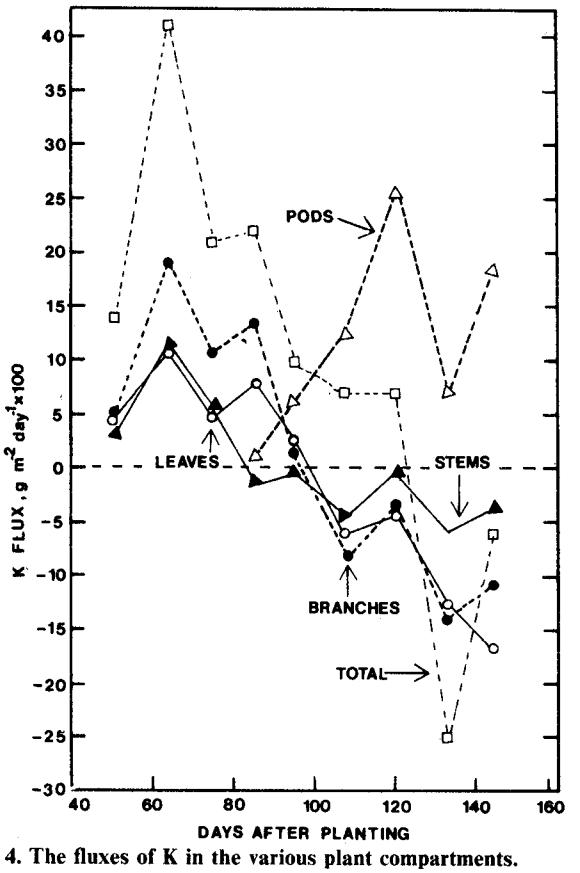

Fig. 4. The fluxes of K in the various plant compartments.

Potassium Fluxes

The average K fluxes for each sampling interval were calculated by the difference in the K contents between each two consecutive sampling intervals divided by the length of the interval. The fluxes were calculated for the plant and each component part and are shown in Fig. 4. Positive fluxes indicate that the K entering the soybean or one of its component parts is greater than the fluxes leaving the compartment. Therefore, positive fluxes indicate that the compartment is accumulating K; negative fluxes indicate that the compartment is losing K.

The K fluxes of the stems, branches, and leaves increased to a maximum during midvegetative growth and then declined. Negative fluxes were calculated for all three compartments during reproductive growth and suggest that these compartments were losing K to the pods faster than they could obtain it from the soil. During vegetative growth the highest K flux was 0.191

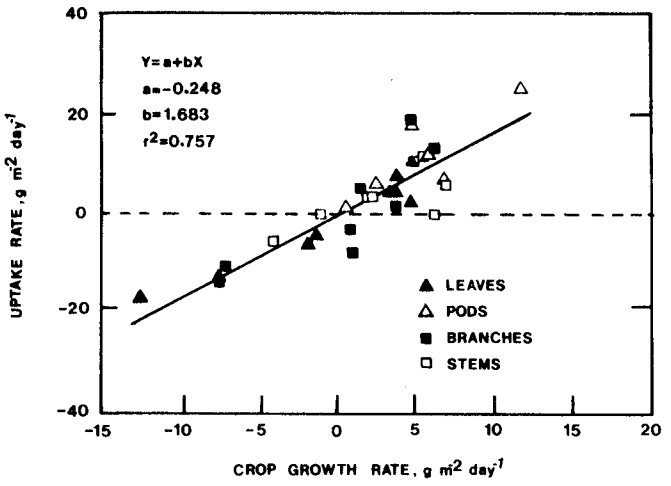

Fig. 5. The relationship between uptake rate and crop growth rate for the different compartments of the plant.

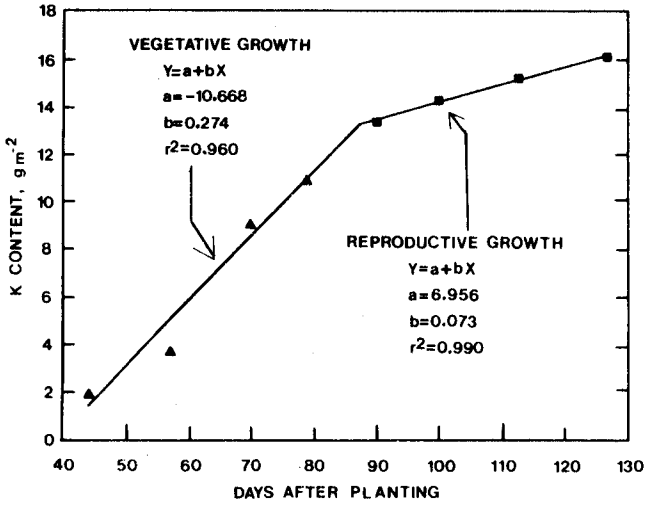

Fig. 6. K content of the plant as a function of time. The triangles represent K contents during vegetative growth and the squares represent K contents during reproductive growth.

g m^{-2} d^{-1} found in the branches during late July. This K flux was followed by fluxes of 0.118 and 0.108 g m^{-2} d^{-1} during the same interval by the stems and leaves, respectively. During reproductive growth the highest K flux was 0.257 g m^{-2} d^{-1} for the pods during late September. K flux decreased faster in the stems than the other compartments during vegetative growth, but during reproductive growth K flux decreased faster in the branches and leaves than in the stems. The decrease in the fluxes can be attributed to senescence and abscission of these plant parts. The general observation of a decrease in fluxes of K during late period of growth and development of soybeans has been reported by Henderson and Kamprath (1970), Harper (1971), and Barber (1978).

The total plant fluxes of K are equivalent to the average uptake rates during the same interval. The maximum K uptake rate occurred during late July and was 0.417 g m^{-2} d^{-1}. The maximum plant uptake rate during reproductive growth was 0.179 g m^{-2} d^{-1} and occurred during mid-September. The negative uptake rates at the end of the growing season are due to abscission of leaves and branches. Negative values of K uptake rates by soybeans late in the growing season have also been reported by Barber (1978). In addition, he noticed that K influx, as calculated per meter of root per day, is great when the plant is young and decreases when the plant becomes older.

Table 1. Transport coefficients for K between the component parts of 'Bragg' soybean during vegetative and reproductive growth.

Interval	K_{sb}	K_{bl}	K_{sp}	K_{lb}	K_{bp}
d	g m^{-2} d^{-1}				
44-57	4.24	1.14			
57-70	14.15	2.52			
70-79	8.28	1.79			
79-90	15.18	2.46			
90-100	3.08	--	4.77	-1.40	0
100-113	4.09	--	6.05	3.32	-2.45
113-127	-15.50	--	23.26	2.42	2.67
127-139	-34.09	--	9.36	7.58	0
139-149	-34.50	--	22.75	10.70	0

The seasonal total plant uptake rates were obtained by plotting Eq. [14] and [19] vs. time and evaluating the slope (Fig. 5). The average seasonal plant uptake rate during vegetative growth was 0.274 g m^{-2} d^{-1} and was 0.073 g m^{-2} d^{-1} during reproductive growth. These results show that these Bragg soybeans extracted K at a greater rate during vegetative growth than during reproductive growth and that these uptake rates were reflected in positive fluxes for the component parts. Fluxes of K for the pods were positive during reproductive growth while the fluxes of the other component parts were negative, an indication that the pods were the primary sinks for K and assimilates during this period.

The relationships between CGR and uptake rate for the component parts are shown in Fig. 6. For the most part the relationships were linear, had a near zero intercept, and were independent of plant part. The linear relationship between K uptake rates and CGR suggests that an influence on dry matter accumulation would directly influence K flux.

Potassium Transport Coefficients

Values of the transport coefficients were calculated from Eq. [11] and [13] for vegetative growth and from Eq. [15], [16], [17], and [18] for reproductive growth (Table 1).

The magnitude of the transport coefficients is an indication of the direction and ease with which K is transported between two compartments. During vegetative growth, K_{sb} was the highest transport coefficient. This result indicates that the main K transport pathway was from the stem to the branch. During late vegetative growth K fluxes in the branches were high relative to those of the stem (Fig. 4). Therefore, the branches were the primary sink for K during this period. During reproductive growth K_{sp} was the highest transport coefficient. These results show that the main transport pathway within the plant compartments during reproductive growth was from the stem to the pods and that the pods were the principal sinks for K. Values of K_{sp} were higher during late than early reproductive growth due to the higher fluxes into the pods relative to those of the stems and branches. The negative K_{lb} during early reproductive growth suggests

that the leaves continued to accumulate K transported from the branches. These could be newly grown leaves on the lateral branches and leaves that continued to expand in the upper part of the canopy after the early initiation of reproductive growth. The net transport of K to the pods from the branches was less significant than transport from the stems and would constitute a minor pathway.

REFERENCES

Baldwin, J.P., P.H. Nye, and P.B. Tinker. 1973. Uptake of solutes by multiple root systems from soils. III. A model for calculating the solute uptake by a randomly dispersed root system developing in a finite volume of soil. Plant Soil 38:621–635.

Baldwin, J.P. 1975. A quantitative analysis of the factors affecting plant nutrient uptake from some soils. J. Soil Sci. 26:195–206.

Barber, S.A. 1978. Growth and nutrient uptake of soybean roots under field conditions. Agron. J. 70:457–461.

Bar-Yousef, B., S. Fishman, and H. Talpaz. 1980. A model of zinc movement to single roots in soils. Soil Sci. Soc. Am. J. 44:1272–1279.

Batchelor, J.T., H.D. Scott, and R.E. Sojka. 1984. Influence of irrigation and growth stage on element concentrations of soybean plant parts. Commun. Soil Sci. Plant Anal. 15:1083–1109.

Biddulph, O. 1959. Translocation of inorganic solutes. p. 553–603. *In* F.C. Steward (ed.) Plant physiology: A treatise, Vol. 2. Academic Press, New York.

Cushman, J.H. 1979. An analytical solution to solute transport near root surfaces for low initial concentration: Applications. Soil Sci. Soc. Am. J. 43:1090–1095.

Fehr, W.R., and C.E. Caviness. 1977. Stages of soybean development. Spec. Rep. no. 80. Cooperative Extension Service. Iowa State Univ. Ames.

Hammond, L.C., C.A. Black, and A.G. Norman. 1951. Nutrient uptake by soybeans on two Iowa soils. Iowa Agri. Exp. Stn. Bull. 384.

Hanway, J.J., and C.R. Weber. 1971. N, P, and K percentages in soybean [*Glycine max* (L.) Merrill] plants. Agron. J. 63:406–408.

Harper, J.E. 1971. Seasonal nutrient uptake and accumulation patterns in soybeans. Crop Sci. 11:347–350.

Henderson, J.B., and E.J. Kamprath. 1970. Nutrient and dry matter accumulation by soybeans. N.C. Agri. Exp. Sta. Tech. Bul. 197.

Itoh, S., and S.A. Barber. 1983. A numerical solution of whole plant nutrient uptake for soil-root systems with root hairs. Plant Soil 70:403–413.

Marriot, F.H., and P.H. Nye. 1968. The importance of mass flow in the uptake of ions by roots from the soil. Int. Cong. Soil Sci., Trans. 9th 1:127–134.

Olsen, S.R., W.D. Kemper, and R.D. Jackson. 1962. Phosphate diffusion to plant roots. Soil Sci. Soc. Am. Proc. 26:222–227.

Passioura, J.B. 1963. A mathematical model for the uptake of ions from the soil solution. Plant Soil 18:225–238.

Passioura, J.B., and M.H. Frere. 1967. Numerical analysis of convection and diffusion of solute to roots. Aust. J. Soil Res. 5:149–159.

Phillips, R.E., T. Nanagara, R.E. Zartman, and J.E. Leggett. 1976. Diffusion and mass flow of nitrate-nitrogen to plant roots. Agron. J. 68:63–66.

Scott, H.D., and D.W. Brewer. 1980. Translocation of nutrients in soybeans. Soil Sci. Soc. Am. J. 44:566–569.

Scott, H.D., and D.W. Brewer. 1982. Characterization of nutrient transport coefficients in field-grown soybeans. Soil Sci. Soc. Am. J. 46:998–1004.

Scott, H.D., R.E. Sojka, D.L. Karlen, F.B. Arnold, V.L. Quisenberry, and C.W. Doty. 1983. Bragg soybeans grown on a southern coastal plains soil. 1.-Dry matter distribution, nodal growth analysis, and sample variability. J. Plant Nutr. 6:133–162.

South Carolina Soil Test Recommendations. 1982. Lime and fertilizer recommendations based on soil test results. Circ. no. 476 Cooperative Extension Service, Clemson University, Clemson, SC.