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MOVEMENT OF METAL CATIONS THROUGH THE SOIL TO THE PLANT ROOT MEMBRANE

Progress Report
for Period September 1, 1975-August 31, 1976

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MASTER

May 1976

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Prepared For

THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
UNDER CONTRACT NO. AT(11-1)-1495

427 attached

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TECHNICAL PROGRESS REPORT

Sept. 1, 1975 - Aug. 31, 1976

ABSTRACT

This project investigates principles and mechanisms governing flux of metal cations, K, Rb, and Cs into plant roots growing in soil. Three soil and seven plant factors have been combined in a mathematical model to test principles and mechanisms developed.

Measurement of K and Rb influx into corn roots growing in solution culture showed that corn roots absorb K and Rb interchangeably over a wide range of K/Rb ratios and concentrations in solution. Equilibration of K and Rb with soil showed that K/Rb in the solution phase was 2 to 4 times the ratio on the exchange phase. Potassium and Rb uptake by corn growing in 4 different soils showed the K/Rb ratio of uptake corresponded with the K/Rb ratio on the exchange sites indicating they determined the K and Rb supply to the root. The data will be evaluated in a mathematical model to aid in determining the mechanisms.

A new procedure was developed for measuring total length of roots in a sample and also the distribution of diameter size classes. A new procedure was also developed for analyzing curves of ion depletion with time from nutrient solutions to determine the factors characterizing influx of ions into intact plants.

INTRODUCTION

The research on this project that is reported herein has complied with the contract requirements as given in the project proposal for this period.

The principal investigator has devoted 20% of his time to this project and expects to continue to devote 20% of his time to the project for the remainder of the current term of the contract.

OBJECTIVES

This continuing research on the principles and mechanism of ion absorption of metal cations from soil is aimed at determining how metal cations are released from the soil, move to the root and are absorbed by the root. An understanding of these principles will allow for development of practices that will either increase or decrease the flux of these cations into the plant root. The research has been conducted under two objectives. The first relates to the chemistry of the cation with the soil surface. The second relates to the flux of the cation to the plant root and includes investigation of those plant and soil factors that affect the flux both in the soil and in the root.

Objective I

Determination of the principles governing the equilibrium and rate of equilibration between metal cations in soil solution and those adsorbed by the solid phase.

Objective II

Determination of the basic nature of metal cation flux through the soil to, and absorption by the root and their description by an objective mathematical model.

SUMMARY OF RESEARCH CONDUCTED IN 1975-1976

The early research in this project emphasized research under objective I. The present research is combining the results obtained under objective I with the research investigations of objective II so that more emphasis is now being placed on objective II.

Research under Objective I

I-a The influence of K level and soil type on the distribution of K and Rb between solution, exchangeable, and non-exchangeable sites in soils.

When K and Rb are present as ions in soil systems they distribute between the various phases present so that when they are compared the equilibrium system shown in equation [1] is attained.

$$\frac{K_1}{Rb_1} \lessgtr \frac{K_{ex}}{Rb_{ex}} \lessgtr \frac{K_{ne}}{Rb_{ne}} \qquad [1]$$

where the subscripts 1, ex, and ne indicate solution, exchangeable and non-exchangeable phases.

An experiment was conducted using 4 soils each at 2 levels of K and one level of Rb to determine the differences between K and Rb in their absorption by the soil and the effects of different soils on this equilibrium. The reason for using K and Rb in this research was to obtain information about this distribution that could be used in plant growth experiments evaluating the flux of ions from the various phases into the roots. Since K and Rb are absorbed interchangeably by the plant root these ions are a unique pair, use of which provides much more information on flux mechanisms that can be obtained using a single ion since all uptake parameters are the same except for the ion flux through the soil.

The characteristics of the 4 soils used are presented in Table 1.

Table 1. Chemical and physical properties of 4 soils used in K-Rb distribution studies.

Soil	pH	Organic carbon %	Clay %	Cation exchange capacity	Exchangeable Ca	Exchangeable K
				-------me per 100 g------		
Zanesville sil	6.3	1.67	12.5	12.9	6.33	0.37
Chalmers sil	5.9	2.56	20.6	31.5	12.25	0.23
Raub sil	6.2	1.54	27.8	21.0	9.66	0.19
Toronto sil	6.3	1.54	19.2	20.4	7.80	0.21

The rates of K and Rb additions to these soils were 0, and 2.5 me K and 0.1 me Rb per 100 g of soil. Nitrate was added as either Ca or K nitrate to give an addition to Zanesville of 0.13 me/100 g and to the other three soils 0.25 me/100 g of soil. Phosphate was also added. The soils were incubated moist for 5 days, air-dried, remoistened and incubated for an additional 21 days before samples were taken for analysis. Analyses were made on soil at 0.3 bar moisture tension. The analyses for K and Rb are shown in Table 2.

Table 2. Distribution of K and Rb in 4 soils.

Soil	Solution		exchangeable		non-exchangeable *	
	K	Rb	K	Rb	K	Rb
	μmoles ml^{-1}		μmoles cm^{-3}		μmoles cm^{-3}	
Zanesville	1.91	0.15	4.67	0.93		0.37(33)†
Zanesville + K	6.22	0.22	8.41	0.81	0(0)	0.49
Chalmers	0.19	0.004	2.65	0.18		1.12(89)
Chalmers + K	0.34	0.003	4.07	0.10	1.83(56)	1.20
Raub	0.18	0.013	2.21	0.63		0.67(60)
Raub + K	0.50	0.016	3.89	0.43	1.57(48)	0.87
Toronto	0.27	0.019	2.25	0.52		0.78(65)
Toronto + K	0.62	0.018	4.02	0.40	1.48(46)	0.90

* Amounts of K and Rb added that were not measured as exchangeable or in solution.

† Values in parenthesis are average percent of applied K or Rb that is present in non-exchangeable form.

Results. On Zanesville sil no K was absorbed into non-exchangeable positions while on Chalmers sil a large fraction was. This reflects the previous experience with these soils and is due to the types of clay minerals present. The relative proportion of K in solution as compared to that adsorbed on exchange sites was most on Zanesville and least on Chalmers indicating the exchange sites on the latter bond K more tightly. Rb followed the same pattern except that a greater proportion of the Rb was adsorbed on exchange sites. When K and Rb were compared, Rb was adsorbed 2.5 to 3.8 times more than K. (Table 3). The ratio of C_l/C_{ex} for both K and Rb varies with soil and K level, hence these soils provide a desireable situation for using the ratio of K/Rb taken up by plants grown on these soils to investigate the mechanisms of ion absorption. This will be reported in II-e.

Table 3. Selectivity of exchange sites for K and Rb on 4 soils.

Soil	$C_l/C_{ex} \times 10^{-1}$ K	$C_l/C_{ex} \times 10^{-1}$ Rb	K/Rb selectivity C_l/C_{ex}	K/Rb selectivity C_{ex}/C_{ne}
Zanesville sil	4.08	1.61	2.58	
Zanesville sil + K	7.41	2.72	2.78	----
Chalmers sil	0.73	0.22	3.47	
Chalmers sil + K	0.83	0.30	2.72	26.7
Raub sil	0.81	0.21	3.83	
Raub sil + K	1.28	0.37	3.51	5.0
Toronto sil	1.18	0.36	3.23	
Toronto sil + K	1.54	0.45	3.42	6.1
Average	2.23	0.78	3.19	

Research under Objective II.

II-a The characteristics of K and Rb absorption by corn (*Zea mays* L.) roots from K and Rb present in aerated solution culture.

A review of the literature indicated that K and Rb are absorbed more or less interchangeably by plant roots, especially when there is much more K present than Rb. However this has not been evaluated critically. The objective of this experiment was to measure K and Rb uptake from solutions in which the K/Rb ratio varied widely and to use the Claassen and Barber procedure to determine I_{max}, maximum influx rate, K_m, concentration of the ion in solution where influx is one-half I_{max}, and C_{min}, the minimum level to which the plant roots can reduce the concentration in solution. The reason for this research was to establish the nonselectivity of absorption between K and Rb so that when studies are made of K and Rb uptake from soil the flux through the soil could be taken as the factor causing differences in K and Rb uptake and hence this approach would facilitate investigation of the mechanisms involved.

Experiments set up to test the hypothesis of non-selectivity consisted of growing corn plants in nutrient solutions in which the K/Rb ratio varied over a wide range. Absorption rates of K and Rb by the corn plants were determined by following solution concentrations of the two ions as the corn plants were allowed to deplete the K and Rb in solution to C_{min}.

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Experiments set up to test the hypothesis of non-selectivity consisted of growing corn plants in nutrient solutions in which the K/Rb ratio varied over a wide range. Absorption rates of K and Rb by the corn plants were determined by following solution concentrations of the two ions as the corn plants were allowed to deplete the K and Rb in solution to C_{min}.

The corn plants were prepared by growing them in a growth chamber for 19 days, then they were grown for 1 day in nutrient solutions in which the K/Rb ratio was the same as that to be used at the start of the depletion experiment. This enabled the roots to equilibrate with this ratio of K/Rb. On the 21st day the solutions were measured every 10 minutes as the plants gradually reduced their concentration of K and Rb. This is the procedure of Claassen and Barber (1974).

Results. The depletion of K + Rb from solution is illustrated by the curve shown in Figure 1 for absorption from solution that was initially 260 μM Rb and 100 μM K. The curve fit the data closely. The values calculated from fitting the curve are I_{max}, K_m, and E and C_{min} which is the measured value in solution at the end of the experiment. They are given in Table 4. There was no relation between I_{max} and the relative proportions of K and Rb in the solution indicating that K and Rb were absorbed equally. When a plot was made of % K or % Rb left in solution vs. time the data for both nutrients fell along one line. The values for K_m were variable but did not relate to proportion of Rb and K present.

The values of I_{max}, E, and K_m were substituted in equation [1] and the data plotted. A plot of the six curves are shown in Figure 2. Differences in the curves probably reflect time of running the experiment rather than differences since we couldn't run them simultaneously.

$$In = \frac{I_{max} C}{K_m + C} - E \qquad [1]$$

The data indicate the K and Rb are absorbed interchangeably over a wide range and that in soil experiments we can assume that this interchangeable absorption by the root occurs.

Table 4. Effect of K and Rb concentrations on the influx parameters of K + Rb by corn roots.

Initial Concentration			K + Rb uptake parameters			
Rb	K	total	I_{max}	E	K_m	C_{min}
μM			pmoles $cm^{-1}sec^{-1}$		μM	μM
320	14	334	5.9	0.9	7 ± 2	1
306	28	334	5.5	0.3	24 ± 5	1
332	60	392	4.7	0.2	26 ± 3	1
260	100	360	6.5	0.5	16 ± 2	1
202	180	382	4.0	0.4	13 ± 3	1
82	264	346	5.0	0.3	23 ± 3	1
Average			5.3	0.3	18	1

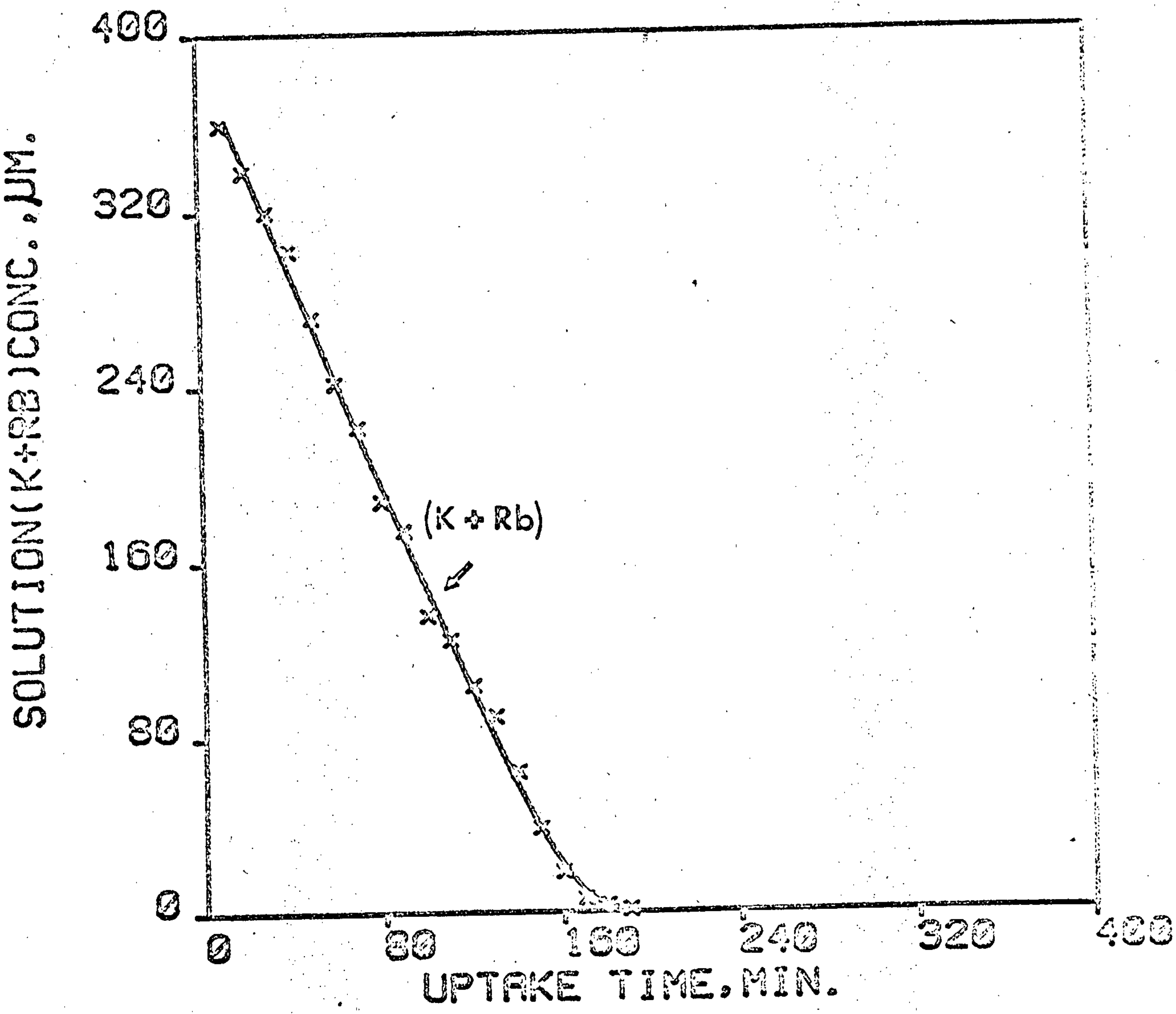

Fig. 1. Depletion of (K + Rb) from 2 liters of nutrient solution by 6, 21-day-old corn plants. The points are observed values. The curve was fit using equation 7.

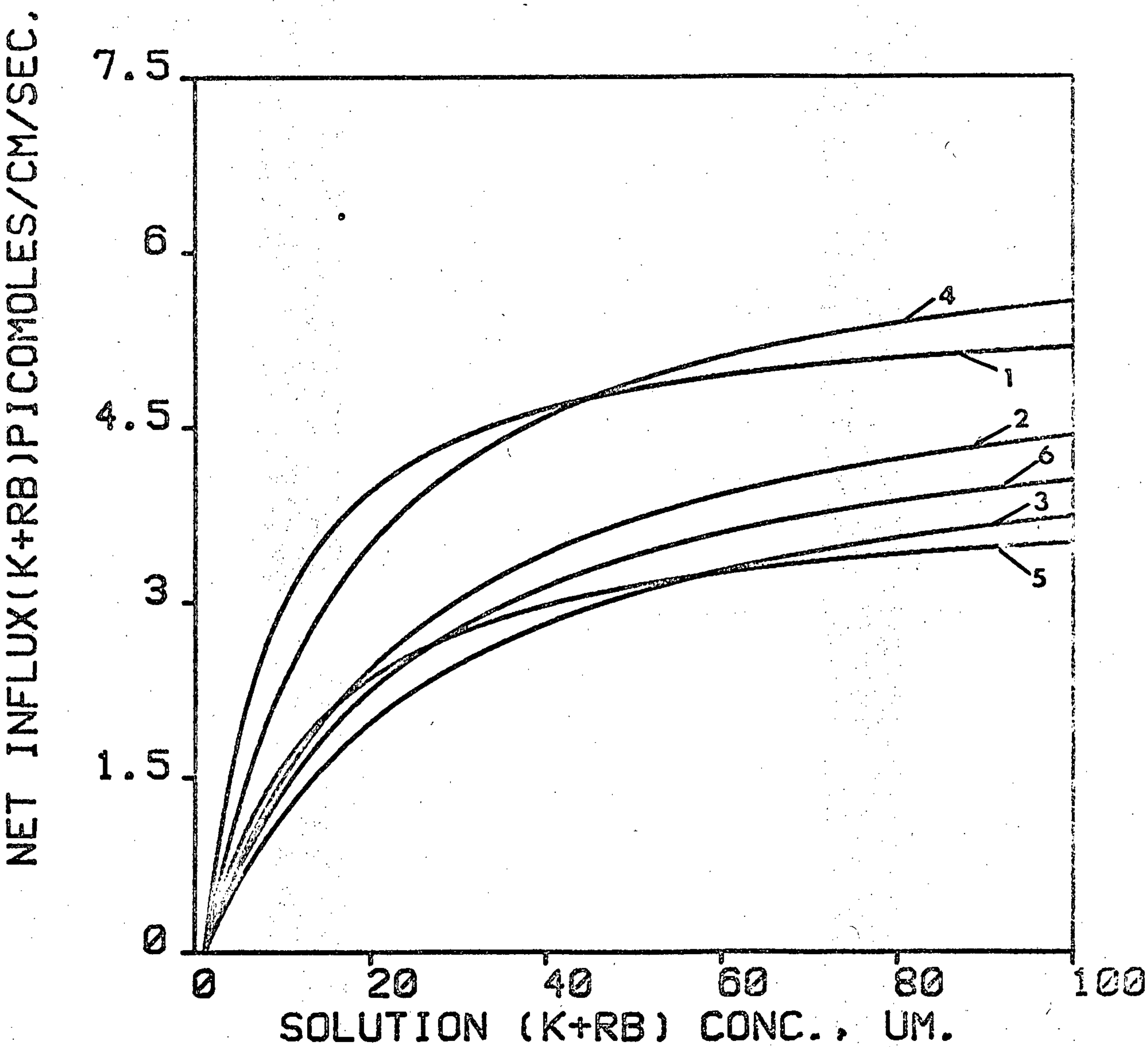

Fig. 2. Net influx of K+Rb as related to concentrations for 6 K/Rb ratios. The initial concentrations were: 1. 320 μM K + 14 μM Rb; 2. 306 μM K + 28 μM Rb; 3. 332 μM K + 60 μM Rb; 4. 260 μM K + 100 μM Rb; 5. 202 μM K + 180 μM Rb; 6. 82 μM K + 264 μM Rb.

II-b Relative rates of absorption of Cs and K from solution by 20-day-old corn plants.

Previous research (Menzel and Heald, 1955) has indicated that Cs is absorbed much more slowly than K even though they are both believed to be absorbed at the same carrier site. Little information is available on Cs absorption by corn as related to K/Cs ratio and K concentrations.

Experiments were conducted in which corn was grown to 19 days in solution cultures with no Cs supplied. Then Cs and K were supplied at five different concentrations to equilibrate the plant roots with the particular K/Cs ratio. Then on the 20th day the solution was renewed at the same K/Cs ratios and the corn plants were allowed to deplete K and Cs from solution. The concentrations of K and Cs in solution were measured every 15 minutes and from this information rates of absorption determined.

In this case there was interaction between K and Cs. Absorption rate of one ion was influenced by the concentration of the second ion so that the usual procedure for determining influx of K and Cs by fitting the data by least squares could not be used.

The depletion data for the system that initially contained 179 μmoles Cs and 185 μmoles K is shown in Figure 3. Since the concentrations were nearly equal initially, it is apparent that K was absorbed faster than Cs. It is also apparent that as the level of K was reduced the rate of Cs absorption increased.

There is apparently a relation that can be expressed by equation [2].

$$I_{Cs} = I_{oCs} - X\ (K/Cs) \qquad [2]$$

where I_{Cs} is the net influx of Cs, I_{oCs} is the influx where no K is present and this rate is decreased in proportion to the ratio of K/Cs when K is present.

Since there is a relation between K concentration and Cs influx, this will be evaluated further using experiments where K levels are maintained constant as Cs is depleted from solution.

Menzel, R.G., and W.R. Heald. 1955. Distribution of potassium, rubidium, cesium, calcium, and strontium within plants grown in nutrient solutions. Soil Sci. 80:287-293.

The data from succeeding experiments will be used to help evaluate the absorption from the systems used here and develop a relation between K and Cs influx as related to their relative concentrations.

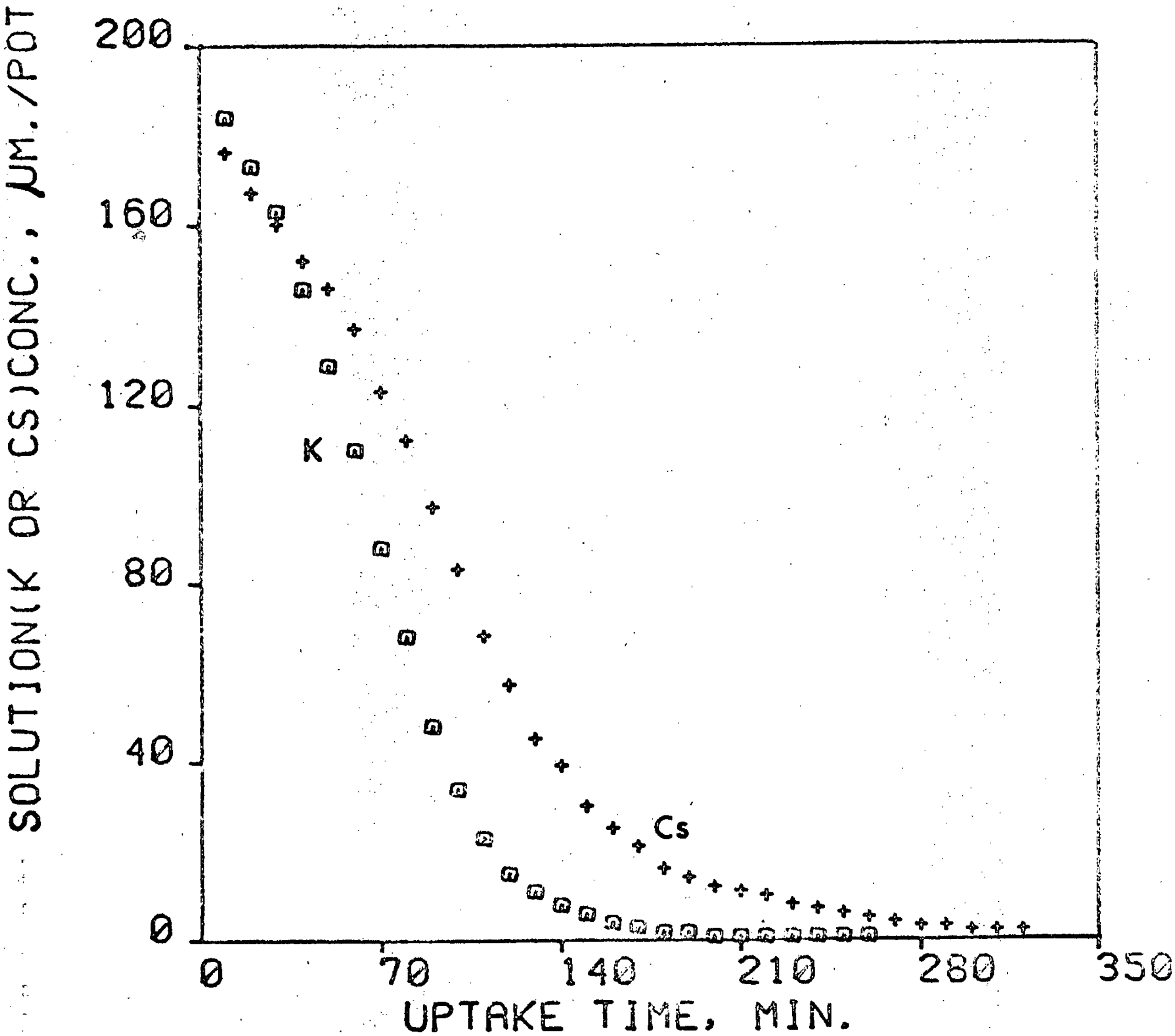

Fig. 3. Depletion of K and Cs from 2 liters of nutrient solution by 6, 20-day-old corn plants.

II-c Developing a procedure for measuring plant root length and root diameter.

In studies with plant roots absorbing nutrients from soil both root length and root diameter are involved in describing the flux of nutrients into the root. The procedure we have used is an adaptation of one developed by Newman (1966) for measuring root length. His method involves measuring the number of root intercepts of lines superimposed on roots spread over a uniform area. The formula for root length is

$$L = \pi \frac{NA}{2H} \qquad [3]$$

where L is total root length, N is the number of intersections, A is the area of the rectangle in which the roots are spread and H is the total length of the straight lines which intercept the roots.

Root diameters were measured by selecting roots at random and measuring their diameters under a microscope.

To improve the measurement and reduce the time involved the roots were spread on a black rectangular area and photographed using Kodalith film. The picture on the film was digitized and placed in the computer. It was then very easy for the computer to measure total root length by counting intersects of all the lines of digitized data and using equation [3] for calculating root length.

A program was also developed to calculate root diameters as each root was contacted. This was done by triangulation every time a line of digitized numbers encountered a root. By placing the measured diameters into categories of size a frequency distribution of root diameters was obtained. The data agreed very well with those done visually but had a much smaller experimental error.

II-d Development of a new statistical procedure for calculating ion absorption parameters of plant roots growing in nutrient solution.

Claassen and Barber (1974) developed a mathematical model for determining ion influx parameters of plant roots from data on the rate of ion depletion from a nutrient solution. Plants were allowed to deplete the ion from solution until a minimum concentration in

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Newman, E.I., 1966. A method of estimating the total length of root in a sample. J. Applied Ecol. 3, 139-145.

solution, C_{min}, was obtained. The concentration in solution was measured at intervals over the time period and data such as that shown in Figure 1 were obtained. The procedure of Claassen and Barber used a computer to fit an integrated rate equation based on Michaelis-Menten kinetics to the data by a least squares procedure. The equation was integrated numerically and the first derivative gave influx at various concentrations. The influx was described by I_{max}, maximum influx at high concentration, K_m, the Michaelis constant, and E, efflux. Efflux was necessary to fit the curve to the data because the plant roots do not completely deplete the ion in solution but only reduce it to a minimum concentration where influx is equal to efflux.

We had difficulties with this procedure in that for some ions unrealistic values of E were obtained and this also caused I_{max} and K_m to be unrealistic. Hence a different approach was used to develop a procedure for determining the influx parameters from the data obtained by the depletion curve.

The new function developed by Neilsen is one which can be integrated analytically and is also explicit in time. The function used with the first model that was integrated numerically was:

$$-v \frac{dC}{dt} = \frac{I_{max} C}{K_m + C} - E \qquad [4]$$

where v is the volume of the solution in the pot, t is time and the other symbols are those defined previously.

The new function is shown in equation [5]:

$$-v \frac{dC_x}{dt} = \frac{I^1_{max} C_x}{K^1_m + C_x} \qquad [5]$$

where C_x is equal to $C - C_{min}$, C_{min} is the minimum concentration reached in the solution. I^1_{max} is maximum net influx, and equal to $I_{max} - E_1$, and K^1_m is for net influx and is equal to $K_m - C_{min}$.

Rearranging equation [5] we get

$$-(I^1_{max}/v)dt = (1 + K^1_m/C_x)dC_x \qquad [6]$$

This can be integrated analytically to give the expression shown in equation [7].

$$t = a -(v/I^1_{max})C_x - (vK^1_m/I^1_{max})\ln C_x \qquad [7].$$

To fit the curve to the data of C vs. t as illustrated in Figure 4, C_x is obtained by subtracting C_{min} from each C. C_{min} is obtained experimentally. The values of C_x vs. t can then be fit by least squares and solved to give values of I^1_{max} and K^1_m.

Data fit by this procedure gave identical results to those obtained using the first function. This procedure uses much less computer time and we have had no difficulties fitting a curve to the data. In addition the new procedure gives the value of standard error of I_{max}, K_m and C_{min}.

II-e Determination of the source of K and Rb using K/Rb ratio of uptake of these ions by corn plants.

When corn plants were grown in solution culture containing K and Rb, the K/Rb ratio of K and Rb absorbed was the same as the K/Rb in solution. The ions were absorbed without discrimination. This concept was used to determine the source of K and Rb absorbed from soil systems. When K and Rb are added to soil, Rb is adsorbed more tightly than K so that the K/Rb ratio in the solution phase is larger than the K/Rb in the exchange phase. In addition on some soils both K and Rb may move to a non-exchangeable phase on soils and the K/Rb on this phase is usually different from the ratio in the solution or exchangeable phase. When plants are grown in soil treated with K and Rb, they will absorb K and Rb without discriminating between them so that the ratio of K/Rb absorbed should reflect the ratio of the phase from which the ions are being absorbed. Since the K/Rb in the solution phase was 2.5 to 3.8 times the K/Rb on the exchange phase, it should not be difficult to identify the source influencing the ratio of K/Rb absorbed.

In addition as K and Rb move to the root by mass-flow and diffusion, the relative amount supplied by each mechanism may also affect the results. As levels of K and Rb in the soil are increased, the proportion of mass-flow supply will increase so this should affect the results. Data were also obtained so that both K and Rb can be put in our mathematical model. If the model is describing the process accurately the data of both K and Rb predicted by the model should agree with the observed uptake by the corn plants.

Procedure: This experiment involved 4 different soils each at 2 levels of K and one of Rb, 3 harvests and three replications. Four corn plants were grown in each pot of 3 kg of soil in a growth chamber. Plants were harvested at 4, 10, and 16 days. Corn plants were grown for the first 4 days in wet paper toweling, then roots trimmed to induce branching and they were transplanted into the soil. Plants growing in the soil were harvested 6 and 12 days after transplanting.

Measurements made on the plants included: shoot weight, root length, root radius, K and Rb content, and amount of water transpired during growth. The soil was equilibrated moist for one month prior to planting the corn. The K/Rb characteristics and other soil properties were described in section I-a. The soil was sampled at planting and after each harvest. Measurements made were K and Rb in solution, K and Rb as exchangeable cations and effective diffusion coefficient of K and Rb.

During growth of the crop the pots were watered daily to 0.3 bar soil moisture tension. Pots were weighed daily to measure water loss. The soil was covered with sand to reduce evaporative loss and pots without plants were included to measure evaporative loss.

Results and Discussion: Relevant experimental data are given in Table 4. The corn plants grew well and there was little difference between soils. Chalmers had the least growth and Raub the most. There was an average growth response of 5% to K application. However while on the average root length was less with additional K the differences were not statistically significant. Root growth characteristics varied with soil as indicated by average root radius. In some soils average radius increased with plant growth while in other soils it decreased.

Flux into the roots was calculated using William's equation (equation 8)

$$\text{Flux} = \frac{U_2 - U_1}{t_2 - t_1} \; \frac{\ln L_2/L_1}{L_2 - L_1} \qquad [8]$$

where U is uptake, t is time and L root length. Subscripts refer to sampling times. The mean flux of K and Rb into the root for the first 6 days was larger than for the second 6 days and the differences varied with soil.

The K/Rb ratio of ion flux into the root is compared with K/Rb ratios in soil solution and on the exchange sites in Table 5. It is apparent that the K/Rb ratio in the plant is much more closely related to the ratio of K and Rb on the exchange sites than the ratio in solution. This is similar to the results we previously obtained for Ca and Sr (Bole and Barber, 1971). The concentrations of K and Rb in solution and on the exchange sites were also determined after harvesting at 12 days and after harvesting at 18 days. The K/Rb ratios were very similar to those shown initially except for about a 10-20 percent reduction in the ratio.

The data obtained have yet to be analyzed through the mathematical model describing ion uptake. It is expected that these data will be a significant test of the model.

Table 4. Growth and average K and Rb flux into corn grown on four soils.

Soil Treatment	Plant Age at Harvest days	Plant Weight g	Root Length m	Water Flux cm $sec^{-1} \times 10^6$	Average Root Radius mm	Flux into Root K pmoles cm^{-1} sec^{-1}	Flux into Root Rb pmoles cm^{-1} sec^{-1}
Zanesville	10	0.34	1.04	0.75	0.19	2.95	0.57
	16	1.61	4.69	1.58	0.21	1.90	0.41
Zanesville + K	10	0.36	1.23	0.68	0.20	3.51	0.30
	16	1.66	4.98	1.67	0.21	2.69	0.54
Chalmers	10	0.31	1.19	0.50	0.18	3.62	0.18
	18	1.45	5.88	1.56	0.17	0.76	0.11
Chalmers + K	12	0.34	1.24	0.60	0.20	2.30	0.15
	18	1.38	5.02	1.45	0.17	1.33	0.07
Raub	12	0.31	1.12	0.52	0.19	1.08	0.34
	18	1.77	9.31	1.59	0.15	0.38	0.13
Raub + K	12	0.36	1.23	0.52	0.19	2.64	0.35
	18	1.83	8.31	1.57	0.16	1.03	0.15
Toronto	12	0.33	1.30	0.68	0.20	1.27	0.31
	18	1.72	6.02	1.62	0.20	0.63	0.17
Toronto + K	12	0.35	1.22	0.94	0.20	2.68	0.33
	18	1.79	5.98	1.68	0.20	1.04	0.22

Table 5. Comparisons of K/Rb ratios of plant uptake (4-10 days) with K/Rb ratio in soil solution and on the soil exchange sites.

Soil	Plant	K/Rb Ratio	
		Soil Solution	Soil Exchange Sites
Zanesville	5.18	12.7	5.02
Zanesville + K	11.70	28.3	10.38
Chalmers	20.10	47.5	14.76
Chalmers + K	15.30	113.0	40.70
Raub	3.18	13.8	3.51
Raub + K	7.54	31.3	9.05
Toronto	4.10	14.2	4.33
Toronto + K	8.12	34.4	10.05

II-e Using the nutrient flux model to calculate Zn absorption.

A mathematical model that was described in the 1975 report and also in a paper by Claassen and Barber (1976) was used to evaluate the flux of Zn to plant roots and the resultant Zn content of the plant. The calculations of this flux are from values in the literature. Conformity between predicted and actual uptake at this stage was determined by determining if the range of Zn concentrations calculated for the plant and comparing the values to those that have been reported in the literature. Future work will test models of this type with experimental data.

Zn flux to the root growing in soil is by diffusion and mass-flow. The lower the level of Zn in the soil, usually the greater is the proportion moving by diffusion. The parameters necessary for calculating the flux are (i) For the soil, Zn in soil solution, C_l, buffering capacity of the solid phase for the solution phase, b, and effective diffusion coefficient, De. (ii) For the plant they are: I_{max}, K_m, and D, that describe the relation between concentration of Zn in solution and net influx of Zn into the root. Root radius, r_o; rate of water uptake, v_o; initial root length and rate of root growth.

Zn was selected because we have a lot of data in this laboratory on the three soil parameters for several soils (Warncke and Barber, 1972, 1973). The values for I_{max}, K_m, and E were estimated from data of Carroll and Loneragan (1969) and Schmid, Hoag, and Epstein (1965). The values for r_o, v_o, L_o, and k were taken from the research of Claassen and Barber (1976) for corn plants growing in the same soil type on which we had Zn data obtained by Warncke and Barber.

The data for the soil and plant parameters used in the computer program are shown in Table 6. On the basis of 17 days growth and a plant dry weight of 2.5 grams, the predicted Zn concentrations that would result in the plant are given in this table.

As Zn level increased uptake increased until a maximum value was obtained where the root was absorbing at close to its maximum influx. The concentrations in the plant range from 4 to 430 μg/g. Carroll and Loneragan obtained values ranging from 20 to 980 depending on species. Usually Zn deficiency reduces yield when Zn concentration drops below 40 μg/g. In our calculations we assumed the same yield of plant. A reduction in yield would cause an increase in Zn concentration. Hence the values we calculated agree fairly well with those reported by Carroll and Loneragan.

These data illustrate the utility of the model for calculating ion uptake. It can be used to determine the influence of varying specific parameters and when these are verified experimentally we will have a much better understanding of the processes involved.

Bole, J.B., and S.A. Barber. 1971. Differentiation of Sr-Ca supply mechanisms to roots growing in soil, clay and exchange resin cultures. Soil Sci. Soc. Amer. Proc. 35:668-772.

Carroll, M.D., and J.F. Loneragan. 1969. Response of plant species to concentrations of zinc in solution. Aust. J. of Agric. Res. 20: 457-463.

Schmid, W.E., H.P. Hoag, and E. Epstein. 1965. Absorption of zinc by excised barley roots. Physiol Pl. 18:860-869.

Warncke, A., and S.A. Barber. 1972. Diffusion of zinc in soil: I. The influence of soil moisture. Soil Sci. Soc. Amer. Proc. 36:39-42.

Warncke, A., and S.A. Barber. 1973. Diffusion of zinc in soil: III. Relation to zinc adsorption isotherms. Soil Sci. Soc. Amer. Proc. 37:355-358.

Table 6. Effect of Zn levels in the soil on the predicted uptake by corn growing in Chalmers silt loam.

Soil Zn levels					
De cm^2/sec x 10^9	C_{li} µmoles/ml	b	C µg/g	Predicted Zn uptake µmoles/plant	Predicted Zn Concentration µg/g
1.0	.0001	200	1.0	0.169	4.3
2.0	.0003	180	2.66	0.681	17.4
5.0	.001	140	6.9	3.069	78.6
6.0	.002	130	12.7	6.269	160
7.0	.003	120	17.7	9.23	236
10.0	.005	80	19.69	12.44	318
50.0	.10	40	157	16.85	431
100	1.0	5	246	16.86	432

The values of the other parameters in the model were: Vo, 3.2×10^{-6} ml/cm^2; I_{max}, 1.5×10^{-7} µmoles cm^{-2}/sec; E, 1.0×10^{-9} µmoles cm^{-2}/sec; Km, 3.0×10^{-4} µmoles/ml; k, 2.0×10^{-6} sec^{-1}; L_o, 500 cm; r, 1.5×10^{-2} cm; t, 5.5×10^5 sec.

TRAINING

Three graduate students have received training on this contract. E.H. Halstead, J.B. Bole, and G.L. Malzer have completed their research for the Ph.D. degree. The first two are employed in research in a university and a government research laboratory, respectively. G.L. Malzer was then employed in a post-doctoral position on the project and subsequently has taken a research teaching position at a university.

The contract has also been used very effectively for post-doctoral training.

Dr. F.E. Khasawneh worked on this research for 14 months and then accepted a position in soil chemistry research with the Tennessee Valley Authority, Muscle Shoals, Alabama.

Dr. A.S.R. Juo did research on this contract for 29 months. He then accepted a position with the International Tropical Research Institute in Nigeria as a soil chemist.

Dr. S.M. Elgawhary, a Ph.D. graduate of Colorado State University did research on the project for 33 months. He has now taken a position as Associate Professor in the Department of Natural Resources and Environmental Science, Alabama A & M University, Huntsville, Alabama.

Dr. G.L. Malzer was a post-doctoral research associate on the project for 9 months. He has now taken a position as Assistant Professor of soils at the University of Minnesota, Minneapolis, Minn.

Dr. V.C. Baligar, a recent graduate of Mississippi State University is presently employed as a post-doctoral associate on the project.

PUBLICATIONS

The following publications have resulted from this contract.

COO-1495-1 Khasawneh, F.E. and S.A. Barber. Investigations of Ca-Sr absorption selectivity in clays and soils. Agronomy Abstracts. Stillwater, Oklahoma, 1966.

COO-1495-2 Technical Progress Report for the Contract Year, June 1, 1966 through May 31, 1967 on project entitled "Movement of Strontium through the Soil to Plant Root Membrane."

COO-1495-3 Halstead, E.H., S.A. Barber, D.D. Warncke and J.B. Bole. Supply of Ca, Sr, Mn and Zn to plant roots growing in soils. Soil Sci. Soc. Am. Proc. 32:69-72, 1968.

COO-1495-4 Khasawneh, F.E., A.S.R. Juo and S.A. Barber. Soil properties influencing differential Ca to Sr adsorption. Soil Sci. Soc. Amer. Proc. 32:209-211, 1968.

COO-1495-5 Barber, S.A. On the mechanisms governing nutrient supply to plant roots growing in soil. 9th Intl. Congr. Soil Sci. Transactions 2:243-250, 1968.

COO-1495-6 Technical Progress Report for the Contract Year June 1, 1967 through May 31, 1968 on the project entitled "Movement of Strontium through the Soil to Plant Root Membrane."

COO-1495-7 Juo, A.S.R. and S.A. Barber. Reaction of Sr with humic acid. Soil Sci. 108:89-94, 1969.

COO-1495-8 Juo, A.S.R. and S.A. Barber. An explanation for the variability in Sr-Ca exchange selectivity of soils, clays and humic acid. Soil Sci. Soc. Am. Proc. 33:36-363, 1969.

COO-1495-9 Technical Progress Report for the Contract Year June 1, 1968 through May 31, 1969 on the project entitled "Movement of Sr through the Soil to Plant Root Membrane."

COO-1495-10 Juo, A.S.R. and S.A. Barber. The retention of Sr by soils as influenced by pH, organic matter and saturation cations. Soil Sci. 108:143-148, 1970.

COO-1495-11 Juo, A.S.R. and J.L. White. The orientation of the dipole movements of hydroxyls in oxidized and un-oxidized biotite. Science 165:804-805, 1969.

COO-1495-12 Technical Progress Report for the Contract Year June 1, 1969 through May 31, 1970 on the project entitled "Movement of Strontium through the Soil to the Plant Root Membrane."

COO-1495-13 Bole, J.B., and S.A. Barber. Differentiation of Sr-Ca supply mechanisms to roots growing in soil, clay, and exchange resin cultures. Soil Sci. Soc. Amer. Proc. 35:768-772, 1971.

COO-1495-14 Elgawhary, S.M., and S.A. Barber. Differential Sr-Ca bonding on soil as influenced by bonding site. Soil Sci. Soc. Amer. Proc. 35:566-571, 1971.

COO-1495-15 Technical Progress Report for the Contract Year June 1, 1970 through May 31, 1971 on the project entitled "movement of Strontium through the Soil to the Plant Root Membrane."

COO-1495-16 Barber, S.A., S.M. Elhawhary, and G.L. Malzer. Characterization of nutrient supply mechanisms to plant roots using double labeling and the ratio of Ca/Sr absorbed. In Proceedings Symposium on the use of Isotopes and Radiation in Research on Soil-Plant Relationships including applications in Forestry. International Atomic Energy Agency - FAO. Vienna, Austria, 1972.

COO-1495-17 Elgawhary, S.M., G.L. Malzer, and S.A. Barber. Calcium and Strontium Transport to Plant Roots. Soil Sci. Soc. Amer. Proc. 36:794-799, 1972.

COO-1495-18 Technical Progress Report for the Contract Year June 1, 1971 through August 31, 1972 on the project entitled "Movement of Strontium through the Soil to the Plant Root Membrane."

COO-1495-19 Elgawhary, S.M., and S.A. Barber. Measurement of uptake of chelated and unchelated Ca and Sr from solution culture. Plant and Soil 39:581-590. 1973.

COO-1495-20 Elgawhary, S.M., and S.A. Barber. Root uptake coefficients for absorption of Ca EDTA and Ca^{++} by tomato plants. Plant and Soil 40:183-191. 1974.

COO-1495-21 Barber, S.A. Plant Nutrient Absorption from Three Sources in the Soils. 10th Intl. Congr. Soil Sci. Transactions (Moscow) IV 217-223. 1974.

COO-1495-22 Technical Progress Report for the Contract Year September 1, 1972 through August 31, 1973 on the project entitled "Movement of Strontium through the Soil to the Plant Root Membrane."

COO-1495-23 Bole, J.B., and S.A. Barber. Effect of relative root retention on uptake and transport of Sr and Ca by soybeans. Agronomy J. 1974.

COO-1495-24 Technical Progress Report for the Contract year September 1, 1973 through August 31, 1974 on the project entitled "Movement of Strontium through the Soil to the Plant Root Membrane."

COO-1495-25 Precipitation of calcium and strontium sulfates around plant roots and its evaluation. Soil Sci. Soc. Amer. Proc. 39:492-495. 1975. Malzer, G.L., and S. A. Barber.

COO-1495-26 Technical Progress Report for the Contract year September 1, 1974 through August 31, 1975 on the project entitled "Movement of Strontium and Casium through the Soil to the Plant Root Membrane."

COO-1495-27 Barber, S.A., and N. Claassen. A mathematical model to simulate metal uptake by plants growing in soil. Proceedings of 15th Hanford Life Sciences Symposium "The Biological Implications of Metals in the Environment." (In press) 1976.

COO-1495-28 Technical Progress Report for the Contract year September 1, 1975 through August 31, 1976 on the project entitled "Movement of metal cations through to the soil to the plant root membrane."

Publications prepared during 1975-1976.

1. Malzer, G.L., and S.A. Barber. 1976. Calcium and strontium absorption by corn roots in the presence of chelates. Soil Sci. Soc. Amer. J. (submitted).

2. Claassen, N., and S.A. Barber. A simulation model for nutrient uptake from soil by a growing plant root system. Agron. J. (submitted).