Plant and Soil 96, 153–164 (1986). Ms. 6471

Cadmium and zinc influx characteristics by intact corn (*Zea mays* L.) seedlings

G.L. MULLINS
Department of Agronomy and Soils, 202 Funchess Hall, Auburn University, AL 36849-4201, USA

and L.E. SOMMERS
Department of Agronomy, Purdue Univ., West Lafayette, IN 47907, now Department of Agronomy, Colorado State Univ., Fort Collins, CO 805123, USA

Received 1 July 1985. Revised March 1986

Key words Cadmium Cd and Zn uptake Heavy metals *Zea mays* L. Zinc

Summary Cadmium and zinc uptake parameters were determined for intact corn (*Zea mays* L.) seedlings grown for 15 and 22 d in nutrient solutions containing levels of Cd and Zn that were similar to those found in soil solutions. Uptake of both elements was assumed to follow Michaelis-Menten kinetics. Calculations were based on the concentrations of free ionic Cd (Cd^{2+}) and Zn (Zn^{2+}) rather than the total solution concentration. Rates of Zn uptake were measured by determining depletion of Zn for periods of up to 30 h from solutions containing initial concentrations of 1.5 and 10μmol Zn l^{-1}. Depletion curves suggested that Zn uptake characteristics were similar at both levels of Zn in solution. The Imax for Zn uptake decreased from 550 to 400 pmol m^{-2} root surface s^{-1} between 16 and 22 d of growth while Km decreased from 2.2 to 1.5 μmol Zn^{2+} l^{-1}. Cadmium uptake parameters were measured by controlling Cd^{2+} activities in nutrient solution between 6.3 to 164 nmol l^{-1} by continuous circulation of nutrient solution through a mixed-resin system. Imax for Cd uptake was 400 pmol m^{-2} root surface s^{-1} at 15 and 22 d of growth. The magnitude of Km increased from 30 to 100 nmol Cd^{2+} l^{-1} during this time period. The Km value suggests that corn is efficient for Cd uptake. The results of these uptake studies are consistent with the observed uptake of Zn and Cd by corn seedlings in soils.

Introduction

One of the major factors that controls the accumulation of Cd and Zn in plant tissue is the inherent uptake characteristics of the root system. The rate and degree of Cd and Zn accumulation will depend on the plant species and variety[4,5,7,9,17,18,19,20,26]. Both passive and active mechanisms have been used to explain Zn and Cd uptake. Passive uptake is implicated at high solution concentrations of Zn and Cd where these ions can bind to root cell walls and/or diffuse into the interior of cells[13,27]. Cadmium and Zn are taken up actively at concentrations normally found in soil solutions[8,14]. Zinc uptake by intact rice (*Oryza sativa* L.) seedlings has been shown to be metabolically controlled at concentrations < 5 μmols/l $^{-1}$ while both passive and metabolic uptake occur at greater concentrations[14]. Cadmium uptake by intact soybean (*Glycine max* L.) plants was metabolically controlled over a concentration range of 0.01 to 0.40 μmol l^{-1} (ref.[8]). These Zn and Cd concentrations are similar to the ranges found in soil solutions from normal and sludge treated soils[3, 23].

Kinetic parameters describing the relationship between solution concentration and plant uptake are needed to predict ion uptake by plants with mechanistic models[2, 12]. Nutrient uptake kinetics have been shown to follow Michaelis-Menten kinetics[25] and described by the equation

$$\mathrm{In} = \frac{\mathrm{Imax}\ \mathrm{C}}{\mathrm{Km} + \mathrm{C}} \tag{1}$$

where In is the net nutrient influx rate, Imax is the maximum nutrient influx rate, C is the concentration of nutrient in solution, and Km is an uptake constant. It follows that Km is the nutrient concentration where In = 1/2Imax. Claassen and Barber[11] adjusted Equation (1) to account for the efflux (E) of a nutrient from plants roots into the surrounding solution.

The objective of this study was to measure Cd and Zn influx kinetics for intact corn (*Zea mays* L.) seedlings. Uptake parameters were measured at Cd and Zn concentrations that approximate those in the soil solution[23].

Materials and methods

Cadmium and Zn uptake studies were conducted in a growth chamber maintained at 25°C with a 16 h light exposure (37 W m^{-2}). Seeds of *Zea mays* L. cv Becks 65X were wrapped in paper towels and germinated in aerated tap water for 6 d. Roots of seedlings were trimmed to 4 cm per plant before transplanting into 3 l pots that contained the appropriate nutrient solution.

Zinc influx kinetics

Zinc uptake was measured with the solution depletion procedure of Claassen and Barber[11]. Corn seedlings were transplanted into a complete nutrient solution and depletion curves were determined for triplicate pots after the corn seedlings had grown for 16 and 22 d. The nutrient solution was adjusted to pH 5.5 with saturated $Ca(OH)_2$ and contained the following (in $\mu mol\ l^{-1}$): $Ca(NO_3)_2$, 1000; $Ca(H_2PO_4)_2$, 500; K_2SO_4, 500; $MgSO_4$,1000; NH_4NO_3, 1500; H_3BO_3, 46; HCl, 20; $CuSO_4 \cdot 5H_2O$, 0.3; $Fe_2(SO_4)_3$, 75; DTPA, 75; $MnSO_4 \cdot H_2O$, 9; $Na_2MoO_4 \cdot 2H_2O$, 0.8; $ZnSO_4$, 0.8. Nutrient solution in the pots was continuously aerated and was replaced after the initial 4 d of growth and then after every 48 h. There were four corn seedlings per pot in the 1.5 $\mu mol\ l^{-1}$ Zn treatment and five corn seedlings per pot in the 10 $\mu mol\ l^{-1}$ Zn treatment.

Since DTPA forms a stable Zn complex that is not readily used by corn[15], DTPA was removed from nutrient solution 2 d before determining Zn influx. Approximately 12 h prior to determining rates of Zn uptake seedlings were placed in pots with 1.5 l of nutrient solution containing no Zn or DTPA. The concentration of Zn in solution was adjusted to either 1.5 or 10 $\mu mol\ l^{-1}$ with $ZnSO_4$, and starting at 0.5 h after adding Zn, samples were taken every 0.5 or 1.0 h from each pot for periods up to 30 h. The solution volume was maintained at 1.5 l with deionized water to adjust for loss by sampling and evapotranspiration. Dilution of Zn in solution by sampling and addition was not important, because $< 10\%$ of the total volume was removed during the sampling period and because Zn uptake was rapid. Zinc concentrations were measured by flame atomic absorption.

The corn seedlings were harvested after completing Zn uptake measurements and root length was measured with the line intersect method[29]. Average root radius was calculated from the relationship

$$r_o = (F_{wr}/\pi L)^{1/2} \tag{2}$$

where r_o is the average root radius, F_{wr} is the fresh weight of roots and L is the root length. Equation (2) assumes that the roots have a density of $1\,g\,cm^{-3}$. The root growth constant (k) was calculated by assuming exponential root growth. Values for k were calculated with the expression

$$k = \ln(L/Lo)/T \tag{3}$$

where Lo is the initial root length and L is the root length after a growth period of time T.

Zinc influx rates were calculated from the depletion curve data (Fig. 1) with the Williams[31] equation

$$In = U/(T_2 - T_1)\cdot((LnL_2 - LnL_1)/(L_2 - L_1))/2\pi r_o \tag{4}$$

where In is the average Zn influx rate (mol Zn m^{-2} root surface area s^{-1}), U is the amount of Zn taken up during the time period $T_2 - T_1$ (*i.e.* the amount of Zn removed from solution between each sampling time (Fig. 1)), and L_1 and L_2 are the root length at time T_1 and T_2, respectively. The time between sampling ($T_2 - T_1$) was either 0.5 or 1.0 h except for an 8 h period between 16 and 24 h. The root length at the beginning and end of each sampling period was calculated with Equation (3) by knowing the root growth constant (k) and total root length at the end of the experiment. Average Zn influx rates for each sampling period were paired with Zn concentrations at the beginning of each sampling period and the data were fitted to Equation (1) by nonlinear regression. Kinetics were based on the concentration of Zn^{2+} computed from the total concentration of metals and ligands by the computer program GEOCHEM[28].

Cadmium influx kinetics

Cadmium uptake was measured in nutrient solution culture using a mixed resin system to maintain constant concentrations of nutrients and Cd[10]. In this system the concentrations of Ca, Mg and K were controlled with Dowex-50-X8, P with aluminum saturated Amberlite-IR-120, Cd, Cu, Fe, Mn, and Zn with Chelex 100 and solution pH with Bio-rex 70. Equililbrium between the mixed resin system and the nutrient solution was aided with the continuous flow of solution over the resin.

Operation of the resin system is based on competitive equilibria between calcium and trace metals[10, 16]. At equilibrium, the selectivity coefficient for Ca-Cd exchange (K^{Ca}_{Cd}) is given as[16]

$$K^{Ca}_{Cd} = \frac{[\text{R-Ca}](Cd^{2+})}{[\text{R-Cd}](Ca^{2+})} \tag{5}$$

where R-Ca and R-Cd$^{(*)}$ are the concentrations of Ca and Cd on the resin and parentheses indicate activity of Ca^{2+} and Cd^{2+} in solution. Equation (5) can be rearranged to give

$$pCd = pCa + pK^{Ca}_{Cd} + \log(R - Ca/R - Cd) \tag{6}$$

where p indicates the negative logarithm. Expected pCd values were calculated for the resin mixtures used (Table 1) by assuming that $pCa = 2.80$ and $pK^{Ca}_{Cd} = 4.50$[16].

The Ca, Mg, and K saturated resins were prepared by leaching H-Dowex-50-X8 (20–50 mesh) with 1 *M* metal nitrate solutions. All resins were stored moist in a desicator. Aluminum saturated resin was generated by leaching H-Amberlie-IR-120 (20–50 mesh) with 0.33 *M* $AlCl_3$ followed by 0.200 *M* Na_2CO_3 to give an Al:OH ratio of 1:2, and P was then added at a rate of 0.5 meq $H_2PO_4\,g^{-1}$ wet resin.

Calcium saturated resin at pH 6.0 was generated from Na-Chelex 100 (100–200 mesh) according to the method of Hendrickson[16]. Cadmium, Cu, Mn, and Zn saturated resins were generated by equilibrating Ca-Chelex 100 with 500 ml of 0.1 *M* $Ca(OAc)_2$ containing 63 mmol of the respective metal nitrate in solution. After 4 h, the metal saturated resins* were adjusted to pH 6, filtered under suction and stored moist. Bio-rex 70 (20–50 mesh) at pH 6.0 was generated from the Na^+ form using the same procedure that was used to prepare the Ca-Chelex 100. Concentrations of metals on the prepared resins were determined by atomic absorption after extracting 0.1 g samples of wet resin with 1 *M* HNO_3 (Table 2).

[*] Metal-resins will be designated as R-Ca, *etc.* It should be noted that all resins contain Ca plus a trace metal. In all resin mixtures, R-Ca refers to the weighted concentration of Ca on all resins present and R-Cd refers to the weighted concentration of Cd on all resins present.

Table 1. Composition of the metal-Chelex 100 portion of mixed resin systems (metals in g)

Treatment No.	Metal-saturated Chelex-100					RCa/RCd*	Resin mix**	Expected pCd***	Observed pCd+
	Ca	Cu	Mn	Zn	Cd		Cd resin		
1	0	0	0	0	1.000	0.41	0	6.91	6.79
2	0	0.359	0.144	0.503	0.900	0.75	1.12	7.18	6.92
3	0.724	0.359	0.144	0.503	1.000	1.50	1.73	7.48	6.87
4	1.292	0.359	0.144	0.503	0.700	2.85	3.28	7.75	6.97
5	1.795	0.359	0.144	0.503	0.055	41.35	50.91	8.92	8.13
6	1.632	0.326	0.131	0.457	0.255	8.45	10.00	8.23	7.60
7	1.709	0.342	0.137	0.479	0.133	16.50	20.01	8.52	7.71
8	1.751	0.350	0.140	0.490	0.068	32.58	40.00	8.81	7.80
9	1.773	0.355	0.142	0.496	0.035	64.69	79.92	9.11	7.92
10	1.784	0.357	0.143	0.499	0.017	129.03	159.91	9.41	8.20

*RCa and RCd are the concentrations of Ca and Cd on the Chelex resins (mmol g^{-1} resin).

**Resin mix = sum of Ca-, Cu-, Mn- and Zn-Chelex 100.

***Calculated with Equation (6).

+Mean of samples (Day 0, 7, 15) taken from resin-pot systems used to grow corn seedlings for 15 d.

Table 2. Amounts of macronutrients and trace metals extracted from stock resins

Resin	Element	Amount extracted by 1 M HNO_3
		mol · kg^{-1}[†]
Ca-Dowex 50-X8	Ca	1.25
Mg-Dowex 50-X8	Mg	1.15
K-Dowex 50-X8	K	2.13
PO_4-Al-Amberlite IR-120	P	0.46
Ca-Chelex 100	Ca	0.977
Cd-Chelex 100	Cd	0.902
	Ca	0.368
Cu-Chelex 100	Cu	1.18
	Ca	0.223
Fe-Chelex 100	Fe	0.993
	Ca	0.541
Mn-Chelex 100	Mn	0.882
	Ca	0.155
Zn-Chelex 100	Zn	1.04
	Ca	0.349

[†] Wet resin weight.

Ten resin mixtures were prepared (Table 1) to provide an expected Cd activity range of 0.39 to 123 nmol l^{-1}. Initially, Cu-, Zn-, Mn- and Ca-Chelex resins were mixed at a weight ratio of 5:7:2:25. The Cu-Zn-Mn-Ca-Chelex resin mixture was then added to Cd-Chelex at weight ratios ranging from 10 to 160 (Table 1). Each resin mixture also received 75.75 g Ca-Dowex, 6.15 g K-Dowex, 22.35 g Mg-Dowex, 24.00 g P-Al-Amberlite and 0.200 g Fe-Chelex. Resin mixtures for treatments 1–5 received 37.50 g Bio-rex 70 while resins for treatments 6–10 received 15.5 g Bio-rex 70.

The resin mixtures for the different treatments were slurried into PVC columns (7.6 × 15.2 cm). Foam-rubber plugs wrapped in glass wool and parafilm wrapped rubber stoppers were used to retain the resin in the columns. March model 1E submersible pumps were used to continuously circulate the nutrient solution from the pots through the resin columns. The average flow rate for all systems was 618 ml min^{-1} (CV 20.4%), resulting in a total exchange of nutrient solution in the 31 pots every 5 min. Some variability in flow rates was caused by bacterial growth on the inner surface of the tubing used. Bacterial growth was profuse on tygon tubing and thus glass was used wherever possible.

Three seedlings were transplanted into each pot after the solution had been circulating through the columns for at least 24 h. For treatments 1–5, two experiments were conducted: the first involved growing corn plants for 22 d while the second was for 15 d. The nutrient solution in the pots was changed and allowed to equilibrate for 24 h before planting the second crop. Only one growth period of 15 d was used for treatments 6–10.

The composition of the initial nutrient solution was the same as that used to study Zn uptake except that no Cu, Mn, Zn or Fe-DTPA were added and that the P concentration was 20 μmol l^{-1}. Additional nutrient solution containing 100 μmol NO_3-N l^{-1}, 30 μmol Ca l^{-1}, 76 μmol K l^{-1}, 12 μmol PO_4-P l^{-1}, 7 μmol SO_4-S l^{-1}, 0.92 μmol B l^{-1} and 0.016 μmol Mo l^{-1} was supplied by Marriott bottles to replace water losses by evapotranspiration and to replace part of the macro- and micronutrients taken up by the corn plants. Iron was added to each pot by adding 75 μmol of $FeSO_4$ on day one followed by 15 μmol of $FeSO_4$ every 48 h. Iron was also supplied in foliar applications as a 1% Fe solution containing 0.02% Dupont WX surfactant and was applied periodically with a small paint brush. After 10 d of corn growth, 3 mmol of KNO_3 and 45 μmol KH_2PO_4 were added to each pot.

Samples of nutrient solution were collected periodically from each pot for analysis. Solution pH was measured with a glass electrode, concentrations of Ca, Mg and K by flame atomic absorption, the phosphate by Murphy and Riley[24] procedure and sulfate by the $BaCl_2$ turbidimetric method[1].

The shoots and roots were harvested at the end of each growth period and roots were rinsed in deionized water before drying. Shoots and roots were separated, dried at 60°C and digested with $HClO_4:HNO_3$. Calcium, Cd, Cu, K, Mg, Mn and Zn in the digests were measured by flame atomic absorption. Root length was measured by the line intersect method[29] and average root radius was calculated with Equation (2). Average Cd influx rates were calculated with Equation (4) where U was the seedling content of Cd after the 15 and 22 d growth periods ($T_2 - T_1$), paired with the corresponding average Cd^{2+} concentration measured during the growth period, and fitted to Equation (1) by nonlinear regression. Concentrations of Cd^{2+} were calculated from the nutrient solution data (Figs. 2, 3 and 4) with the computer program GEOCHEM[28]. Cadmium activities (Table 1) were calculated for the average concentration of Cd^{2+} calculated by GEOCHEM, using the Debye-Huckel equation[21] and ionic strength estimated with GEOCHEM. One cannot assume that $Cd_T = Cd^{2+}$ since GEOCHEM calculated that approximately 20% of Cd_T existed as a soluble complex with sulfate. Other soluble species were $< 0.1\%$ of Cd_T.

Results and discussion

Zinc influx kinetics

The 16 d corn plants had an average wet root weight of 13.1 g plant^{-1} (CV 21.8%) while the 22 d plants had an average wet root weight of 33.7 g plant^{-1} (CV 8.5%) and, as expected, the older plants depleted Zn from solution faster than the younger seedlings (Fig. 1). Zinc depletion curves from the 1.5 and 10 μmol l^{-1} treatments followed the same form (Fig. 1) which suggests the same uptake kinetics are operating at the two initial Zn concentrations. Depletion curve data for the Zn treatments were therefore combined for each date and fitted to Equation (1) by nonlinear regression.

The Km values for Zn in Table 3 are lower than the value of 16 μmol l^{-1} previously measured for excised barley roots[6]. One possible reason for our lower values of Km is that the lowest Zn concentration in Bowen's[6] study was 20 μmol l^{-1} whereas the highest concentration in our study was 10 μmol l^{-1}. The values in Table 3 are in agreement with Km and Vmax values of 3.18 μmol Zn l^{-1} and 0.53 μmol g^{-1} dry roots h^{-1}, respectively, that were reported for the first phase of Zn uptake by

Table 3. Kinetic parameters for Cd and Zn uptake by intact corn seedlings

Seedling age (d)	Cd[¶]		Zn[†]	
	Imax[+] (pmol m^{-2} s^{-1})	Km[‡] (nmol l^{-1})	Imax (pmol m^{-2} s^{-1})	Km (μmol l^{-1})
16[++]	400	30	550	2.2
22	400	100	400	1.5

[+] Imax = maximum metal influx rate.

[‡] Km = metal concentration where net influx rate = $\frac{1}{2}$Imax.

[¶] Determined in mixed resin system.

[†] Determined by depletion of solution Zn.

[++] Does not include the germination period of 6 d.

intact barley roots[30]. Veltrup[30] observed three uptake phases for barley roots at Zn concentrations ranging from 0.1 to 1380 μmol l^{-1}. A phase change in Zn uptake kinetics was not apparent in the present studies since there were no abrupt changes in the slopes of the Zn depletion curves (Fig. 1). In addition, the same uptake kinetics appeared to be operating in the 1.5 and 10 μmol l^{-1} Zn treatments. Both Imax and Km values for Zn uptake by corn decreased with age (Table 3). Mengel and Barber[22] measured Zn influx rates for corn plants grown under field conditions and found that Zn influx decreased from 10.98 to 0.578 μmol m^{-1} roots d^{-1} between ages of 20 and 30 d.

Cadmium influx kinetics

The ten mixed resin systems resulted in solution Cd activities that ranged from 6.3 to 164 nmol l^{-1} while the anticipated range was from 0.39 to 123 nmol l^{-1}. It is not known why there was such a large difference between the expected and observed pCd in some of the solutions. This contrasts with the work of Checkai[10] who reported that measured and predicted pCd values were similar with resin systems using Ca-, Cu-, Mn-, and Zn-Chelex/Cd-Chelex* ratios similar to those listed in Table 1. The primary variable in the mixed resin system of this study was the concentration of Cd^{2+} in solution and which, as expected, controlled Cd uptake by corn (Table 4). Cadmium concentrations in the roots were higher than the shoots at 15 and 22 d. Average concentrations of Ca, K, Mg, P, Cu, Mn and Zn in the shoots of the 15 d plants were 128, 728, 82, 114, 0.17, 1.80 and 0.82 mmol kg^{-1}, respectively, while average concentrations of Ca, K, Mg, P, Cu, Mn and Zn after 22 d were 144, 675, 63, 127, 0.12, 1.88 and 0.77 mmol kg^{-1}, respectively. Coefficients of

Table 4. Concentrations of Cd in corn seedlings grown in the mixed-resin system for 15 and 22 d

Treatment	pCd[+]	15 d		22 d	
		Shoots	Roots	Shoots	Roots
1	6.79	1.15	4.00	0.71	4.35
2	6.92	1.78	6.59	0.74	4.73
3	6.87	1.46	4.93	0.98	5.41
4	6.97	1.05	5.87	0.67	4.67
5	8.13	0.03	0.54	0.04	0.55
6	7.60	0.28	5.11	–	–
7	7.71	0.21	6.95	–	–
8	7.80	0.07	0.78	–	–
9	7.92	0.05	0.21	–	–
10	8.20	0.05	0.36	–	–

[+] Mean of samples (Day 0, 7, 15) taken from resin-pot systems used to grow corn seedlings for 15 days.

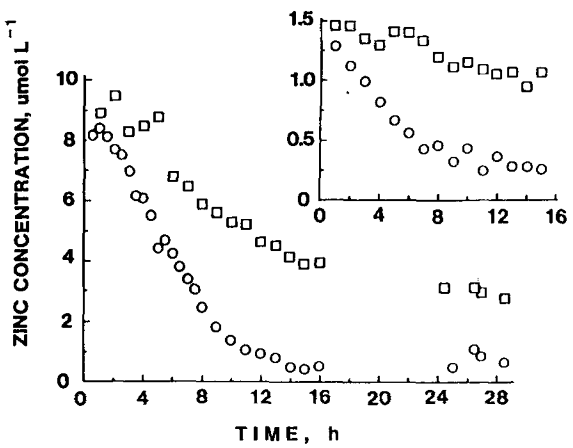

Fig. 1. Depletion of Zn from solution by intact corn seedlings for initial concentrations of 1.5 and 10 μmol L^{-1}. The seedlings had been grown in complete nutrient solution for either 16 (□) or 22 (○) d when Zn uptake was measured.

variation for all nutrient element at both harvest dates ranged from 9 to 38%.

In the presence of corn seedlings the concentration of K and Ca (Fig. 2) and Mn, Zn and P (Fig. 3) in the nutrient solutions decreased with time. Solution pH decreased between 0 d and 7 d (Fig. 2), but increased thereafter due to the addition of 3 mmol KNO_3 per pot at 10 d. The concentrations of Cd, Cu, Mn and Zn in the nutrient solutions also decreased with time (Fig. 3 and 4). Growing tomato (*Lycopersicon esculentum* Mill.) plants in a similar mixed resin system[10] for 25 d also resulted in decreases in the concentration of most ions in solution. Checkai[10] attributed decreases in solution concentrations to diffusion limitations from the resin to tomato roots. We minimized diffusion limitations in our study by continuously circulating the nutrient solution through columns containing the appropriate resins. Decreasing nutrient concentrations indicate that rates of ion uptake by plants are faster than combined rates of desorption from the resins and distribution through the pot. The resin columns retained the capacity to control solution concentrations (treatments 1–5) since a 24 h equilibration period between the first and second corn crop was sufficient to adjust trace metal concentrations to the same or higher levels than those observed initially. Decreases in trace metal concentrations with time were also coincident with decreases in macronutrient concentrations and to changes in pH of the nutrient solution. It is anticipated that changes in Cd concentrations with time had minimal affect on the root absorption characteristics for Cd (Table 3) since the ten treatments established a Cd^{2+} range of approximately 26 fold and the range between treatments remained relatively constant during the two growth periods.

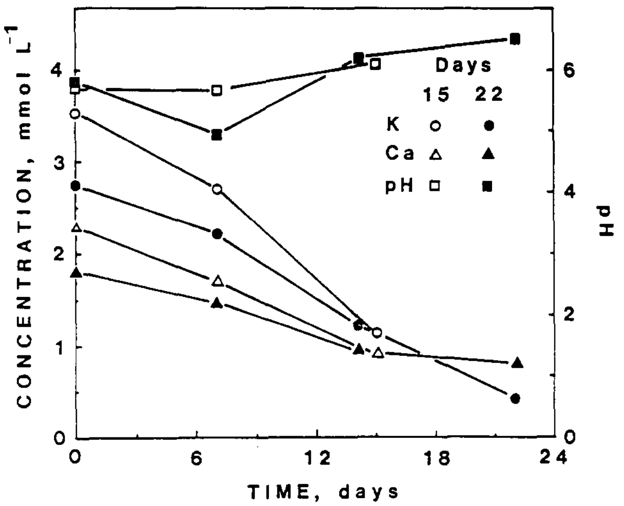

Fig. 2. Changes in solution pH and concentration of Ca and K with time in the mixed resin system. Each point is the mean for Treatments 1–5.

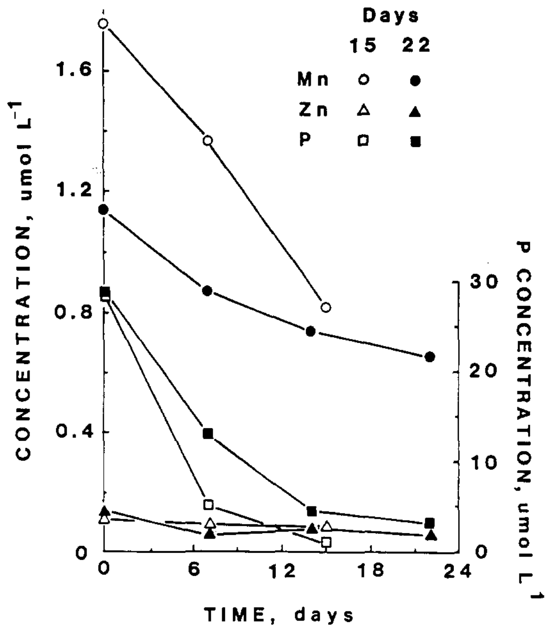

Fig. 3. Changes in solution concentrations of Mn, P and Zn with time in Treatments 1–5 of the mixed resin system.

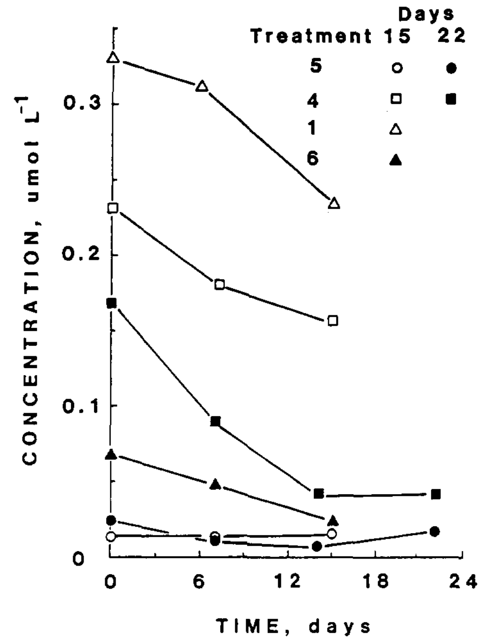

Fig. 4. Changes in the Cd concentration with time in selected treatments of the mixed resins system.

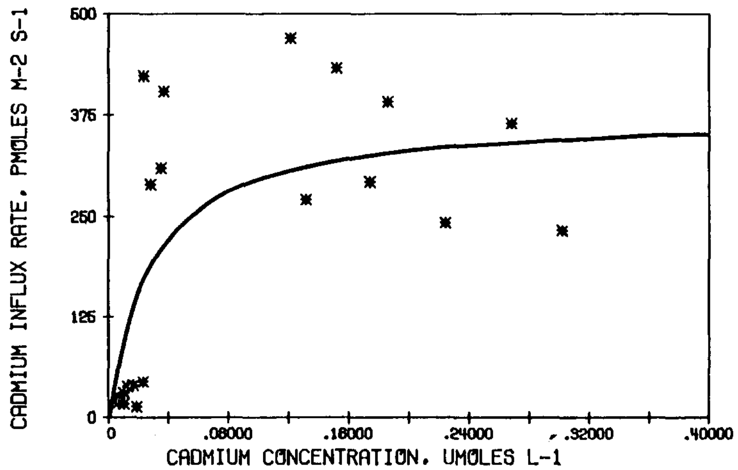

Fig. 5. Average Cd influx rates for the mixed resin system at 15 d plotted as a function of the free Cd concentration in solution. The curve was generated with equation (1) and the Cd influx parameters for the 15 d corn seedlings (Table 4).

Cadmium influx rates were a function of Cd concentration in solution and ranged from 20 to 450 pmol m^{-2} root surface s^{-1} at 15 d (Fig. 5) and from 20 to 260 pmol m^{-2} s^{-1} at 22 d. The calculated Km values (Table 3) are lower than a Km of 220 nmol Cd_T l^{-1} reported for phase one uptake by intact soybean plants[8]. It was not possible to distinguish multiphasic Cd uptake patterns for corn (Fig. 5) with the data obtained in the current study. The Km values (Table 3) show that corn is very efficient at accumulating Cd at low Cd concentrations. Calculated Imax values for Cd and Zn (Table 3) are similar in magnitude.

The mixed resin system of Checkai[10] was used to measure Cd uptake parameters since this sytem can maintain Cd in solution at levels similar to soil solution concentrations of Cd. Cadmium concentrations in soil solutions are usually < 0.1 μmol l^{-1}[13,23], and it would be difficult to maintain this Cd level in normal nutrient solutions. The establishment and operation of the mixed-resin system is time consuming, but it should be an important aid in future studies of trace metal-plant interactions. Macronutrient-plant interactions can also be studied if improvements in the resin system are made to insure that constant ion concentrations can be maintained in the presence of an expanding root system. Decreases in ion concentration with time in the presence of growing roots probably reflect a combination effect of diffusion limitations, resin desorption kinetics and flow rate of nutient solution. It is further suggested that wider resin:plant and solution:plant ratios be used. Having a larger reservoir of resin and nutrient solution should also help in maintaining constant ion concentrations in the presence of a growing root system.

Acknowledgements The authors express thanks to the Tennessee Valley Authority for providing financial support for this research (Contract No. TV-58640A).

References

1 American Public Health Association. 1980. Standard Methods for the Examination of Water and Wastewater. 15 ed. American Public Health Association, American Water Works Association, Water Pollution Control Federation, Washington, DC.

2 Barber S A and Cushman J H 1981 Nitrogen uptake model for agronomic crops. *In* Modeling nutrient transport and transformations in land treatment of wastewater Ed. I K Iskandar Wiley-interscience, New York. pp 382–409.

3 Behel D Jr, Nelson D W and Sommers L E 1983 Assessment of heavy metal equilibria in sewage sludge-treated soils. J. Environ. Qual. 12, 181–186.

4 Bingham F T, Page A L, Mahler R J and Ganje T J 1975 Growth and cadmium accumulation of plants grown on a soil treated with a cadmium-enriched sewage sludge. J. Environ. Qual. 4, 207–211.

5 Boggens S F, Willavize S and Koeppe D E 1978 Differential response of soybean varieties to soil cadmium. Agron. J. 70, 756–760.

6 Bowen J E 1981 Kinetics of active uptake of boron, zinc, copper and manganese in barley and sugarcane. J. Plant Nutr. 3, 215–223.

7 Carroll M D and Loneragan J F 1969 Response of plant species to concentrations of zinc in solution. II. Rates of zinc absorption and their relation to growth. Aust. J. Agr. Res. 20, 457–463.

8 Catalado P A and Wildung R E 1978 Soil and plant factors influencing the accumulation of heavy metals by plants. Environ. Health Perspectives 27, 149–159.

9 Chang A C, Page A L, Foster K W and Jones T E 1982 A comparison of cadmium and zinc accumulation by four cultivars of barley grown in sludge-amended soils. J. Environ. Qual. 11, 409–412.

10 Checkai R T 1983 Cadmium uptake by plants from a mixed-resin hydroponic system. Ph.D. Thesis. University of Wisconsin-Madison. Diss. Abstr. 84-02821.

11 Claassen N and Barber S A 1974 A method for characterizing the relation between nutrient concentration and flux into roots of intact plants. Plant Physiol. 54, 564–568.

12 Claassen N and Barber S A 1976 Simulation model for nutrient uptake from soil by a growing plant root system. Agron. J. 68, 961–964.

13 Cutler J M and Rains D W 1974 Characterization of cadmium uptake by plant tissue. Plant Physiol. 54, 67–71.

14 Giordano P M, Noggle J C and Mortved J J 1974 Zinc uptake by rice, as affected by metabolic inhibitors and competing cations. Plant and Soil 41, 637–646.

15 Halvorson A D and Lindsay W L 1977 The critical Zn^{2+} concentration for corn and the nonabsorption of chelated zinc. Soil Sci. Soc. Am. J. 41, 531–534.

16 Hendrickson L L, Turner M A and Corey R B 1982 Use of Chelex-100 to maintain constant metal activity and its application to characterization of metal complexation. Anal. Chem. 54, 1633–1637.

17 Hinesly T D, Alexander D E, Redborg K E and Ziegler E L 1982 Differential accumulations of cadmium and zinc by corn hybrids grown on soil amended with sewage sludge. Agron. J. 74, 469–474.

18 Hinesly T D S, Alexander D E, Ziegler E L and Barrett G L 1978 Zinc and Cd accumulation by corn inbreds grown on sludge amended soil. Agron. J. 70, 425–428.

19 Jarvis S C, Jones F H P and Hopper M J 1976 Cadmium uptake from solution by plants and its transport from roots to shoots. Plant and Soil 44, 179–191.

20 John M K and VanLaerhoven C J 1976 Differential effects of cadmium on lettuce varieties. Environ. Pollut. 10, 163–173.

21 Lindsay W L 1979 Chemical equilibria in soils. John Wiley and Sons, New York.

22 Mengel D B and Barber S A 1974 Rate of nutrient uptake per unit of corn root under field conditions. Agron. J. 66, 341–344.

23 Mullins G L 1985 Characterizing plant uptake of Cd and Zn from soils treated with sewage sludge. Ph.D. Thesis. Purdue Univ. Diss. Abstr. 85-20055.

24 Murphy J and Riley J P 1962 A modified single solution method for determination of phosphate in natural waters. Anal. Chem. Acta. 27, 31–36.

25 Nissen P 1973 Kinetics of ion uptake in higher plants. Physiol. Plant 28, 113–120.

26 Page A L, Bingham F T and Nelson C 1972 Cadmium absorption and growth of various plant species as influenced by solution cadmium concentration. J. Environ. Qual. 1, 288–291.

27 Rathore V S, Wittwer S H, Jywng W A, Bajaj Y P S and Adams M W 1970 Mechanism of zinc uptake in bean (*Phaseolus vulgaris*) tissues. Physiol. Plant 23, 908–919.

28 Sposito G and Mattigod S V 1979 GEOCHEM: A computer program for calculating chemical equilibria in soil solutions and other natural water systems. Kearney Foundation of Soil Sci., Univ. of Calif., Riverside.

29 Tennant D 1975 A test of a modified line intersect method of estimating root length. J. Ecol. 63, 995–1001.

30 Veltrup W 1978 Characteristics of zinc uptake by barley roots. Physiol. Plant 42, 190–194.

31 Williams R F 1946 The physiology of plant growth with special reference to the concept of net assimilation rate. Ann. Bot. N.S. 10, 41–72.