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ent in samples taken at random or on a fixed schedule, low flow concentrations will be most heavily weighted, since flow is relatively low most of the time. If there is a dependence of concentration on discharge, the flux so determined will be too low if concentration is directly related to discharge (Fig. 2), and too high if the relationship is inverse (Fig. 7). The degree of dependence (slope of the regression) and nature of the flow duration distribution will determine the magnitude of the error. In the study reviewed here, the errors in loss calculated in such a way would range from slight in the case of DUP, where there is no dependence on discharge to severe in the case of SPP and suspended solids, where concentration increases markedly with discharge.

LITERATURE CITED

1. Association of Official Agricultural Chemists. 1955. Official methods of analysis, Washington, D. C. p. 35.
2. Child, D., R. T. Oglesby, and L. S. Raymond, Jr. 1971. Land use data for the Finger Lakes Region of New York State. Publ. No. 33. Cornell Univ. Water Res. and Marine Sci. Center, Ithaca, N. Y.
3. Chow, V. T. 1964. Handbook of applied hydrology. McGraw-Hill, N. Y.
4. Day, P. R. 1965. Particle fractionation and particle-size analysis. p. 552-561. *In* C. A. Black (ed.) Methods of soil analysis. Part I. Am. Soc. of Agron., Madison, Wis.
5. Dunn, B. 1970. Time-of-travel studies in the Fall Creek Basin, Tompkins County, New York. Rep. of Invest. R1-11, U. S. Dep. of the Interior Geol. Surv. State of New York Conserv. Dep. Water Resour. Div. p. 17.
6. Fiske, C. H., and Y. Subbarrow. 1925. The colorimetric determination of phosphorus. J. Biol. Chem. 66:375-400.
7. Johnson, A. H., D. R. Bouldin, and G. W. Hergert. 1975. Some observations concerning the preparation and storage of stream samples for dissolved inorganic phosphate analysis. Water Resour. Res. 11:559-562.
8. Menzel, D. W., and N. Corwin. 1965. The measurement of total phosphorus in seawater based on the libration of organically bound fractions by persulfate oxidation. Limnol. Oceanogr. 10:280-282.
9. Olsen, S. R., C. V. Cole, F. S. Watanabe, and L. A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. 939. Washington, D. C.
10. Rigler, F. H. 1968. Further observations inconsistent with the hypothesis that the molybdenum blue method measures orthophosphate in lake water. Limnol. Oceanogr. 13:7-13.
11. Ryden, J. C., J. K. Syers, and R. F. Harris. 1973. Phosphorus in runoff and streams. Adv. Agron. 25:1-41.
12. Taylor, A. W., and H. M. Kunishi. 1971. Phosphate equilibrium on stream sediment and soil in a watershed draining an agricultural region. J. Agric. Food Chem. 19(5):827-831.

Uptake of Cadmium by Soybeans as Influenced by Soil Cation Exchange Capacity, pH, and Available Phosphorus[1]

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ABSTRACT

The accumulation of cadmium (Cd) and its affect on vegetative growth of soybeans (*Glycine max* [L.] Merr. var. Amsoy) in soils with a range in cation exchange capacity (CEC), pH, and available phosphorus (P) were investigated in greenhouse experiments. Cadmium uptake decreased as soil pH and CEC increased, while increasing available soil P was related to increased Cd accumulation. Cadmium extracted from the soil by Bray P_1 reagent, Bray P_2 reagent, 2*N* $MgCl_2$, and 0.1*N* EDTA was significantly correlated with plant Cd concentrations. The growth of the soybean shoots was generally depressed when tissue concentrations reached 3-5 μg Cd/g dry weight. Cadmium uptake by soybeans was correlated with the ratio of added Cd to the Cd sorptive capacity of soil.

Additional Index Words: soil extractants, cadmium sorption, heavy metal pollution.

Recent concern for the involvement of Cd in human health problems such as hypertension (Schroeder, 1965), emphysema and chronic bronchitis (Lewis et al., 1969), and other diseases has initiated studies relating to many aspects of Cd in the environment. Elevated environmental levels of Cd may come from a variety of sources such as smelting industries (Buchauer, 1973), impurities in agricultural chemicals (Barrows, 1966), sewage sludge (Jones et al., 1973), and attrition of automobile tires (Lagerwerff and Specht, 1970). Levels in soil in excess of 1,700 μg Cd/g of soil have been reported near Zn smelters (Buchauer, 1973), and Lagerwerff and Specht (1970) found up to 1.82 μg Cd/g of soil close to highways.

In view of the importance of plants in most food chains (both natural and agricultural), a number of studies have recently been directed towards plant accumulation and effects of Cd. Various plants such as corn (*Zea mays* L.), tomato (*Lycopersicum esculentum*), radish (*Raphanus sativus*), and Swiss chard (*Beta vulgaris cicla*) efficiently accumulate Cd from nutrient solutions (Page et al., 1972; Turner, 1973; Root et al., 1975). Hydroponic solution concentrations of 1 μg/ml led to substantial uptake and the depression of yield of vegetative portions of the plants. Cadmium uptake from soil systems has also been studied (e.g., Lagerwerff, 1971; John et al., 1972; Jones et al., 1973; Haghiri, 1973). With wheat (*Triticum x-aestivum*) and soybeans grown in a silty clay loam soil, visual symptoms of Cd toxicity began to occur at 2.5 μg Cd/g of soil (Haghiri, 1973).

The soil factors affecting Cd uptake by plants have been investigated by several workers. Lagerwerff (1971) reported a slight increase in Cd uptake by radish tops and roots due to reduction of the soil pH from 7.2 to 5.9. The Cd concentration in oat shoots (*Avena sativa*) was re-

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Table 1—Characteristics of experimental soils

Soil number	Soil	CEC	Bray P_1	pH	Cd sorption
		meq/100 g soil	kg/ha		μg/g soil
1	Cisne silt loam	6.8	92	4.5	605
3	Cisne silt loam	8.5	119	6.1	2,000
4	Cisne silt loam	6.7	37	7.0	1,700
4L†	Cisne silt loam	6.7	37	7.9	1,759
5	Cisne silt loam	7.9	72	6.0	1,400
6	Cisne silt loam	7.7	10	5.5	1,130
8	Sidell silt loam	15.9	85	6.5	3,900
9	Drummer silty clay loam	30.3	49	6.1	4,700
10	Bloomfield loamy sand	2.3	140	5.7	590

† Soil 4 with 1% $CaCO_3$ added.

duced by addition of organic matter to the soil and the effect was attributed to the increase of the soil CEC (Haghiri, 1974). In this study, high levels of Zn reduced Cd concentration in soybean shoots, although growth was also depressed at these Zn levels. John et al. (1972) also found that organic matter and soil reaction were significant contributing variables in the uptake of Cd by lettuce (*Lactuca sativa*) and radish.

Inasmuch as the soil factors influencing Cd uptake are not yet well understood, the present study with soybean plants utilizing a wide range of soil types and Cd treatment levels was undertaken. In addition, attempts were made to correlate soil extraction of the metal with plant uptake as a tool which might be used to predict potentially hazardous Cd levels in a variety of soil types.

METHODS AND MATERIALS

The surface horizon of nine Illinois agricultural soils were selected to provide a range in cation exchange capacity (CEC), pH, and available phosphorus (Table 1). Cadmium sorption capacities (Cd_s) were obtained from adsorption isotherms for all nine soils. The procedure used to measure Cd_s was the same as had been previously used to measure Pb sorption capacities (Hassett, 1974). Finely powdered $CdCl_2$ was added to the soils at rates of 0, 1, 10, and 100 μg Cd/g dry weight of soils using small samples of each soil as a carrier. The soils were then thoroughly mixed in a mechanical mixer and 500 g of each soil was placed in pots 10.16 cm in diameter. Three replicate pots were prepared for each treatment. The soils were watered and allowed to dry four times so that the Cd could react with the soil.

Soybeans (*Glycine max* [L.] Merr. var. Amsoy) were planted and, after emergence, thinned to two plants per pot. The experiment was conducted in a greenhouse with the day length controlled at 14 hours. The pots were watered daily with measured amounts of distilled water to be certain that the Cd was not leached through the soil. Four weeks after emergence, the shoot portions were harvested, washed, dried at 60C, and the dry weights determined. The plant material was dry ashed at 490C for 4 hours, allowing 4 hours for the muffle furnace to heat from the ambient temperature. The ash was taken up in constant boiling HCl diluted to 3*N*. Previous work established that wet ashing the samples gave the same Cd contents (Root et al., 1975).

Soil parameters were determined as follows: available soil P using the Bray P_1 reagent (0.025*N* HCl + 0.03*N* NH_4F) according to the procedure of Bray and Kurtz (1945), CEC by the ammonium acetate method (Chapman, 1965), and pH on a 1:5 soil to distilled water slurry.

Extractable Cd was determined by shaking 5-g soil samples from each pot for 2 hours with 50 ml of 0.1*N* EDTA, 2*N* $MgCl_2$, the Bray P_1 reagent, or the Bray P_2 reagent (0.1*N* HCl + 0.03*N* NH_4F). The soil was removed from the solutions by filtration and the Cd content of plant and soil samples was determined by atomic absorption spectroscopy as previously reported (Root et al., 1975).

Table 2—Effects of soil characteristics on Cd concentrations and vegetative yield of 4-week-old soybean shoots

Soil number	Added Cd, μg/g soil: 0		1		10		100	
	Cd†	Dry weight†	Cd†	Dry weight†	Cd†	Dry weight†	Cd†	Dry weight†
	μg/g	g	μg/g	g	μg/g	g	μg/g	g
1	1.36	0.29	8.97	0.27	51.4	0.14	–‡	–‡
3	2.36	0.33	4.08	0.31	26.8	0.22	87.2	0.11
4	0.24	0.33	0.80	0.42	5.04	0.22	37.9	0.16
4L	0.94	0.28	0.80	0.34	3.25	0.33	10.3	0.22
5	1.86	0.39	2.74	0.42	19.9	0.35	67.4	0.12
6	0.62	0.46	2.36	0.32	15.9	0.34	48.5	0.12
8	0.45	0.43	1.44	0.33	4.14	0.38	36.40	0.23
9	0.46	0.44	0.90	0.45	4.04	0.40	13.73	0.29
10	0.47	0.57	5.54	0.47	64.20	0.13	38.20	0.08

† All values are the average of 3 replicate samples.
‡ Plants died shortly after germination.

RESULTS AND DISCUSSION

Plant Cd concentration and vegetative yield, as influenced by soil Cd, varied widely in the nine soils tested (Table 2). Extensive Cd accumulation and growth inhibition was especially apparent in the low pH and low CEC soils (soils 1 and 10). At the 100 μg Cd/g soil treatment for Bloomfield loamy soil (soil 10), the plant Cd concentration was less than at 10 μg Cd/g soil due to severe stunting of the plant and minimal root development. Plants grown in the high P_1 test soils also had consistently high concentrations of Cd.

Correlations obtained from linear regression analysis across all soils and all Cd rates are shown in Table 3. Significant correlations of plant Cd concentration with soil CEC, Bray P_1 test, and the interactions of CEC × pH and P_1 × pH were obtained. In addition, plant Cd concentration was significantly correlated with soil Cd treatment level and the dry weight of the shoots. The vegetative yield of the plants was significantly correlated with CEC, soil Cd, and the CEC × pH interaction. The absence of a significant correlation between plant Cd concentration and soil pH is somewhat surprising, and it is probably attributable to the absence of data for the highest soil Cd level in soil 1 (the most acid soil). Plants grown on soil 1 at the highest Cd level died shortly after germination and the shoots did not emerge. That soil acidity is an im-

Table 3—Correlation coefficients (*r*) from linear regression analysis across all soils and soil Cd treatments of plant Cd concentrations and vegetative yield with soil properties, soil Cd content, and plant dry weight

Variable	Plant Cd: All soils	Plant Cd: Minus soil 4L	Dry weight: All soils	Dry weight: Minus soil 4L
	μg/g dry weight		g	
CEC	–0.21*	–0.25*	0.27**	0.26*
pH	–0.16	–0.04	0.01	0.05
P_1	0.28**	0.23*	–0.13	–0.15
CEC × P_1	–0.06	–0.13	0.15	0.14
CEC × pH	–0.22*	–0.24*	0.27**	0.26*
P_1 × pH	0.25*	0.22*	–0.12	–0.14
CEC × P_1 × pH	–0.07	–0.12	0.15	0.14
Soil Cd concentration	0.58**	0.63**	–0.59**	–0.60**
Dry weight	–0.69**	–0.72**		

*,** Indicate significance at 5% and 1% level, respectively.

portant factor affecting Cd uptake by soybeans is apparent, in that plants grown on the acid soil at intermediate soil Cd levels contained high Cd concentrations and were very stunted (Table 2).

Regression analysis of the data (Table 2) omitting soil 4L, which had been altered by the addition of 1% calcium carbonate, produced similar results (Table 3). Calcareous soils with high pH values are not typical of the other soils used in this experiment, and thus soil 4L was omitted from the analysis on this basis.

In view of the anomalous results with two of the nine soils at the highest soil Cd level, the data were analyzed within soil Cd treatments. In general the same type of relationships are apparent in the analysis within soil Cd levels (Table 4) as were evident when the analysis was done across all soils. One important exception is that soil pH significantly correlated with plant Cd concentrations in the 1 and 10 μg Cd/g soil treatments, although not at the 100 μg Cd/g soil level, again probably due to the loss of data for the 100 μg Cd/g soil treatment on the acid soil due to death of the plants. Also, the correlations of shoot dry weight with the CEC × P_1 × pH interaction was significant at the highest Cd level. As before, exclusion of soil 4L from the analysis did not appreciably change the results.

The effect of CEC on the availability of cations to plants has been extensively studied. The importance of soil CEC in controlling Cd uptake has been noted by John et al. (1972), Jones et al. (1973), and Haghiri (1974). Our results basically agree with the earlier work in that Cd uptake at any given level of applied Cd was found to decrease with an increase in CEC.

Table 4—Correlation coefficients (*r*) from linear regression analysis within soil Cd treatments of plant Cd concentrations, and vegetative yield with soil properties and plant dry weight

Variable	Soil Cd	Plant Cd: All soils	Plant Cd: Minus soil 4L	Dry weight: All soils	Dry weight: Minus soil 4L
	μg/g	μg/g dry weight		g	
CEC	1	−0.33	−0.38	0.16	0.15
	10	−0.46*	−0.53**	0.61*	0.65**
	100	−0.36	−0.55*	0.70**	0.84**
pH	1	−0.57**	−0.55**	0.10	0.24
	10	−0.53**	−0.47*	0.37	0.34
	100	−0.26	−0.17	0.26	0.14
P_1	1	0.48**	0.44*	0.48	0.01
	10	0.61**	0.58**	−0.63**	−0.62*
	100	0.40	0.30	−0.33	−0.29
CEC × P_1	1	−0.09	−0.18	0.01	−0.04
	10	−0.24	−0.35	0.37	0.42*
	100	−0.06	−0.27	0.53*	0.71**
CEC × pH	1	−0.39*	−0.43*	0.18	0.17
	10	−0.51**	−0.56**	0.64**	0.67**
	100	−0.39	−0.54*	0.74**	0.85**
P_1 × pH	1	0.32	0.28	0.06	0.03
	10	0.45*	0.42*	−0.50	−0.48*
	100	0.42	0.37	−0.30	0.27
CEC × P_1 × pH	1	−0.17	−0.24	0.01	−0.03
	10	−0.30	−0.40	0.38	0.44
	100	−0.04	−0.22	0.53*	0.68**
Dry weight	1	−0.20	−0.24		
	10	−0.76**	−0.76**		
	100	−0.54**	−0.52*		

*,** Indicate significance at 5% and 1% level, respectively.

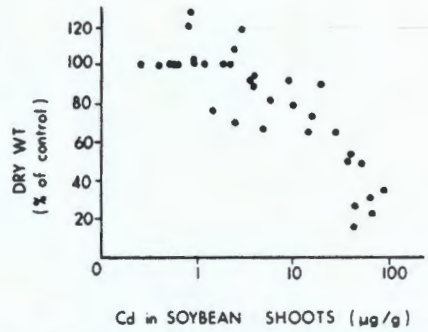

Fig. 1—The effect of tissue content of Cd on the dry weight of 4-week-old soybean shoots.

Lagerwerff (1971), John et al. (1972), and others have shown the effect of soil acidity on the uptake of Cd. Plant availability of Cd appears to be affected by soil acidity in a manner similar to that of other metals such as Ni, Zn, Fe, and Cu (Lindsay, 1972). Cd availability increases with increasing soil acidity, probably due to increased solubility of Cd compounds such as hydroxides, phosphates, and carbonates. Greater competition for exchange sites due to increased levels of ions such as Fe^{3+}, Mn^{2+}, Zn^{2+}, and H^+ in acid soils may also be a factor.

High levels of available soil P, as measured by the Bray P_1 test, were previously found to reduce Pb uptake by corn plants (Miller et al., 1975b), although no appreciable effect of P on Pb uptake by soybeans was found (Miller et al., 1975a). If the apparent stimulation of Cd uptake by soybeans is indeed due to P, an explanation in not readily evident. One possibility is that high P levels provide a readily available counterion that accompanies Cd into the root, or vice versa if the anion is considered to be the primary species accumulated. In addition it has been shown that P enhances Ca uptake by corn roots (Miller et al., 1972) and by isolated corn mitochondria (Elzam and Hodges, 1968). It is possible that Cd and P have a similar relationship in soybeans. Further experimentation is in progress pertaining to the mechanism of the P affect on Cd uptake.

The relationship between vegetative growth and plant Cd content at all treatment combinations is shown in Fig. 1. The threshold of vegetative yield reduction occurs at 3 to 5 μg Cd/g dry weight of tissue, which is similar to the results of Haghiri (1973) with wheat and soybeans.

The Cd sorption capacities (Cd_s) of the soils used in this experiment, as obtained from adsorption isotherms, vary widely (Table 1). Examination of the soil characteristics indicates that soil CEC is the primary soil factor controlling Cd_s, but comparison of soils number 1 and 10 illustrates the importance of soil pH. Simple linear coorelations between the Cd_s value of the soils and the measured shoot concentrations of Cd at each soil Cd level were made (Table 5). The correlations were calculated for all soils exclusive of soil 4L. The negative coefficients of correlation reflect the tendency of less plant Cd accumulation to occur from soils with a greater capacity to sorb Cd, as would be expected. However, significance at the 5% level was obtained only at the 10 μg Cd/g soil level when soil 4L was not included.

If the total Cd added to each soil (Cd_t) is divided by the Cd_s of that soil, the resultant value reflects the degree

Table 5—Correlation coefficients (r) between Cd concentrations in soybean shoots (Cd_p) at each level of soil Cd and the Cd sorption capacities (Cd_s) of the soils

Soil Cd	Correlation coefficient (r) of Cd_s with Cd_p	
	All soils	Minus soil 4L
μg/g		
1	−0.60	−0.65
10	−0.65	−0.71*
100	−0.45	−0.66

* Significant at 5% level.

Table 6—Correlation coefficients (r) of Cd concentrations in soybean shoots and Cd added to soils with extractable Cd

	Soil extractable Cd, μg/g			
	Bray P_1	Bray P_2	2N $MgCl_2$	0.1N EDTA
Plant Cd, μg/g	0.865**	0.689*	0.700*	0.650*
Soil Cd, μg/g	0.800**	0.988**	0.900**	0.997**

* Significant at 5% level.
** Significant at 1% level.

of saturation of Cd_s in each soil at each Cd concentration. The linear correlation coefficients for these values with plant Cd concentrations were r = 0.77 for all soils, and r = 0.83 for all soils exclusive of 4L. Both were significant at the 1% level. This illustrates that the uptake of Cd by soybeans was related to the amount of Cd in the soil relative to its capacity to sorb Cd. A similar relationship was found with Pb uptake by soybeans and corn (Miller et al., 1975a, 1975b).

The soils used in this experiment were extracted with four reagents and simple linear correlations were run between extractable soil Cd and both plant Cd and soil Cd concentrations. Table 6 illustrates that Cd extracted by the Bray P_1 reagent correlates best with plant Cd (r = 0.865) and the poorest with soil Cd (r = 0.800). The Bray P_2 reagent, 2*N* $MgCl_2$, and 0.1*N* EDTA extracted nearly all of the Cd from the soil, and thus correlations with soil Cd levels were quite high. Soil extraction of Pb by the Bray P_1 reagent was previously found to be highly correlated with Pb levels in corn and soybean (Miller et al., 1975a, 1975b). The Bray P_1 reagent appears to have some promise as a soil extractant for predicting Cd and Pb uptake by plants, although further experimentation needs to be done, especially under field conditions.

The results presented here indicate that soil CEC, pH, and available P are important soil factors affecting plant Cd accumulation. It would be expected that problems with plant Cd toxicity would more readily occur at lower soil Cd levels in sandy soils or those low in organic matter, rather than in heavier soils high in clay and/or organic matter. Acid soils would also be prone to presenting a Cd hazard at lower soil Cd levels. The majority of agricultural soils in the Midwest have medium to high CEC's (8 to 30 meq/100 g of soil), intermediate Bray P_1 tests (45 to 67 kg P/ha soil), and are maintained at pH 6 or above by application of lime. Thus, soil levels of Cd far in excess of those commonly encountered would have to occur for appreciable plant Cd accumulation to occur in most soils.

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LITERATURE CITED

1. Barrows, H. L. 1966. Soil pollution and its influence on plant quality. J. Soil Water Conserv. 21:211-216.
2. Bray, R. H., and L. T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59:39-45.
3. Buchauer, M. J. 1973. Contamination of soil and vegetation near a zinc smelter by zinc, cadmium, copper, and lead. Environ. Sci. Technol. 7:131-135.
4. Chapman, H. D. 1965. Cation exchange capacity. *In* C. A. Black (ed.) Methods of soil analysis. Part 2. Agronomy 9: 891-901. Am. Soc. of Agron., Madison, Wis.
5. Elzam, O. E., and T. K. Hodges. 1968. Characterization of energy-dependent Ca^{+2} transport in maize mitochondria. Plant Physiol. 43:1108-1114.
6. Haghiri, F. 1973. Cadmium uptake by plants. J. Environ. Qual. 2:93-96.
7. Haghiri, F. 1974. Plant uptake of cadmium as influenced by cation exchange capactiy, organic matter, zinc, and soil temperature. J. Environ. Qual. 3:180-183.
8. Hassett, J. J. 1974. Capacity of selected Illinois soils to remove lead from aqueous solution. Commun. Soil Sci. Plant Anal. 5:499-505.
9. John, M. K., C. J. VanLaerhoven, and H. H. Chuah. 1972. Factors affecting plant uptake and phytotoxicity of cadmium added to soils. Environ. Sci. Technol. 6:1005-1009.
10. Jones, R. L., T. D. Hinesly, and E. L. Ziegler. 1973. Cadmium content of soybeans grown in sewage-sludge amended soil. J. Environ. Qual. 2:351-353.
11. Lagerwerff, J. V. 1971. Uptake of cadmium, lead, and zinc by radish from soil and air. Soil Sci. 111:129-133.
12. Lagerwerff, J. V., and A. W. Specht. 1970. Contamination of roadside soil and vegetation with cadmium, nickel, lead, and zinc. Environ. Sci. Technol. 4:583-586.
13. Lewis, G. P., H. Lyle, and S. Miller. 1969. Association between elevated hepatic water-soluble protein-bound cadmium levels and chronic bronchitis and/or emphysema. Lancet 2: 1330-1333.
14. Lindsay, W. L. 1972. Inorganic phase equilibria of micronutrients in soils. p. 41-57. *In* J. J. Mortvedt, P. M. Giordano, and W. L. Lindsay (ed.) Micronutrients in agriculture. Soil Sci. Soc. Am., Madison, Wis.
15. Miller, J. E., J. J. Hassett, and D. E. Koeppe. 1975a. The effect of soil properties and extractable lead levels on lead uptake by soybeans. Commun. Soil Sci. Plant Anal. 6:339-347.
16. Miller, J. E., J. J. Hassett, and D. E. Koeppe. 1975b. The effect of soil lead sorption capacity on the uptake of lead by corn. Commun. Soil Sci. Plant Anal. 6:349-358.
17. Miller, R. J., J. H. Peverly, and D. E. Koeppe. 1972. Calcium-stimulated ^{32}P accumulation by corn roots. Agron. J. 64: 262-266.
18. Page, A. L., F. T. Bingham, and C. Nelson. 1972. Cadmium absorption and growth of various plant species as influenced by solution cadmium concentration. J. Environ. Qual. 1: 288-291.
19. Root, R. A., R. J. Miller, and D. E. Koeppe. 1975. Uptake of cadmium-Its toxicity, and effect on the iron ratio in hydroponically grown corn. J. Environ. Qual. 4:473-476.
20. Schroeder, H. A. 1965. Cadmium as a factor in hypertension. J. Chronic Dis. 18:647-656.
21. Turner, M. A. 1973. Effect of cadmium treatment on cadmium and zinc uptake by selected vegetable species. J. Environ. Qual. 2:118-119.