Ref
59817
0117

0117

Plant and Soil 70, 335-345 (1983). Ms. 5194
© 1983 *Martinus Nijhoff/Dr W. Junk Publishers, The Hague. Printed in The Netherlands.*

Effects of cadmium and lead on radish plants with particular reference to movement of metals through soil profile and plant

D. H. KHAN and B. FRANKLAND
School of Biological Sciences, Queen Mary College, University of London, Mile End Road, London E1 4NS, UK

9348

Received 23 August 1982. Revised November 1982

Key words Cadmium Column Contaminant Lead Metal Radish *Raphanus sativa* L.

Summary Studies were made of the effects of insoluble and soluble compounds of Cd and Pb on the growth of radish plants. The effect of Cd toxicity was progressive chlorosis, particularly of the young leaves, followed by necrosis. The effect of Pb toxicity was stunted growth. Root growth was more inhibited than shoot growth in metal-contaminated soils. On a molarity basis Cd was twenty times more toxic than Pb.

A microcosm study involving soil columns showed that Cd and Pb are largely retained within the surface soil. There was very little movement of these metals, particularly of Pb, through the sub-soil horizon. The addition of Cd or Pb to the soils in columns raised the levels of these metals in the plant tissue to phytotoxic concentrations and reduced the growth considerably. Such phytotoxicity seemed to be associated with some reduction of Zn in the plant tissue to near the lower critical level of deficiency threshold value. Of the two metals studied Cd was more concentrated in the plant shoot and Pb in the plant root. Considering this and also the chemical forms of the metals in the soil profile, the mobility of Cd was found to be higher than Pb within the soil-plant system studied.

Introduction

Contaminant metals can often accumulate in considerable amounts in the plant tissue and exceed the levels that are toxic to man or animal before they produce visible phytotoxic effects. This has caused increasing concern with respect to certain heavy metals, particularly Cd and Pb, which have been implicated as potentially hazardous contaminants in the biosphere. These heavy metals tend to accumulate in the plough layers of soils, and are absorbed and retained more in roots than in shoots. This has led to a considerable amount of work on the biogeochemical distribution of toxic heavy metals in soils and plants from contaminated areas, particularly on root crops[4,5,8,10,14,15,17]. However, knowledge is very limited concerning the chemical forms and mobility of heavy metals in the soil in relation to plant growth.

This paper reports observations on the effects of insoluble and soluble compounds of Cd and Pb on the growth of radish plants using potted soils. Based on this, a modified microcosm technique has been employed using the surface and the sub-soil horizons of a brown earth profile to examine the movement of the two heavy metals involved through the soil profile and their effects on the growth of radish plants and tissue concentrations of the metals.

Table 1. Descriptions of soils used

Horizon (depth, cm)	pH (In H_2O)	Levels of heavy metals in soil, $\mu g\ g^{-1}$				
		Digest/ Extract	Pb	Cd	Zn	Cu
1. Brown earth, Dytchleys Field Station, Essex. Grassland, recreational. Uncontaminated.						
Ap	5.4	Aqua regia	50.0	0.7	34.2	14.8
(0–20)		EDTA	21.3	0.3	17.0	7.8
2. Brown earth, Weald Country Park, Essex. Parkland with trees and grasses. Uncontaminated.						
Ap	4.6	Aqua regia	37.1	0.5	12.9	5.4
(0–20)		EDTA	20.8	0.3	7.8	1.8
B	4.4	Aqua regia	11.2	0.2	8.2	3.4
(50–70)		EDTA	5.4	0.1	2.3	0.5

Materials and methods

Soils

Two brown earth soils, which represent typical agricultural soils of Britain, were collected from the Dytchleys Field Station near Brentwood and from Weald Country Park, both from Essex. The former soil is slightly acidic but well aggregated; the latter soil is distinctly acidic and almost structureless. The texture of surface soils (Ap horizon) in both profiles is loamy sand; the sub-soil (B horizon) in the Dytchleys profile has a clay loam texture whereas the sub-soil in the Weald Park profile is characterised by a sandy texture. The levels of heavy metals in soils from both locations represent the approximate background levels (Table 1). Soils collected from the field were air-dried, ground to pass through a 2 mm sieve, and homogenized for glasshouse studies.

Dose-response studies

A brown earth soil from the Dytchleys Field Station, sampled from the Ap horizon, has been used. The soils were potted using 300 g soil per pot, and treated with compounds of Cd and Pb; the doses of metal treatments and compounds used are shown in Table 2. A basal dressing of 100 $\mu g\ N\ g^{-1}$, 100 $\mu g\ P\ g^{-1}$ and 100 $\mu g\ K\ g^{-1}$ was added to each pot. The experiment was laid out in triplicate in a randomised design in a glasshouse at 25°C, and left to equilibrate at field capacity for 15 days. Germinated seeds of radish, *Raphanus sativa* L. cv Cherry Belle (the same variety used in all experiments in this study), were sown two per pot, and thinned to one after seedling emergence. Plants were harvested 42 days after sowing at edible stage, roots and shoots being dried at 60°C and weighed. A separate experiment using similar metal treatments and the same soil from Dytchleys was carried out to study the effects of metals on the seedling growth of radish 10 days after sowing, the experiment being laid out with two replicates in a randomised design.

Soil column studies

Draggan and Van Voris[6] employed a microcosm technique to study the movement of contaminants through columns using only surface soils but without growing plants. This technique has been further developed in this study using soils from the plough layer and the sub-soil of a brown earth profile from Weald Country Park (levels of heavy metals in this soil being lower than those in Dytchleys soil). The columns were set up using two 10 cm portions of PVC pipes of 10 cm diameter for each column, the upper 10 cm pipe filled with 1 kg of the surface soil (Ap) and the lower 10 cm pipe with 1 kg of the sub-soil (B). The columns rested on a circular perspex frame fitted with a nylon mesh, columns being placed on funnels to collect the leachate. The top 5 cm layer of soils was contaminated by mixing in Cd or Pb in soluble or as insoluble forms, the metal treatments shown in Table 4. A basal dressing of 100 $\mu g\ N\ g^{-1}$, 100 $\mu g\ P\ g^{-1}$ and 100 $\mu g\ K\ g^{-1}$ was given to the top 5 cm layer of soils. The experiment was laid out with three replicates in a randomised design. Distilled water, aerated for 1h at room temperature (pH 6.1), was used to irrigate the columns to field capacity and left to equilibrate at 25°C in a glasshouse for 15 days. The aerated water contained 0.1 μg Cd and 0.5 μg Pb per litre, and the plastic column immersed for 100 days released 0.7 μg Cd and 0.3 μg Pb per litre.

Three germinated seeds of radish were sown in each column and thinned to two seedlings. The plants were irrigated three times every week using aerated distilled water, which amounted to about 250 ml per column per week at the early stage of growth and 350 ml at the more advanced stage of growth. The total amount of water added to each column during the 42 days of the experiment was 1.5 ± 0.1 litre. This corresponds to nearly double the amount of the average rainfall in Britain. The amount of leachate collected from each column until harvest was 500 ± 60 ml. The growth measurements at harvest (42 days after sowing) involved leaf area using a KGM VIDAIDS leaf area quantifier, and dry weights of roots and shoots. While irrigation of the soil continued through the growing period, the soils settled down in the columns by 1 cm. After harvest the soils were sampled from layers at 0–5, 5–10 and 15–20 cm depths. Because of the settlement of the soil in columns, the actual depths of soils sampled have varied within ± 0.5 cm for each layer. The sub-soil was distinct because of the sharp boundary shown by the brownish yellow colour of the B horizon. The soil samples were air dried. Analysis of variance was used on plant growth data (both dose-response and soil column studies) to assess the statistical significance of the effects observed.

Analytical methods

Soils collected from the field were analysed in duplicate for total contents of Cd, Pb, Zn and Cu after digesting with hot HNO_3 followed by aqua regia ($HCl + HNO_3$), the extractable contents of metals after shaking the soils with 0.05 *M* NH_4-EDTA (diammonium salt of ethylenediaminetetra-acetic acid) at pH 7 for 30 min, the soil to solvent ratio being 1:5. The heavy metals were analysed using atomic absorption spectrophotometers (with background corrections for Cd), the lower concentrations of metals in the graphite furnace and the higher concentrations in the acetylene flame. Soil pH was determined with a glass electrode[1].

Soils sampled from soil columns were analysed for the total and EDTA extractable contents of Cd and Pb as described. The water-soluble metals were analysed after shaking the soils for 30 min (soil to water ratio of 1:40). The leachates from columns were centrifuged at 17000 rpm, the supernatant being analysed for the total soluble amounts of Cd and Pb. Plant roots and shoots were thoroughly washed in tap water to remove any adhering soil particles, then washed three times in distilled water, dried and ground. Plant materials were drenched with 2 *M* H_2SO_4, left at 60°C for 1h, then at 130°C overnight, and dry-ashed at 450°C for 4h.[13] Dry ashing was repeated when carbon-free ash was not produced. The ash was extracted with 6 *M* HCl, evaporated to dryness, the residue taken up in conc. HCl, filtered and analysed for Cd, Pb, Fe, Zn and Cu. The analyses of soils, leachates and plant samples for heavy metals were carried out on samples from each of the three replicated columns. Results of soils and plant analyses have been expressed on an oven-dry basis.

Results

Dose-response studies

Cd added as chloride or oxide progressively reduced the yields of shoot and root of radishes grown on soils from Dytchleys (data recorded at the edible stage of growth, Table 2). Soils treated with Cd at 50 $\mu g\ g^{-1}$ as chloride or 500 $\mu g\ g^{-1}$ as

Table 2. Growth of radish plants in potted soils

Metal treatment $\mu g\ g^{-1}$	Metals added	Dry weight, g/plant	
		Shoot	Root
Control	–	1.07	1.29
Cd 10	$CdCl_2$	0.83	0.86**
Cd 50	$CdCl_2$	0.74*	0.54**
Cd 100	$CdCl_2$	0.29**	0.33**
Cd 500	$CdCl_2$	0.00**	0.00**
Cd 100	CdO	0.76*	0.82**
Cd 500	CdO	0.21**	0.31**
Cd 1000	CdO	0.00**	0.00**
Pb 100	$PbCl_2$	0.98	1.11
Pb 500	$PbCl_2$	1.01	0.98*
Pb 1000	$PbCl_2$	0.91	0.89**
Pb 5000	$PbCl_2$	0.00**	0.00**
Pb 1000	PbO	1.13	0.94*
Pb 5000	PbO	0.82	0.87**
Pb 10 000	PbO	0.59**	0.84**
Cd 10 + Pb 1000	$CdCl_2 + PbCl_2$	0.84	0.90**
Cd 50 + Pb 1000	$CdCl_2 + PbCl_2$	0.26**	0.32**

* Significant effect at 5% level over control
** Significant effect at 1% level over control

oxide produced seedlings with chlorosis in interveinal areas of leaves, this being more pronounced in young leaves. The chlorotic areas produced necrotic patches with advance in growth. At the highest levels of Cd used, the leaves developed severe chlorosis within a week after sowing followed by necrosis, and the plants died two weeks later. Pb added as chloride reduced the shoot growth when the level exceeded 1000 $\mu g\ g^{-1}$, but the root growth was progressively reduced. At the 5000 $\mu g\ g^{-1}$ level of Pb added as chloride, the seedlings ceased growth; they had very thin short stems and small leaves but without any chlorosis, although they survived for nearly three weeks. Pb added as oxide produced a significant inhibition of the shoot growth only at the highest level used, but the root growth was progressively reduced. The combined application of Cd and Pb as chlorides did not show any interaction; the plant growth was reduced very considerably particularly at 50 μg Cd g^{-1} combined with 1000 μg Pb g^{-1}, suggesting additive effects (Table 2).

Levels of metals required to produce 50% inhibition of growth of radishes at both the seedling stage and edible stage, have been calculated from the dose-response curves (Table 3); these levels of metals were lower for roots than shoots and were higher at the seedling stage than at the edible stage.

Table 3. Levels of Cd and Pb producing 50% inhibition of plant growth

Plant growth stage	Plant part	Metals added as	
		Chloride	Oxide
(a) Levels of Cd producing 50% inhibition, $\mu g\ g^{-1}$ soil			
Seedling growth 10 d after sowing	Shoot	90	460
	Root	27	340
Growth 42 d after sowing	Shoot	70	190
	Root	44	170
(b) Levels of Pb producing 50% inhibition, $\mu g\ g^{-1}$ soil			
Seedling growth 10 d after sowing	Shoot	2800	22,000
	Root	2400	10,000
Growth 42 d after sowing	Shoot	2000	12,000e
	Root	1800	10,000

e = extrapolated

Soil column studies

Results show that Cd applied at both 50 and 100 $\mu g\ g^{-1}$ levels reduced the root and shoot growth and also leaf areas, whereas Pb inhibited growth only at the 1000 $\mu g\ g^{-1}$ level (Table 4a). Plants grown in the Cd-treated soils, particularly at the 100 $\mu g\ g^{-1}$ level, developed toxicity symptoms in the leaves as observed in pot studies. Analyses of plant tissue show that the level of Cd ($\mu g\ g^{-1}$) was one and half times higher in the shoot than in the root, but the level of Pb was nearly four times higher in the root than in the shoot (Table 4b). The levels of Fe, Zn and Cu were greater in the shoot than in the root.

Table 5 shows the distributions of Cd and Pb in the soil profile. The amounts of Cd and Pb retained in each layer were calculated from the measured levels of the metals in the soil (assuming 5 cm layer of soil contained ca. 0.5 kg soil). The calculations were based on: EDTA soluble equals EDTA extractable less water soluble metal; and EDTA insoluble equals total (aqua regia) less EDTA extractable metal. In control soil columns the leachate contained 2 μg Cd and 20 μg Pb. A portion of this originated from the PVC column and also from the aerated water used in irrigation, although it is likely that a considerable proportion of the metals from these sources would have been absorbed in the soil colloidal complex.

Table 4. Growth of radish plants in soil columns and metal concentrations in plant tissue

(a) Growth measurements

Metal treatment $\mu g\ g^{-1}$	Metals added	Dry weight, g/plant			Leaf area cm^2/plant
		Shoot	Root	Shoot + Root	
Control	–	1.04	1.87	2.91	310
Cd 50	$CdCl_2$ + CdO, 1:1	0.85**	1.27**	2.12	240**
Cd 100	$CdCl_2$ + CdO, 1:1	0.77**	1.07**	1.84	208**
Pb 500	$PbCl_2$ + PbO, 1:1	0.99	1.78	2.77	298
Pb 1000	$PbCl_2$ + PbO, 1:1	0.93*	1.49**	2.42	276**

* Significant effect at 5% level over control
** Significant effect at 1% level over control

(b) Metal levels in plant tissue

Metal treatment $\mu g\ g^{-1}$	Levels of metals, $\mu g\ g^{-1}$				
	Cd	Pb	Fe	Zn	Cu
Levels in shoot					
Control	1.3	3.7	167	26	6.9
Cd 50	54	4.8	145	21	6.5
Cd 100	66	4.0	145	17	6.4
Pb 500	1.1	42	164	16	6.0
Pb 1000	1.4	68	152	15	3.8
Levels in root					
Control	0.5	5.4	115	15	2.9
Cd 50	33	5.5	94	15	2.4
Cd 100	42	5.4	89	14	2.4
Pb 500	0.6	142	108	14	1.7
Pb 1000	0.8	314	86	12	1.6

Large concentrations of Cd and Pb were retained in the top 5 cm soil. When compared with control values, the levels of metals in the 5–10 cm layer are considerable, such amounts being attributable to (a) the transport of the metals by the growing plant roots, (b) the actual movement of the metals in soluble form or physically carried by soil colloids and (c) the physical contamination of the upper part of the 5–10 cm layer due to contact with the 0–5 cm layer and settlement of the soil in the columns. However, the amounts of Cd and Pb accumulated below 10 cm, which could only arise by actual movement of these metals, are very little (Table 5). Data further show that a considerable proportion of the added metals are in the EDTA soluble fraction, the water soluble fraction containing very small amounts of these metals. Compared to Pb, Cd was present in greater concentrations in both the EDTA and water soluble fractions.

Table 5. Distribution of Cd and Pb in soil profile

Cd in soil horizons

Metal treatment $\mu g\ g^{-1}$ (Amount added to top soil)	Depth cm	Cd, mg		
		EDTA		Water soluble
		Insoluble	Soluble	
Control	0–5	0.22	0.11	0.02
	5–10	0.19	0.12	0.01
	10–15	0.07	0.06	0.01
	15–20	0.07	0.07	0.01
	Leachate			0.002
Cd 50	0–5	2.62	14.19	0.13
(25 mg Cd as	5–10	1.75	3.82	0.06
$CdCl_2$ + CdO in	10–15	0.45	0.70	0.03
1:1 ratio)	15–20	0.27	0.35	0.02
	Leachate			0.03
Cd 100	0–5	9.74	27.22	0.23
(50 mg Cd as	5–10	2.22	7.25	0.13
$CdCl_2$ + CdO in	10–15	0.67	0.73	0.05
1:1 ratio)	15–20	0.50	0.57	0.02
	Leachate			0.04

Pb in soil horizons

Metal treatment $\mu g\ g^{-1}$ (Amount added to top soil)	Depth cm	Pb, mg		
		EDTA		Water soluble
		Insoluble	Soluble	
Control	0–5	12.2	9.1	0.09
	5–10	11.9	8.4	0.09
	10–15	5.9	1.9	0.08
	15–20	5.8	2.0	0.08
	Leachate			0.02
Pb 500	0–5	98.7	132.1	0.72
(250 mg Pb as	5–10	22.1	12.6	0.16
$PbCl_2$ + PbO in	10–15	6.2	2.2	0.10
1:1 proportion)	15–20	6.0	2.3	0.09
	Leachate			0.04
Pb 1000	0–5	155.1	312.0	1.11
(500 mg Pb as	5–10	25.2	13.8	0.19
$PbCl_2$ + PbO in	10–15	6.4	2.3	0.15
1:1 proportion)	15–20	6.4	2.5	0.14
	Leachate			0.07

The movement of Cd and Pb in the soil profile and their translocation to the plant root and shoot are shown in Fig. 1, the values being expressed as percentages of the metals added to the soil at 100 μg Cd g^{-1} and 1000 μg Pb g^{-1}. Fig. 1 shows that very small amounts of the contaminant metals, particularly in the case of Pb, moved from the surface (0–10 cm) to the sub-soil (10–20 cm); the leachates contained only 0.1% of the added Cd and 0.01% of the added Pb. With

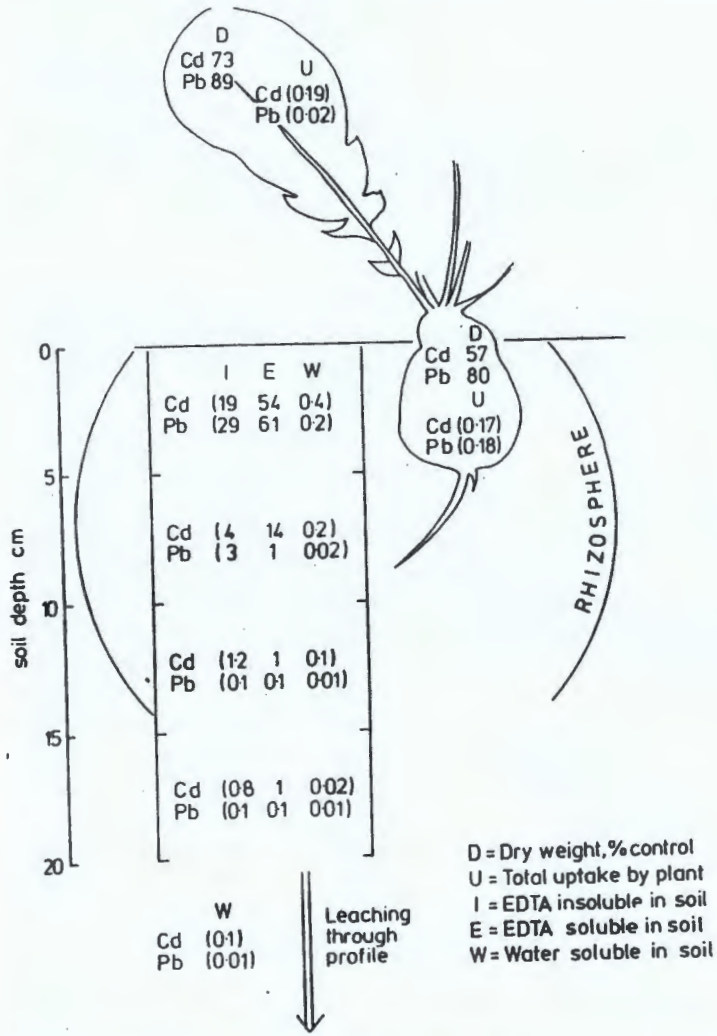

Fig. 1. Distribution of Cd and Pb in soil profile and translocation to radish plant (values within parentheses are percentages of total amounts of contaminant metals added at 100 μg g^{-1} of Cd and 1000 μg g^{-1} of Pb to the top 5 cm soil).

regard to plant tissue the total content of Cd was nearly the same for both root and shoot, whereas there was much less Pb in the shoot than in the root.

Discussion

Considering the levels required to produce 50% inhibition of growth at different stages, it appears that Cd was nearly 20 times more toxic than Pb, the levels being calculated on a molarity basis (Table 3); Cd added as oxide at 180 μg g^{-1} produced such inhibition of growth at the edible stage, this being nearly three times higher than that required in the soluble form. Using data on the grain yields of plants grown in some Japanese soils contaminated with CdO (cited from Friberg *et al.*[7]) 50% inhibition of growth was found at 42 μg g^{-1} level in the case of wheat and at 1532 μg g^{-1} level in the case of rice. The root, particularly of seedlings, was more affected than the shoot in metal contaminated soils. The absence of severe toxicity symptoms in plants grown in Pb-contaminated soils could be partly due to the lower absolute toxicity of Pb and partly due to the restricted transport to the shoot. It is generally understood that roots act as a barrier to the movement of toxic heavy metals through the soil-plant system[9]. However, there is no evidence in this study that the movement of Cd from radish root (which is in part a swollen stem, with small amounts of fibrous roots) into the shoot is restricted (Table 4). Several investigators, more recently Davis and Carlton-Smith[5], found higher concentrations of Cd in roots than in leaves of many crop plants grown in sludge-treated soils. The study with soil columns showed that the effects of Cd and Pb, added in both soluble and insoluble forms, on plant growth are comparable to those observed in pot experiment. This was because most of the added metals in the column were bound in the surface soil, allowing only very small amounts of Cd and Pb to move through the profile (Table 5). This suggests that the soil acts as a natural reservoir for contaminant metals[12]. A very small amount of the added Cd or Pb was present in the sub-soil and much less in the leachate from the whole profile (Fig. 1). The relatively higher mobility of Cd than Pb was evident from the distributions of the metals in the EDTA and water soluble fractions. This lends support to observations from a recent soil column study which showed greater mobility of Cd than Pb through the soil profile; the movement of Cd led to a build up in the concentration of the metal below the surface layer of soils[2]. A similar increase in the concentration of Cd in the sub-surface soil was also reported by Tyler and McBride[16]. The immobility of Pb in the soil has been however reported by several investigators[2,12,18]. Though the observed translocation of heavy metals was very small in this study, the process involves several inorganic and organic mobilizing agents[3]. Leaching the columns with aerated water probably introduced inorganic acids that resulted from the presence particularly of CO_2[11] and also SO_2 in the air.

In addition to aerial deposition, the accumulation of contaminant metals in

surface soils under plant cover (Pb being retained more than Cd) is affected by processes in the rhizosphere involving soil, plant root and microbial interactions. It should be noted that the amounts of Cd and Pb removed by the plant are considerably higher than those leached out of the profile (Fig. 1). The lack of appreciable leaching of toxic heavy metals through the sub-soil increases the soil burden of such metals; this in turn raises the levels of toxic metals in the food chain.

The high levels of contaminant metals in the plant tissue reached phytotoxic concentrations. It is not however certain whether the toxicity symptoms produced in the plant were solely due to the excessive levels of Cd or Pb in the plant tissue or that the toxicity was associated with ionic imbalance involving other essential trace metals. The tissue concentration of trace metals studied showed reductions of certain essential trace metals, particularly Zn, in the shoots of radish plants in metal contaminated soils, but the levels are not below the lower critical levels of deficiency threshold values[5]. In soils contaminated with Cd, chlorosis was particularly marked in the young leaves of radish plants, a symptom resembling that of Fe deficiency, although there was no evidence of the latter from the Fe uptake data. The measured levels of contaminant metals in tissues are indicators of potential toxicity but the development of toxicity may be associated more with the localization and chemical forms of the metals at the cellular level.

Acknowledgements The work was supported by a research grant award by The Leverhulme Trust. We thank Dr. D. M. Hunt for use of atomic absorption spectrophotometers and Mr A. J. MacLellan for technical help.

References

1 Avery B W and Bascomb C L 1974 Soil Survey Laboratory Methods. Soil Survey Technical Monographs No. 6. Rothamsted Experimental Station, Harpenden, Herts, U.K.
2 Biddappa C C, Chino M and Kumazawa K 1982 Migration of heavy metals in two Japanese soils. Plant and Soil 66, 299–316.
3 Bloomfield C 1981 The translocation of metals in soils. *In* The Chemistry of Soil Processes. Eds. D J Greenland and M H B Hayes, pp 463–504. John Wiley and Sons.
4 Davies B E and Ginnever R C 1979 Trace metal contamination of soils and vegetables in Shipham, Somerset. J. Agric. Sci. Camb. 93, 753–756.
5 Davis R D and Carlton-Smith C 1980 Crops as indicators of the significance of contamination of soil by heavy metals. Technical Report TR 140. Water Research Centre, UK.
6 Draggan S and Van Voris P 1979 The role of microcosm in ecological research. Inter. J. Environ. Studies 13, 83–85.
7 Friberg L, Piscator M, Nordberg G and Kjellstrom T 1974 Cadmium in the Environment. CRC Press, Cleveland, Ohio.
8 John M K 1973 Cadmium uptake by eight foodcrops as influenced by various soil levels of cadmium. Environ. Pollut. 4, 7–15.
9 Jones L H P and Clement C R 1972 Lead uptake by plants and its significance for animals. *In* Lead in the Environment. Ed. P Hepple, pp 29–33. Applied Science Publishers, Barking, Essex.

10 Kerin Z 1975 Relationship between lead content in the soil and in the plants contaminated by industrial emissions of lead aerosols. Symp. Proc. Inter. Conference on Heavy Metals in the Environment. Vol. II, Part 2, pp 487–502. Toronto.
11 Khan D H 1959 Release of iron oxide in red-brown soil formation from the weathering of limestone. I. Effect of carbonic acid. J. Sci. Food Agric. 10, 483–486.
12 Khan D H 1980 Lead in the soil environment. Technical Report No. 21. Monitoring and Assessment Research Centre, Chelsea College, London.
13 Ministry of Agriculture, Fisheries and Food 1973 The Analysis of Agricultural Materials. Tech. Bull. 27. HMSO, London.
14 Richardson S 1980 Composition of soils and crops following treatment with sewage sludge. *In* Inorganic Pollution and Agriculture. MAFF Reference Book 326. pp 252–264. HMSO, London.
15 Ter Haar G 1972 The sources and pathways of lead in the environment. Proc. Inter. Symp. on Environmental Health Aspects of Lead. pp 59–76. Amsterdam.
16 Tyler L D and McBride M B 1982 Mobility and extractability of cadmium, copper, nickel, and zinc in organic and mineral soil columns. Soil Sci. 134, 198–205.
17 Webber J 1973 Uptake of cadmium by crops. Report of Inter – Research Council Committee on Pollution Research, Cadmium in the Environment, UK pp 13–14.
18 Zimdahl R L and Hassett J J 1977 Lead in soil. *In* Lead in the Environment. Eds. W R Boggess and B G Wixson. pp 93–98. US National Science Foundation, Washington, D.C. Report No. NSF/RA-770214.