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Cadmium uptake by lettuce varieties

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Abstract

The uptake of cadmium (Cd) by lettuce (*Lactuca sativa* L.) varieties was studied in a soil and water culture experiment. In the soil experiment, sandy soils from both a Cd-contaminated and a non-contaminated area were used, whereas the water culture experiment included three Cd levels (0, 0.03 and 0.1 mg l^{-1}). Fresh and dry yields of shoots and roots were hardly affected by Cd in both experiments. The lettuce varieties showed a close similarity in shoot Cd concentration, ranging from 8.23 to 10.72 $\mu g\ g^{-1}$ DW for the Cd-contaminated soil and from 3.96 to 8.83 $\mu g\ g^{-1}$ DW in the water culture at the highest Cd level tested. These results are contradictory to published data on large genotypic variation of Cd concentration in lettuce. Based on the narrow range in shoot (and root) Cd concentration among varieties, it is unwarranted to use lettuce as a pilot plant in comparative physiological investigations on Cd uptake and distribution.

Keywords: cadmium, *Lactuca sativa* L., soil cadmium, genotypic variation, water culture, lettuce

Introduction

There is no clear division between elements which are toxic to plants and those which have a beneficial or even essential effect. Some elements are essential at low concentrations, but are toxic at high levels. Unlike these elements, Cd is always toxic to both plants and animals. No beneficial effects of Cd on plants or animals have been reported.

Cadmium is readily taken up by plants from the soil and may accumulate to high levels before visual symtoms reveal its internal damage (Adriano, 1986). Accumulation in the edible parts of vegetables represent a direct pathway for incorporation into the human food chain. Subsequent intake by humans can cause a real danger for functioning of organs, such as kidney and liver (Bernard & Lauwerys, 1984).

One possible way to reduce the amount of Cd entering the plant food chain will be the regulation of Cd bio-availability in soils. An alternative strategy will be the use and/or development of species which do not concentrate appreciable amounts of Cd or retain absorbed Cd predominantly in the roots. Screening tests will reveal intra-specific plant response to Cd and can be used as a basis for eventual breeding

Table 1. Shoot Cd concentrations ($\mu g\ g^{-1}$ DW) of lettuce varieties exposed to Cd-contaminated media.

Number of varieties	Range ($\mu g\ g^{-1}$ DW)	Medium	Reference
9	0.4-22.6	sand-solution	John & van Laerhoven (1976)
6	14-29	soil	Crews & Davies (1985)
9	3.8-8.1	sewage sludge	Chaney & Feder (1980, ref. 1)
60	1.4-5.5	sewage sludge (municipal)	Yuran & Harrison (1986)
60	3.7-11.9	sewage sludge (industrial)	Yuran & Harrison (1986)

programmes. Genotypic variation in shoot Cd concentration has been reported to occur in several species, e.g. barley (Petterson, 1977), carrot (Harrison, 1986), cucumber (Harrison & Staub, 1986), maize (Hinesly et al., 1978) and soybean (Bogess et al., 1978). Extensive screening research including many different varieties has been carried out with lettuce (Table 1).

In order to evaluate the potential of the latter strategy, the uptake and distribution of cadmium by 16 commercially available lettuce varieties grown on an in situ Cd-contaminated sandy soil was assessed. Growth and Cd uptake were compared with that of plants grown on a sandy soil from a non-contaminated area. In another experiment we have tried to reproduce the variation in plant Cd concentration as reported by John & van Laerhoven (1976) as an initial step towards detailed physiological investigations on Cd uptake and distribution.

Materials and methods

Several lettuce varieties were screened on two different growth media, viz. soil and a quartz sand-solution culture.

Soil experiment

The in situ Cd-contaminated sandy soil was collected in the south-western part of the Netherlands (De Kempen) from an area contaminated in the past by a zinc smelter. The non-contaminated sandy soil was taken from the surroundings of Wageningen. After drying, both soils were passed through a 2 mm sieve and analysed for several characteristics (Table 2). Soil moisture content was adjusted with a full-strength Hoagland solution at 50% of the maximum water-holding capacity in the Cd-contaminated soil and to 60% in the non-contaminated soil, resulting in roughly comparable supply of water (and nutrients) to both soils. The pots were filled with 2.3 kg of moist soil, after covering the bottom with fine gravel. Another raising by 10 % of the maximum water-holding capacity with the same nutrient solution was accomplished after filling the pots. The pots were then transferred to a greenhouse in which a minimum temperature of 15 °C was maintained. As the experiment was carried out in the spring season, additional light was provided by HPL lamps.

Table 2. Characteristics of the in situ Cd-contaminated sandy soil and the sandy soil from the non-contaminated area

Constituent	-Cd	+Cd
pH-H_2O	6.6	6.0
pH-KCl	5.5	5.2
Organic C (%)	1.0	2.4
Maximum water-holding capacity (ml kg^{-1} dry soil)	210	290
Total N ($\mu g\ g^{-1}$ dry soil)	602	986
Cd (0.01 M $CaCl_2$) ($\mu g\ g^{-1}$ dry soil)	0.0	0.56

The experiment comprised 16 lettuce varieties and for each variety four replicates per soil were used. This collection can be considered as a representation of commercially available lettuce varieties in the Netherlands. The names of the varieties and the concomitant breeding station are: Jacky, Cindy and Wendy (Nickerson-Zwaan BV); Tannex and Ewex (Huizer Zaden BV); Benita and Mirena (Nunhems Zaden BV); Petra, Soraya and Reskia (Rijk Zwaan BV); Donatan and Pandorian (Pannevis Zaden BV); Clarion (Enza Zaden BV); Meikoningin, Esol and Suzan (not specified).

About ten seeds per variety were sown in each pot. After germination the soil surface was covered with fine gravel to minimize evaporation. The moisture content was maintained throughout the experiment by daily weighing each pot, followed by adjustment with demineralized water. In the course of the experiment, plant number was reduced by several harvests to arrive at one plant per pot. Starting two weeks before final harvest, every other day 50 ml of a full-strength Hoagland solution was applied to each pot to support growth, until 300 ml was added.

Plants were harvested after 65 days of growth. Leaf number, as an indication of plant development, and shoot fresh weight were determined immediately after harvest. The roots were separated from the soil by prolonged and careful washing until adhering soil particles had been removed completely. Root fresh weight was then determined after gentle drying between kleenex tissues. Shoot and root material was dried at 70 °C for at least 24 h and reweighed. Prior to analysis the samples were ground using a stainless steel grinder. Because of similar patterns observed in all harvests with respect to both growth and Cd uptake, only data of the final harvest are presented.

Water culture experiment

The water culture experiment was arranged in detail according to John & van Laerhoven (1976). Five head lettuce varieties (Imperial 847, Pennlake, Hanson, Great Lakes 659, and PI 176587), two leaf lettuce varieties (Early Prize Head and Salad Bowl) and a cos lettuce variety (White Paris) were used in our experiment. With one exception (PI 176587) these varieties were also used by John & van Laerhoven (1976).

Table 3. Composition of the basal nutrient solution

Nutrient	Source	Nutrient concentration (mg l^{-1})
K	KNO_3	500
Ca	$Ca(NO_3)_2 \cdot 4H_2O$	200
Mg	$MgSO_4 \cdot 7H_2O$	50
N	NH_4NO_3	43
P	$NH_4H_2PO_4$	25
Fe	$Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$	4
B	H_3BO_3	0.27
Mn	$MnCl_2 \cdot 4H_2O$	0.27
Zn	$ZnSO_4 \cdot 7H_2O$	0.03
Cu	$CuSO_4 \cdot 5H_2O$	0.10
Mo	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	0.01

Of each variety, four seeds were sown in a 0.4-l PVC cylinder, which was filled with a mixture of quartz sand and a basal nutrient solution and stopped with a removable bottom. The composition of the basal nutrient solution is given in Table 3. For each variety, nine cylinders were used. Plants were grown in a growth chamber at 20/15 °C day (16 h)/night (8 h), dewing point 16.5/11.9 °C and light intensity 125 W m^{-2} (HPL). After germination the surface was covered with fine gravel to minimize evaporation. After 14 days plant numbers were reduced to one per cylinder. At 28 days after sowing, the bottom was removed from each cylinder and placed on the surface of a 0.7 l cylinder filled with the same sand-solution mixture. The whole set-up was placed inside a 4.5 l polyethylene pot (Figure 1). Basal nutrient solution, containing 0, 0.03 or 0.1 mg Cd l^{-1} (from $CdCl_2$), was added one cm above the rim of the 0.7 l cylinder. Each treatment consisted of three replicates for each variety. Solutions were renewed weekly and solution levels were maintained by daily adjustment with demineralized water. Compressed air was used to aerate the nutrient solutions.

Plants were harvested after 21 days of Cd exposure. Shoot fresh weight and leaf number were determined immediately after harvest. Roots were soaked for one minute in demineralized water, carefully dried between kleenex tissues and then weighed. Shoot and root dry weight was determined after drying for at least 24 h at 70 °C. Prior to analysis, roots were ground in a mortar with pestle and shoots in a stainless steel grinder.

Chemical tissue analysis

Analytical procedures were carried out according to procedures in use at the Department of Soil Science and Plant Nutrition (Walinga et al., 1989). Dry shoot and root samples (2 g) were digested in 20 ml of a $HNO_3/HClO_4/H_2SO_4$ mixture with carborundum beads. After predigestion overnight at room temperature, the solution was moderately heated to about 170 °C for at least 40 minutes until most of the nitric acid had distilled off. The temperature was then raised stepwise until the

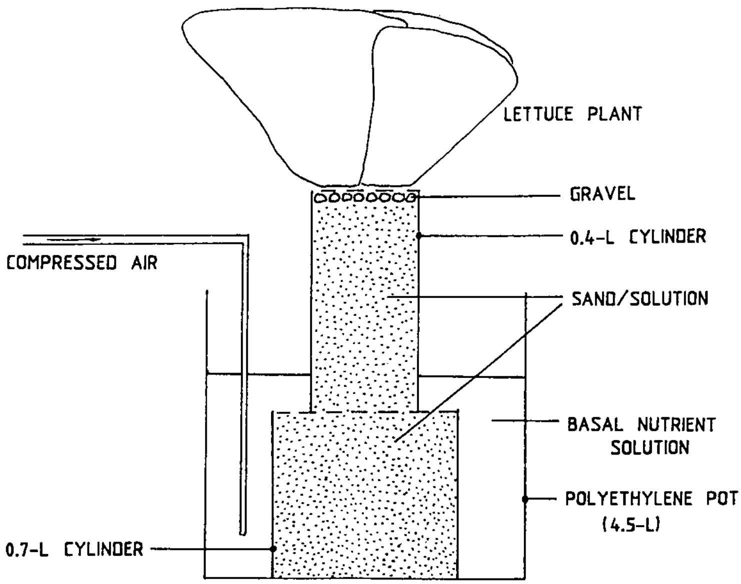

Fig. 1. Schematic section of the equipment.

$HClO_4$ attacked the remaining organic matter. After the digest had turned colourless, the digestion was continued for 1 h more. About 20 ml of demineralized water was added to the cooled solution and boiled for 10 minutes. The resulting solution was then diluted to standard volume, filtered and analysed for Cd by atomic absorption spectrometry using an air-acetylene flame and a hollow cathode lamp. The absorption was determined at 228.8 nm with Smith-Hieftje background correction (van der Lee et al., 1987)

For all other elements (N, P, K, Ca and Mg), 0.3 g dry plant material was digested in a glass tube with 2.5 ml of a H_2SO_4/salicylic acid/selenium mixture. After incubation for two hours at room temperature the mixture was heated for at least 2 h at 100 °C. After cooling, three times 2 ml 30 % H_2O_2 was successively added. The tubes were heated again at 330 °C until the digest had turned colourless. Finally, 48.3 ml of demineralized water was added to the cooled digest and thoroughly shaken. This solution was allowed to stand overnight. Nitrogen and phosphorus were determined by automatized colorimetric methods, magnesium by atomic absorption, and calcium and potassium by atomic emmission spectrometry.

Results and discussion

Soil experiment

Fresh and dry matter yields of 16 lettuce varieties grown for 65 days on an in situ Cd-contaminated sandy soil as compared with plants grown on a sandy soil from a

Table 4. Fresh and dry yields (g/plant; $n = 4$) of 16 lettuce varieties grown for 65 days on an in situ Cd-contaminated sandy soil as compared with plants grown on a sandy soil from a non-contaminated area.

Variety	Fresh shoot		Fresh root		Dry shoot		Dry root	
	−Cd	+Cd	−Cd	+Cd	−Cd	+Cd	−Cd	+Cd
Esol	50.9g-i[1]	59.8b-h	7.2h	12.5c-h	5.4a-h	5.0d-h	0.8g-i	1.1d-i
Meikoningin	57.2c-h	64.2a-e	20.0ab	20.3a	5.1d-h	4.6f-h	1.7a	1.3b-f
Suzan	58.0b-h	66.6a-d	11.1e-h	19.4ab	5.9a-e	5.3b-h	1.0f-i	1.3b-f
Mirena	49.1hi	63.6a-e	11.7d-h	16.4a-d	4.9e-h	5.3b-h	1.0f-i	1.3b-f
Cindy	49.8g-i	60.5a-g	7.4h	15.6a-e	5.1d-h	5.0d-h	0.7i	1.1d-i
Benita	49.8g-i	68.6ab	11.0e-h	18.5ab	5.6a-g	6.3a-c	1.2c-h	1.6a-c
Wendy	50.4g-i	57.3c-h	9.5f-h	14.7b-f	5.3b-h	4.6g-h	0.9g-i	1.0e-i
Ewex	50.5g-i	59.4b-h	11.7d-h	15.5a-e	5.8a-f	5.4a-h	1.1d-i	1.3b-g
Tannex	50.3g-i	71.0a	11.0e-h	19.6ab	5.6a-g	6.0a-d	1.1d-i	1.4a-e
Jacky	54.2e-i	64.3a-e	8.2gh	11.8d-h	4.9e-h	4.7e-h	0.7i	0.9g-i
Clarion	64.0a-e	68.2a-c	18.8ab	17.5a-c	6.5a	5.0d-h	1.5a-d	1.2c-h
Donatan	45.0i	67.5a-c	7.7h	13.2c-g	4.4h	4.9d-h	0.8h-i	1.0e-i
Pandorian	52.1f-i	62.4a-f	16.4a-d	15.8a-e	5.3b-h	4.7f-h	1.3b-f	1.2c-h
Petra	50.6g-i	49.0hi	15.9a-e	11.8d-h	5.6a-h	4.6g-h	1.3b-f	0.9g-i
Soraya	55.8d-i	59.2b-h	19.4ab	17.7a-c	6.4ab	5.2c-h	1.6ab	1.2b-h
Reskia	54.7e-i	66.6a-d	19.8ab	19.1ab	4.9d-h	4.9d-h	1.4a-e	1.2b-h
All varieties mean	52.7A	63.0B	12.9A	16.2B	5.4A	5.1B	1.1A	1.2B

[1] Within blocks (fresh shoot, fresh root, dry shoot, dry root), values followed by the same letter are not significantly different at the 5 % level according to Duncan's New Multiple Range Test (DNMRT).

non-contaminated area, are given in Table 4. Although all plants were fully developed with an average leaf number of 34, fresh yields were far less than crops commonly sold in the market. Fresh and dry weight of shoots and roots of plants grown on the same soil showed little variation. The tendency towards a higher fresh yield by a lower dry yield of plants grown on the Cd-contaminated soil as compared to plants grown on the non-contaminated soil may be attributed to different soil characteristics.

In Table 5, Cd concentration in shoots and roots and the shoot/root Cd distribution ratio of the 16 varieties are presented. As expected the plants grown on the contaminated soil had a much higher shoot and root Cd concentration than those grown on the control soil. Shoot Cd concentration ranged from 0.52 to 1.20 $\mu g\ g^{-1}$ DW for the control plants and from 8.23 to 10.72 $\mu g\ g^{-1}$ DW for the Cd-treated plants. Expressed on the basis of Cd amounts per organ, there was a huge difference in shoot/root Cd distribution in plants from both soils. Among varieties grown on the same soil the variation in the distribution ratio was small. The mean Cd distribution ratio for all varieties tested may provide a rough indication of the relative Cd translocation in lettuce plants grown on both soils. In the control plants about 95 % of the absorbed Cd was transported to the shoot, whereas in the Cd-treated plants this was about 78 %.

Table 5. Cadmium concentration ($\mu g\ g^{-1}$ DW; $n = 4$) in shoots and roots and Cd distribution ratio of 16 lettuce varieties grown for 65 days on an in situ Cd-contaminated sandy soil as compared with plants grown on a sandy soil from a non-contaminated area.

Variety	Shoot		Root		Distribution ratio[1]	
	–Cd	+Cd	–Cd	+Cd	–Cd	+Cd
Esol	0.78i[2]	8.83f-h	0.41f	9.45de	12.18	4.29
Meikoningin	0.93i	9.01e-h	0.47f	15.03ab	5.77	2.12
Suzan	0.79i	9.52c-f	0.46f	13.57a-c	10.58	1.39
Mirena	0.83i	9.94a-d	0.35f	7.70e	11.91	5.16
Cindy	0.73i	9.68c-e	0.45f	14.16a-c	11.31	3.13
Benita	0.56i	9.40c-f	0.05f	6.42e	54.17	5.88
Wendy	0.59i	9.39c-f	0.25f	14.10a-c	14.16	2.97
Ewex	0.64i	9.14d-g	0.30f	13.57a-c	11.46	2.91
Tannex	0.55i	9.00e-h	–[3]	12.22b-d		3.13
Jacky	0.63i	8.17f-h	0.25f	11.51b-d	16.58	4.08
Clarion	0.87i	10.67ab	0.15f	13.91a-c	25.19	3.30
Donatan	0.87i	10.10a-c	0.25f	11.18cd	19.56	4.31
Pandorian	0.85i	10.47ab	0.10f	14.72a-c	33.30	2.89
Petra	0.53i	8.23h	0.10f	12.24b-d	22.98	3.51
Soraya	0.52i	8.53g-h	0.10f	11.62b-d	20.74	3.19
Reskia	1.20i	10.72a	0.20f	16.68a	21.04	2.63
All varieties mean	0.74A	9.45B	0.24A	12.38B	19.39	3.43

[1] Cadmium distribution ratio: shoot/root Cd amount.
[2] Within blocks (shoot,root), values followed by the same letter are not significantly different at the 5 % level (DNMRT).
[3] Not detectable.

Water culture experiment

Fresh and dry shoot yields and dry shoot/root ratios of 8 lettuce varieties grown on a sand/solution culture at increasing Cd concentrations are presented in Table 6. Fresh yields of the different varieties were higher than in the soil experiment, but still lower than marketable material. Within each treatment, fresh weight among varieties was comparable, whereas increased external Cd concentrations had no effect on fresh yields within each variety. The same pattern was found for shoot dry yields (Table 6). Percentage dry matter in shoot material was thus maintained between narrow limits (7.7 to 8.1 %) irrespective of the level of Cd supply. Root dry weights (data not shown) showed the same picture as shoot dry weights, resulting in roughly the same shoot/root ratio for all treatments (Table 6). Consequently, growth reduction or stimulation after Cd exposure as found by others (Page et al., 1972; Turner, 1973) was not confirmed in the present experiment.

Shoot and root Cd concentrations in the 8 lettuce varieties are given in Table 7. Both organs showed a clear increase in Cd concentration as a response to a higher Cd level in solution. In all treatments the Cd concentration in both shoots and roots differed slightly among varieties. This difference can be visualized as the ratio be-

Table 6. Fresh and dry yields (g/plant; n = 3) and dry shoot/root ratios of 8 lettuce varieties grown for 42 days on a sand/solution culture at 3 Cd concentrations (mg l^{-1}) in solution. Cadmium was applied 21 days before harvest.

Variety	Shoot fresh yield			Shoot dry yield			Dry shoot/root ratio		
	solution Cd conc.			solution Cd conc.			solution Cd conc.		
	0.0	0.03	0.1	0.0	0.03	0.1	0.0	0.03	0.1
Imperial 847	77.5b-e[1]	92.8a-c	86.7a-d	6.0b-h	7.3ab	6.8a-d	1.7	2.9	3.2
Pennlake	76.5b-f	95.2a-c	75.6b-f	6.4a-g	7.3ab	6.7a-e	3.6	3.5	2.7
Hanson	64.2d-g	63.1e-g	53.8f-g	4.7f-h	4.6g-h	4.0h	3.5	3.5	3.2
Great Lakes 659	65.1d-g	61.5e-g	74.7c-f	5.8b-h	5.0d-h	6.4a-g	3.3	3.1	4.4
PI 176587	95.3a-c	98.7ab	99.8a	7.6ab	7.7a	8.0a	4.0	5.5	5.1
Early Prize Head	66.4c-g	64.3d-g	54.3f-g	4.9e-h	5.3d-h	4.1h	2.8	3.2	2.9
Salad Bowl	61.7e-g	62.9e-g	79.3a-e	5.5.c-h	5.3d-h	6.4a-g	2.7	2.7	3.2
White Paris cos	90.0a-c	79.2a-e	78.8a-e	7.4ab	6.3a-g	6.6a-f	4.1	3.3	3.5
All varieties mean	71.4A	77.2A	75.4A	5.8A	6.1A	6.1A	3.1	3.3	3.3

[1] Within blocks (shoot fresh yield, shoot dry yield), values followed by the same letter are not significantly different at the 5 % level (DNMRT).

Table 7. Cadmium concentration ($\mu g\ g^{-1}$ DW; n = 3) in shoots and roots of 8 lettuce varieties grown for 42 days on a sand/solution culture at 3 Cd concentrations (mg l^{-1}) in solution. Cadmium was applied 21 days before harvest.

Variety	Shoot Cd			Root Cd		
	solution Cd conc.			solution Cd conc.		
	0.0	0.03	0.1	0.0	0.03	0.1
Imperial 847	0.10g[1]	2.13fg	3.96d-f	0.29fg	3.01d-g	6.71cd
Pennlake	0.07g	2.91ef	4.62c-e	0.10g	3.90d-f	6.45cd
Hanson	0.23g	2.54ef	5.30b-d	0.14g	5.26d	11.28ab
Great Lakes 659	0.09g	1.97fg	4.62c-e	0.97e-g	4.95d	11.31ab
PI 176587	0.03g	2.53ef	6.06bc	0.15g	3.92d-f	10.54ab
Early Prize Head	0.08g	2.78ef	8.38a	0.11g	4.48de	13.17a
Salad Bowl	0.14g	1.96fg	6.14bc	0.25fg	3.31d-g	9.38bc
White Paris cos	0.02g	2.62ef	7.12ab	0.14g	3.53d-g	9.41bc
All varieties mean	0.10A	2.43B	5.78C	0.27A	4.05B	9.78C

[1] Within blocks (shoot Cd, root Cd), values followed by the same letter are not significantly different at the 5 % level (DNMRT).

tween the highest and lowest Cd concentration in any particular variety. This ratio was for both shoot and root about 1.6 at the 0.03 mg l^{-1} and 2.0 at the 0.1 mg l^{-1} Cd level. This is in the same order as found in our soil experiment (1.3 and 2.2 for shoot and root, respectively) and also in accordance with values reported by other authors (Crews & Davies, 1985; Chaney & Feder, in Anonymous, 1980). The varieties with the highest and lowest Cd concentration in any plant part are different within treatments, although not always significant. According to Yuran & Harrison (1986), such relative concentration differences also occur in year-to-year experiments. This is surprising in view of the genetic background in Cd concentration by lettuce (Thomas & Harrison, 1989). In conclusion, it is unwarranted to use lettuce in physiological research concerning genotypic variation, because of the narrow range in Cd uptake among varieties and the inconsistency of this relative concentration in time.

As already mentioned, the ratio between highest and lowest shoot Cd concentration in plants grown at the 0.1 mg l^{-1} Cd level is about 2 (3.96 to 8.38 $\mu g\ g^{-1}$ DW). This is much lower than the 66.5 (0.4 to 26.6 $\mu g\ g^{-1}$ DW that was found by John & van Laerhoven (1976). This discrepancy is noteworthy in view of the identical experimental conditions and exactly the same setup. Moreover, John & van Laerhoven (1976) have reported that in several varieties a high shoot Cd concentration after three weeks of Cd (0.1 mg l^{-1}) exposure (viz. 2.5, 4.6 or 22.6 $\mu g\ g^{-1}$ DW) had decreased to a background level (0.4 $\mu g\ g^{-1}$ DW) in the subsequent two weeks, although the plants were grown at the same Cd concentration. Mere dilution effects are far from sufficient to explain such a drastic decrease. Our root Cd data at the 0.1 mg l^{-1} Cd level seem also not in accordance with John & van Laerhoven (1976). After three weeks of exposure to Cd, we found considerable Cd concentrations in all lettuce roots. The absence of Cd in roots after five weeks of Cd (0.1 mg l^{-1}) exposure, as reported by John & van Laerhoven (1976), is very unlikely and gives rise to major controversy. Textbook material based on these data (Marschner, 1983) should therefore at least be re-evaluated.

The shoot/root Cd concentration ratios and shoot/root Cd distribution ratios of the 8 lettuce varieties are given in Table 8. The shoot Cd concentration in each variety was lower than the root Cd concentration, as shown by Cd concentration ratios being <1. The order of the Cd distribution ratios is in agreement with those presented in the soil experiment. When ratios are expressed in terms of distribution over plant organs, it is clearly revealed that each variety translocated the absorbed Cd predominantly to the shoot (Table 8). Similar distribution patterns have been reported by others (John, 1973; Jarvis et al., 1976; Hatch et al., 1988).

Table 9 gives an overview of the shoot and root concentrations of N, P, K, Ca and Mg in all varieties at the three Cd levels in solution. Cadmium did not affect the concentrations of these nutrients in both plant organs. It may thus be concluded that the uptake mechanisms for these nutrients are not affected by relatively high Cd concentrations in solution.

Table 8. Shoot/root Cd concentration and distribution ratios of 8 lettuce varieties grown for 42 days on a sand/solution culture at 3 Cd concentrations (mg l^{-1}) in solution. Cadmium was applied 21 days before harvest.

Variety	Concentration ratio[1]			Distribution ratio[2]		
	solution Cd conc.			solution Cd conc.		
	0.0	0.03	0.1	0.0	0.03	0.1
Imperial 847	0.34	0.71	0.59	0.60	2.06	1.86
Pennlake	0.70	0.75	0.72	2.52	2.58	1.96
Hanson	1.64	0.48	0.47	5.76	1.68	1.51
Great Lakes 659	0.09	0.40	0.41	0.28	1.43	1.67
PI 176587	0.20	0.65	0.57	0.69	2.29	2.12
Early Prize Head	0.73	0.62	0.64	2.01	1.97	1.81
Salad Bowl	0.56	0.59	0.65	1.53	1.60	2.07
White Paris cos	0.14	0.74	0.76	0.59	2.44	2.67
All varieties mean	0.55	0.62	0.60	1.75	2.01	1.96

[1] Cadmium concentration ratio: shoot/root Cd concentration.
[2] Cadmium distribution ratio: shoot/root Cd amount.

Table 9. Mean concentration (mmol kg^{-1} DW) and standard deviation (in brackets) of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) in shoots and roots of all varieties grown for 42 days on a sand/solution culture at 3 Cd concentrations in solution. Cadmium was applied 21 days before harvest.

Treatment (mg Cd l^{-1})	Nutrient	Nutrient concentration (mmol kg^{-1} DW)	
		Shoot	Root
0.00	N	2506 (179)	1945 (225)
0.03		2482 (171)	1927 (186)
0.10		2430 (140)	1904 (229)
0.00	P	105 (14)	93 (12)
0.03		104 (10)	118 (29)
0.10		107 (15)	114 (42)
0.00	K	1605 (105)	1431 (175)
0.03		1574 (137)	1436 (180)
0.10		1543 (94)	1475 (237)
0.00	Ca	158 (22)	113 (25)
0.03		162 (26)	92 (12)
0.10		162 (27)	95 (16)
0.00	Mg	72 (7)	72 (11)
0.03		73 (8)	72 (10)
0.10		73 (5)	75 (13)

Conclusions

Cadmium hardly influenced fresh and dry yields of shoots and roots of lettuce grown on Cd-contaminated soil or water culture. The Cd concentration in both plant organs increased considerably in all varieties tested as a consequence of increased level of external Cd supply. In both soil and water culture experiments, lettuce translocated the absorbed Cd predominantly to the shoot.

A narrow range in genotypic variation among all varieties was observed in both experiments. The huge variation in shoot Cd concentration at 0.1 mg Cd l^{-1} in solution as reported by John & van Laerhoven (1976) is contradictory to our results and should for several reasons be re-evaluated.

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