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Original Research

Cadmium and Lead Accumulation and Distribution in the Organs of Nine Crops: Implications for Phytoremediation

A. Sękara*, M. Poniedziałek, J. Ciura, E. Jędrszczyk

Agricultural Academy, Department of Vegetable Crops and Horticultural Economics, 29 Listopada 54, 31-425 Kraków, Poland

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Abstract

Field experiments were carried out from 1999 to 2001 with nine crops (red beet, field pumpkin, chicory, common bean, barley, white cabbage, maize, alfalfa and common parsnip) to determine the cadmium and lead accumulation and distribution in the plants' organs. Based on the obtained results, species suited for phytoremediation were selected. Within the red beet, field pumpkin, chicory, common bean, white cabbage and parsnip the maximum Cd and Pb content was found in leaves. The red beet was characterized by the highest cadmium concentration ratio (shoots/roots). The red beet and common parsnip were characterized by the highest lead concentration ratios (shoots/roots). The phytoremediation efficiency of the investigated crops depended on the biomass production and the possibility of metal accumulation in harvestable organs.

Keywords: heavy metals, phytoextraction, vegetables, barley, alfalfa

Introduction

Phytoextraction is one of the phytoremediation strategies based on the use of green plants to remove pollutants (i. e. heavy metals) from soil. Its efficiency depends on the chemical property of the element removed and its uptake, translocation and accumulation by plants in harvestable organs. According to Ebbs et al. [1], plant species suitable for phytoremediation may not be limited to hyperaccumulators (plants genetically and physiologically capable of the accumulation of a great amount of toxic metals). The authors cited have suggested that a greater shoot biomass can more than compensate for lower shoot metal concentration. The total amount of metal removed from soil is a result of the metal content in the harvestable tissues and of the plant biomass per area unit. Some experiments were conduced to select crop plants suitable for phytoremediation [2, 3]. The obtained results allowed the selection of some species particularly prone to extract heavy metals from soil, i.e. sunflower, maize, mustard, barley, and pumpkin. In combination with soil amendment some agronomic crops might be used for the clean-up of contaminated soil.

Cadmium is a mobile element, easily absorbed by roots and transported to shoots. It is uniformly distributed in plant organs while in the case of the poorly mobile elements (i. e. lead) their level decreases in the following order: roots > shoots > leaves > fruits > seeds. This distribution is due to the mobilization of the protective mechanisms of plants, which inhibits the transport to further tissues and organs. Straczynski [4] recommended hemp and flax for cadmium phytoextraction. Some works have indicated Indian mustard (*Brassica juncea*) as an effective species in lead remediation because of its great biomass production, but it accumulated 95% of lead in its roots [5]. Low metal transport from

*Corresponding author; e-mail: agnieszka.sekara@vp.pl

roots to shoots is a limiting factor for the use of many crops in phytoextraction. This is the reason why remediation efficiency should be tested between high biomass species with harvestable storage roots.

Cadmium and lead are the most dangerous metals for human health. In Poland, soil pollution with the elements mentioned is only a local problem, i.e. near roads and in industrial and urban areas. Poniedzialek et al. [6] found differences between crops in the level of heavy metal accumulation in particular organs. They mention that metals' absorption and transport can be modified by many factors, i.e. cultivar, timing of production, and locality. It is necessary to test the phytoremediation efficiency of different crops in environmental conditions of Poland.

According to Vassilev et al. [3] there are two general approaches for the further development of metal phytoextraction: genetic transformations to improve plant factor and agronomy – related optimisations in many different aspects, i.e. screening for high metal uptake and tolerance. To overcome the main biological bottlenecks limiting successful phytoextraction, a good knowledge of metal uptake, plant defence network against metal as well as some possibilities to reduce chronic metal toxicity is fundamental.

The aim of investigations was do determine cadmium and lead accumulation and distribution in the organs of nine crops. The results obtained will allow for the selection of species for further investigations determining agronomy-based optimizations as a tool for the improvement of metal phytoextraction.

Experimental Procedures

A field experiment was conduced at the Agricultural Academy Research Station near Kraków (Poland) between 1999 and 2001, on soil classified as *Eutric Cambisols*, with loess as the basement complex, pH_{KCl} 4.8, 1.2% organic carbon. Soil contained 0.58 mg kg^{-1} of exchangeable Cd (1.81 mg kg^{-1} of total Cd) and 8.21 mg kg^{-1} of exchangeable Pb (22.00 mg kg^{-1} of total Pb). To determine exchangeable Cd and Pb content, soil samples (10 g) were treated with 100 cm^3 0.01 M $CaCl_2$ and shaken for 2 hours. After filtration of the solids, Cd and Pb were obtained by AAS method, using Varian-SpectrAA 20 and air/acetylene flame under standard operating conditions. Total Cd and Pb content was determined by AAS method, after wet-mineralization of soil samples (1.000 g) in a microwave oven MDS 2000 CEM, in the presence of 30% HNO_3. pH was measured using a potentiometric method in 1 mol·dm^{-3} KCl solution. Organic carbon content was determined using Tiurin's method, based on the oxidizing of C to CO_2, using potassium dichromate as an oxidant [7].

The objects of investigations were nine crops selected according to their different taxonomy position and information cited in literature about their remediation efficiency: red beet (*Beta vulgaris var. cicla* L.) — 'Wodan F_1', field pumpkin (*Cucurbita pepo* L. *convar. giromontiana* Greb.) — 'Astra F_1', chicory (*Cichorium intybus var. foliosum* Hegi) — 'Rubello F_1', common bean (*Phaseolus vulgaris* L.) — 'Tara', barley (*Hordeum vulgare* L.) — 'Stat', white cabbage (*Brassica oleracea var. capitata* L.) — 'Krautman F_1', maize (*Zea mays* L. *convar. saccharata* Koern.) — 'Trophy F_1', alfalfa (*Medicago sativa* L.) — 'Vela', common parsnip (*Pastinaca sativa* L.) — 'Półdługi Biały'.

Crops were grown under standard agronomic conditions on experimental plots (9 m^2) in four replications, using the random blocks method. Crops were harvested at the stage of harvest maturity. The fresh weight and the heavy metals content were determined in the morphological organs of the investigated crops: red beet — roots and leaves; chicory — roots, rosette leaves, and head; field pumpkin — roots, stem, leaves, and fruits; common bean — roots, stem, leaves, and pods; barley — roots, straw, and grain; white cabbage — roots, stem, rosette leaves, and head; maize — roots, stem, leaves, husks, shank, and grain; alfalfa — roots and shoots; and common parsnip — roots and leaves. Plant samples were rinsed in demineralized water, dried at 105°C, and ground using a colloidal grinder (Retsch). Analyses of Cd and Pb content were carried out using AAS method, following prior dry-mineralization of 5.000 g plant samples at 500°C, and dissolution of ash at 20% HNO_3 [7]. The mean concentrations of heavy metals in aerial parts of investigated plants were calculated according to the formula: mean conc. = sum of (metal conc. in each plant part x fraction each part contributes to total shoot biomass).

The results were statistically evaluated using analyses of variance, significant differences between means were calculated using the Student t test at p=0.05. Coefficients of simple correlation were calculated between the amount of metals in particular plant organs.

Results and Discussion

The possibility of using crops as phytoremediants depends on the accumulation and distribution of metals among their morphological organs. Plants characterized by high biomass production and intensive heavy metals accumulation in shoots can be used as phytoremediants [1]. According to Vassiliev et al. [3] more detailed information about the biomass crops' ability to withstand metal as well as to accumulate it in the shoots is needed.

Red beet accumulated high amounts of cadmium and lead in leaves (2.65 and 8.71 mg kg^{-1} d. wt, respectively). The roots contained 2.8 times less cadmium and 3.6 less lead than the leaves (Figs. 1, 2). A significant correlation coefficient was found between the amount of cadmium in the leaves and roots of red beet (r = 0.900) (Fig. 3). This confirmed the thesis that plants accumulate cadmium and distribute it between tissues proportionally to its level in the soil. Such a correlation was not observed in the case of lead, which is almost immobile. Gambus [9] compared the

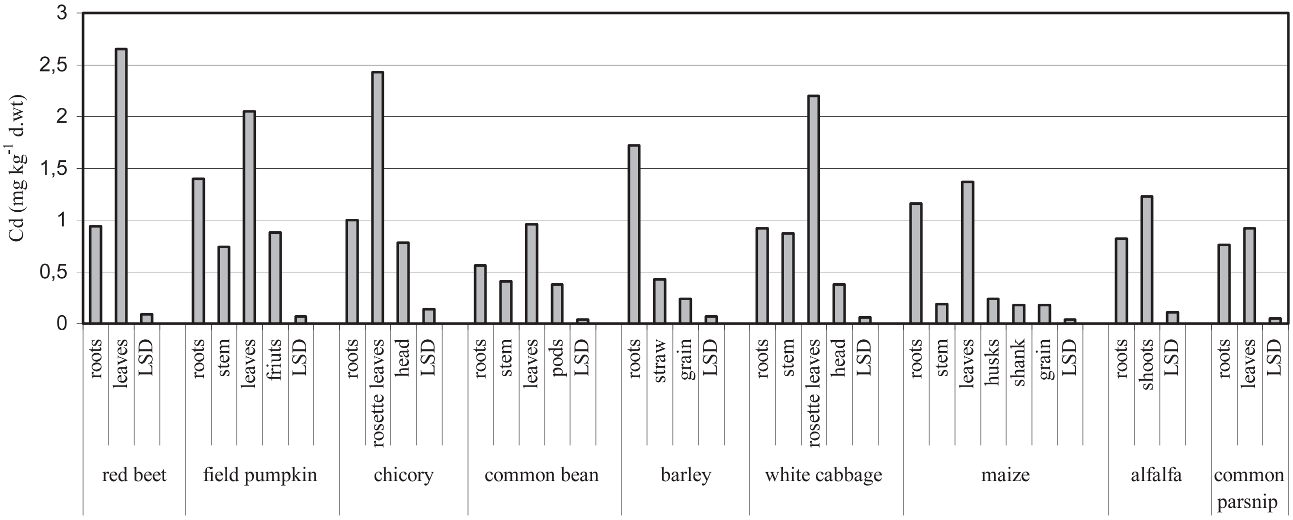

Fig. 1. Cadmium distribution among organs of investigated crops (mg kg^{-1} d. wt).

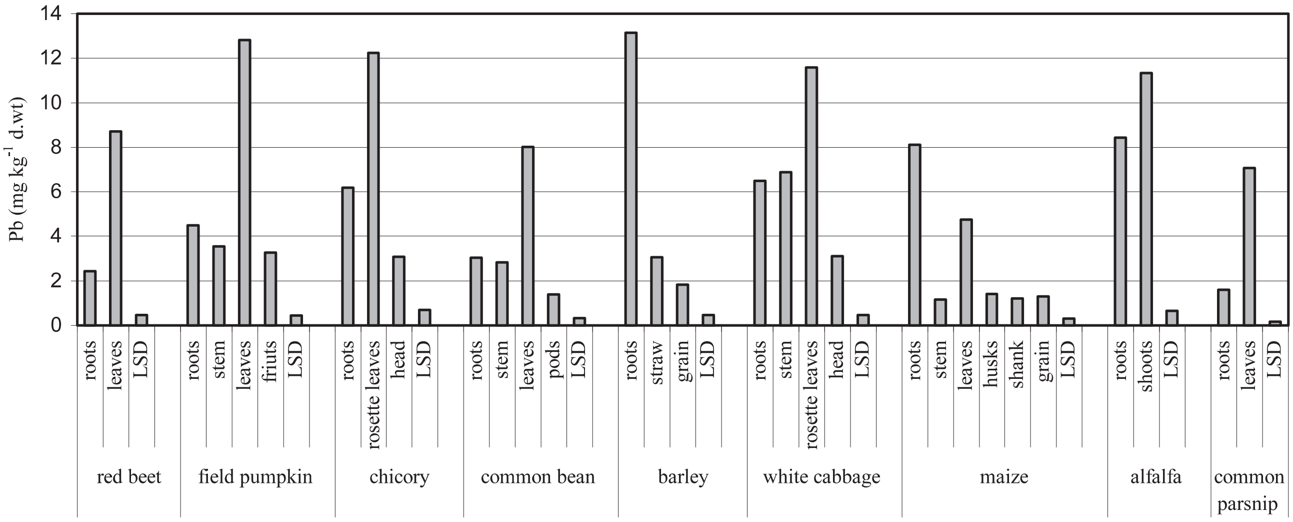

Fig. 2. Lead distribution among organs of investigated crops (mg kg^{-1} d. wt).

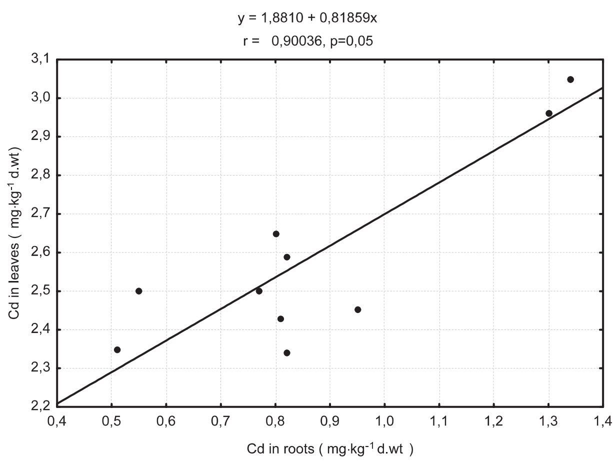

Fig. 3. Relationship among the Cd concentration in roots and leaves of the red beet.

capacity of seven species of vegetables to take up heavy metals. He found a higher accumulation of Cd in the leaves of red beet in comparison with the storage roots, while less mobile lead was accumulated especially in the roots.

Field pumpkins accumulated most of the cadmium and lead in the leaves (2.05 and 12.81 mg kg^{-1} d. wt, respectively). The least amounts of both elements were found in the stem and fruits (Figs. 1, 2). Aboveground harvestable organs contained a mean of 1.37 mg kg^{-1} d. wt of cadmium and 7.55 mg kg^{-1} d. wt of lead — half as much as the roots (Table 1). The amount of cadmium in the roots of pumpkin was proportional to the stem (r = 0.969) and leaves (r = 0.908) (Fig. 4). Mills [10] investigated the mobility and distribution of lead in cucumber. He found that the distribution of Pb is a passive process and that the level of metal decreased towards the shoot tip of the investigated species.

The rosette leaves of chicory stood out with their high accumulation of both cadmium and lead (2.43 and 12.25

Table 1. Cadmium and lead accumulation in roots and shoots of investigated crops (mg kg^{-1} d. wt).

	Red beet	Field pumpkin	Chicory	Common bean	Barley	White cabbage	Maize	Alfalfa	Common parsnip
	Cadmium								
Roots	0.94	1.40	1.00	0.56	1.72	0.92	1.16	0.82	0.76
Shoots	2.65	1.37	1.43	0.51	0.38	0.75	0.39	1.23	0.92
Concentration ratios (shoots/roots)	2.81	0.97	1.43	0.91	0.22	0.81	0.33	1.50	1.21
$LSD_{0.05}$ for species 0.31 $LSD_{0.05}$ for organs n.s. $LSD_{0.05}$ for interaction 0.44									
	Lead								
Roots	2.44	4.49	6.20	3.03	13.14	6.49	8.12	8.44	1.61
Shoots	8.71	7.55	6.73	3.79	2.81	4.99	1.75	11.33	7.06
Concentration ratios (shoots/roots)	3.56	1.68	1.08	1.25	0.21	0.76	0.21	1.34	4.38
$LSD_{0.05}$ for species 1.81 $LSD_{0.05}$ for organs n.s. $LSD_{0.05}$ for interaction 2.56									

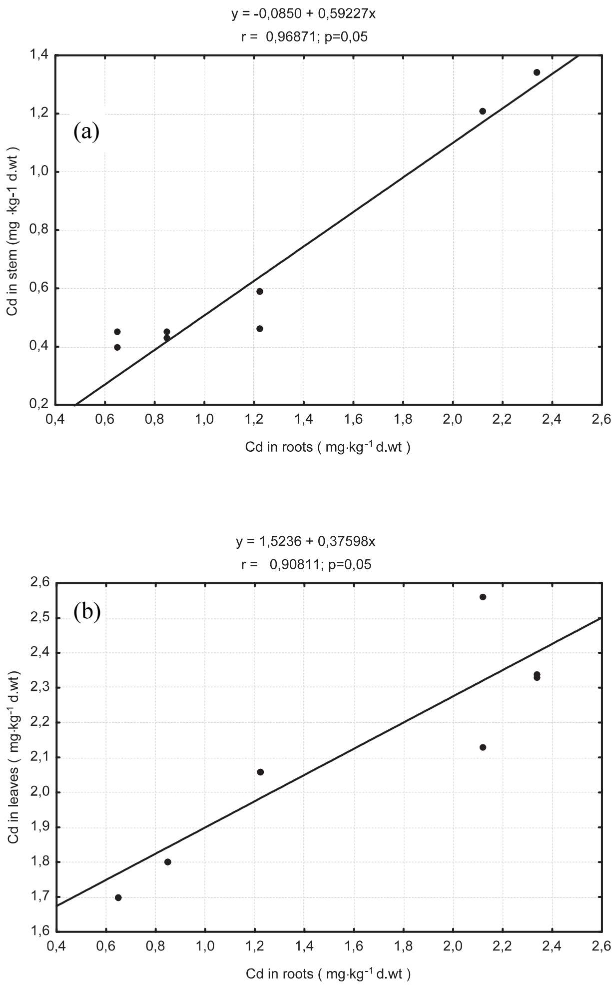

Fig. 4. Relationship among the Cd concentration in roots and stem (a), roots and leaves (b) of the field pumpkin.

mg kg^{-1} d. wt). The levels of these elements in the leaves formed in the head were three times lower (Figs. 1, 2).

The common bean belonged to those species with the lowest heavy metals accumulation, especially in the pods. The organs that were the most contaminated with cadmium and lead were the leaves (0.96 mg kg^{-1} d. wt of Cd and 8.01 mg kg^{-1} d. wt of Pb) (Figs. 1, 2). Significant correlation coefficients were found between the amount of cadmium in the roots and the aboveground organs: leaves (r = 0.811), stem (r = 0.968) and pods (0.817) (Fig. 5). The high leaf contamination had no influence on the Cd and Pb levels in pods. According to results obtained by Dollard [11]; there is no movement of foliar applied lead into the pods and seeds of the French bean. Kuboi et al. [12] proved that plants of the *Leguminosae* family are characterized by low trace element absorption. Similar results were obtained by Tlustos et al. [13]. They found the lowest Cd concentration in the pods and seeds of the green bean (in comparison to spinach, radish, carrot and oat) in a pot experiment on three different soils.

Barley accumulated high amounts of both cadmium and lead in the roots (1.72 and 13.14 mg kg^{-1} d. wt respectively). It is about four times more than was found in the straw (0.43 and 3.06 mg kg^{-1} d. wt of Cd and Pb) and seven times more than in the grain (0.24 and 1.84 mg kg^{-1} d. wt of Cd and Pb) (Figs. 1, 2). Significant correlations were found between the levels of cadmium and lead in the roots and in the straw of barley (r = 0.804 and r = 0.995 respectively) (Fig. 6). Fecenko et al. [14] recorded the highest cadmium accumulation in the barley roots, lower in straw and the lowest in grain in an experiment determining cadmium uptake and localization in spring barley. A significantly higher concentration of cadmium and lead in barley roots than in straw was observed by Tlustos et al. [15] in a pot experiment with soil that con-

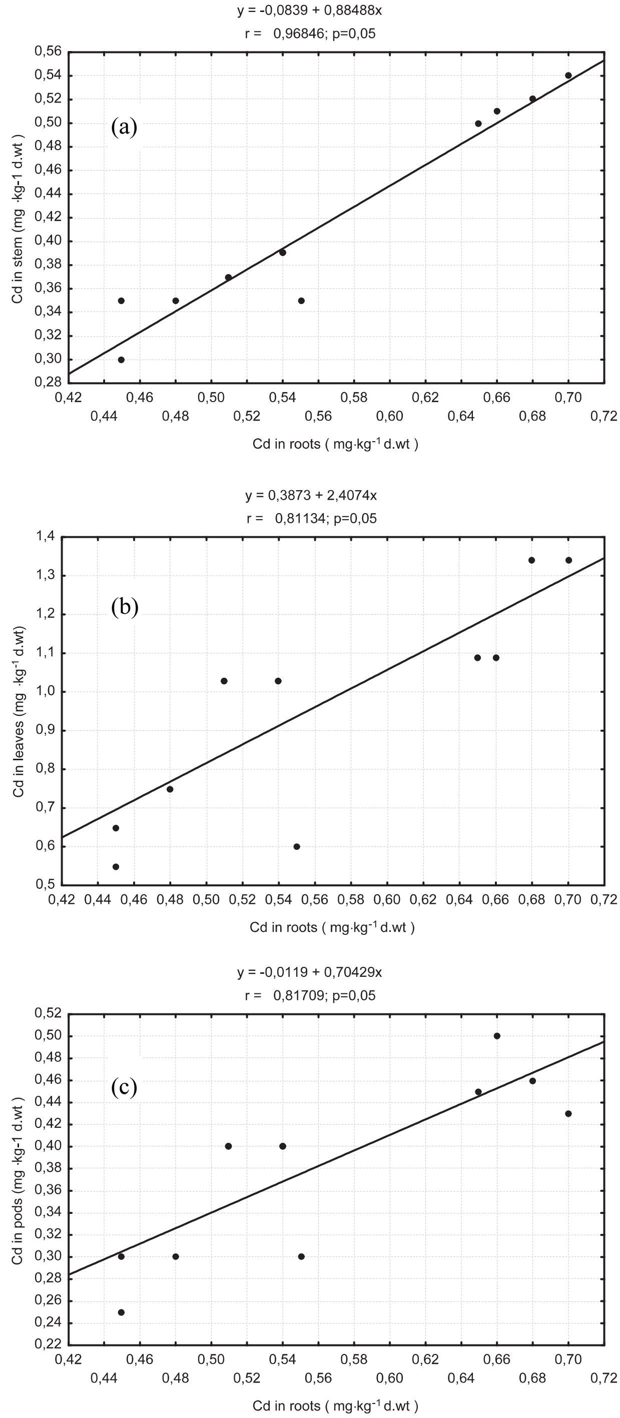

Fig. 5. Relationships among Cd concentrations in roots and stem (a), roots and leaves (b), roots and pods (c) of the common bean.

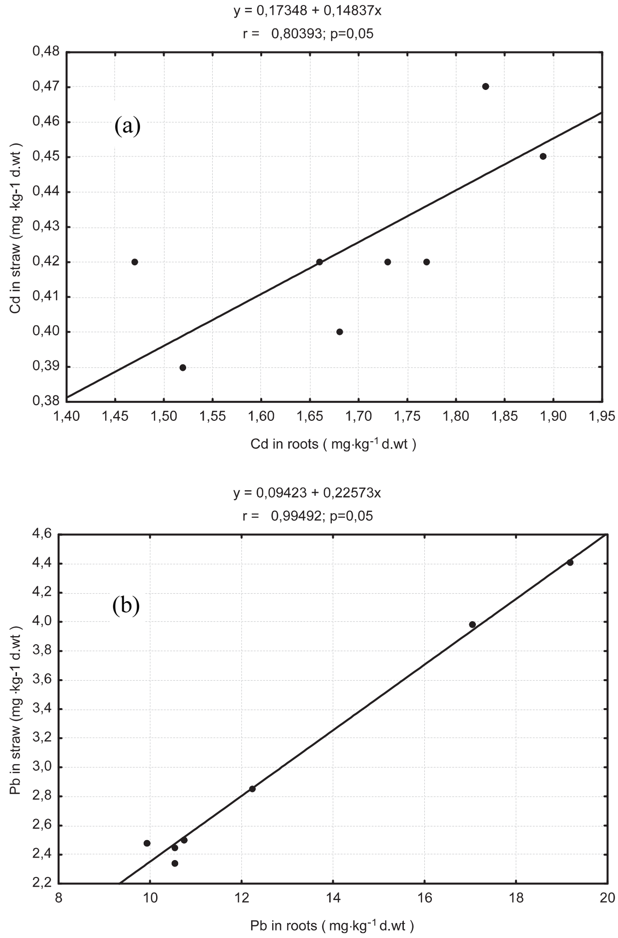

Fig. 6. Relationships among Cd (a) and Pb (b) concentrations in roots and straw of the barley.

tained 0.73 mg kg^{-1} of total Cd and 43.20 mg kg^{-1} of total Pb. Herren and Feller [16] explained the mechanism of phloem and xylem transport of Cd in wheat shoots. They found that a minor quantity of cadmium was transported to the grain via the phloem in control shoots, while a high percentage of this element was retained in the peduncle. Cadmium content in the grain increased in response to the increased cadmium concentration in the feeding solution (0.1 to 10 μM).

In the case of white cabbage, the most cadmium and lead contaminated organs were the leaves of the rosette (2.20 mg kg^{-1} d. wt of Cd and 11.60 mg kg^{-1} d. wt of Pb). The leaves of the head contained only 0.38 mg kg^{-1} d. wt of cadmium and 3.10 mg kg^{-1} d. wt of lead (Figs. 1, 2). Baker et al. [17] compared to the remediation efficiency of six species from the *Brassicaceae* family (two crops and four wild growing hyperaccumulators). In this experiment white cabbage accumulated, in aboveground tissues, amounts of lead and cadmium comparable with those obtained in the present work. The authors suggest that crops are much less effective in remediation than hyperaccumulators in spite of high biomass production.

Maize accumulated the least cadmium in the stem, shank and grain (0.18-0.19 mg kg^{-1} d. wt). Similar results were obtained in the case of lead: no significant differences between steam, husks, shank and grain were found (1.16-1.41 mg kg^{-1} d. wt) and the lowest accumulation in comparison to other organs (Figs. 1, 2). Brennan and Shelley [18] gained insights on the corn mechanisms that control the uptake and translocation of lead from the soil. The results of the model simulations suggest that key plant parameters are the precipitation of lead as Pb-phosphate in roots (only Pb not precipitated is available for translocation to the shoots) and effective root mass. This has explained the highest level

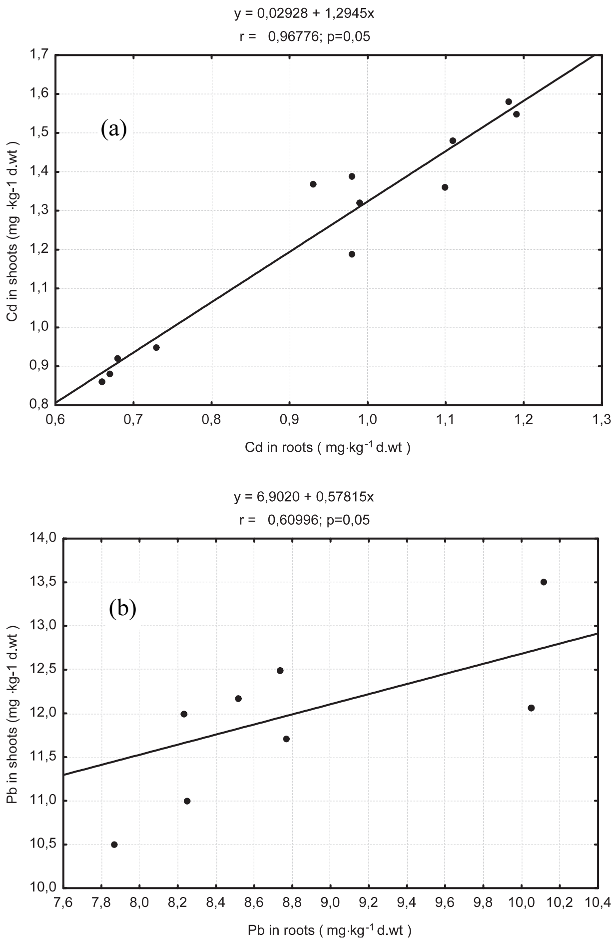

Fig. 7. Relationship among the Cd (a) and Pb (b) concentration in roots and shoots of the alfalfa.

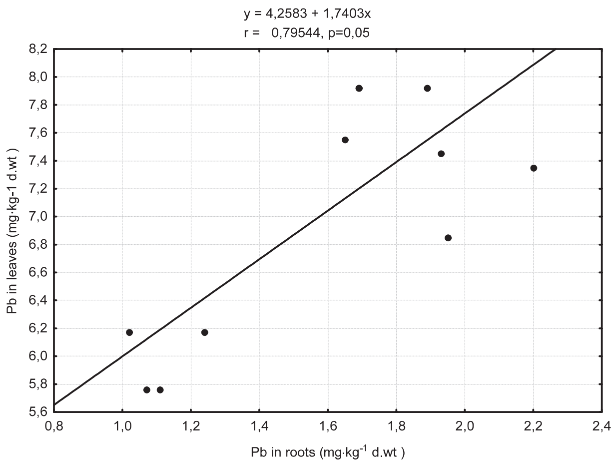

Fig. 8. Relationship among the Pb concentration in roots and leaves of the common parsnip.

of lead in corn roots from the present experiment. Huang and Cunningham [2] reported that of the eleven plant species/cultivars tested, corn accumulated the highest shoot Pb concentration in both solution and soil culture. The shoot lead concentration of corn was significantly higher than that of *Thlaspi rotundifolium*, a reported Pb hyperaccumulator. The highly contaminated soil (2500 mg kg^{-1}) and nutrient solution (20 μM Pb) used in the cited experiment probably caused the unrestricted transport of lead from roots to shoots. In the present experiment the shoot Pb level in corn was four times lower than in the roots (Table 1).

Alfalfa accumulated more of cadmium and lead in shoots (1.23 of Cd and 11.33 of Pb mg kg^{-1} d. wt, respectively) (Figs. 1, 2). Significant correlations were found between the levels of cadmium and lead in the roots and shoots of alfalfa (r = 0.968 and r = 0.610, respectively) (Fig. 7). Peralta-Videa et al. [19] reported the effects of the growth stage on tolerance to heavy metals in alfalfa plants. They found that in the case of highly contaminated soil (500 mg kg^{-1} of Cd), the translocation percent of cadmium from roots to shoots was only 26%. These results demonstrated different metal distribution in plant tissues as affected by high and low metal levels in soil.

The level of cadmium in common parsnip leaves was slightly higher than in roots. The leaves contained four times more lead than the roots (Figs. 1, 2). The amount of lead in the roots of parsnip was proportional to the leaves (r = 0.795) (Fig. 8).

Generally, the gradient of the cadmium and lead concentrations in the plant declines in the order: roots > leaves > seeds [2], but there are some differences among the species. Within the red beet, field pumpkin, chicory, common bean, white cabbage and parsnip the maximum Cd and Pb content was found in the leaves (Figs. 1, 2). In open field experiments total heavy metals level in plants is determined both by absorption from soil and aerial deposition with industrial dusts. McKenna et al. [20] reported that cadmium may be complexed in Cd-binding peptides in roots and old leaves, which act as a barrier to the transport of Cd to young organs. Harrison and Chirgawi [21] showed that the foliar route of metal absorption is of similar importance to the soil-root pathway only in the case of exposed organs (i. e. leaves). The levels of metals in fruits and storage roots resulting from the foliar translocation of the airborne component appeared to be generally low.

Baker [22] suggested three types of plant-soil relationship: accumulators, excluders, and indicators. The operation of these mechanisms can be seen by comparing the metal levels in the roots and aerial parts of plants. Heavy metal concentration ratios (shoot/root) >1 are characteristic for accumulators; <1 for excluders. The data for Cd distribution (Table 1) suggest the consistent differences between species: concentration ratios for red beet, chicory, alfalfa, and common parsnip are characteristic of accumulators, the other species — for excluders. In the case of Pb — the most efficient accumulators are red beet and common parsnip. It should be emphasized that species may act as both accumulators and excluders over different ranges of soil metal concentration. Accumulators and excluders are the extremes of physiological response of plants to heavy metals. "Indicator" behaviour is seen as an intermediate type of response which may or may not reflect a direct link between uptake and metal tolerance [22].

According to Ciura et al. [23] the most effective one in phytoextraction of cadmium was field pumpkin (2.06

mg m^{-2} $year^{-1}$). Because of lower plant fresh weight, red beet was not so effective in cadmium remediation despite high cadmium levels in harvestable organs. Field pumpkin (12.6 mg m^{-2} $year^{-1}$) and alfalfa (11.7 mg m^{-2} $year^{-1}$) were the most effective species in lead remediation. In the case of field pumpkin this resulted in high biomass production. Alfalfa was characterized by a high possibility for lead bioaccumulation [23]. The reported results show that the efficiency of cleaning soils polluted with cadmium and lead depends not only on biomass production but is connected with the possibilities of particular species for metal accumulation in harvestable organs. The efficiency of metal phytoextraction by biomass crops is limited due to the low metal concentration in harvestable parts. If higher shoot metal concentration would be achieved by means of conduced phytoextraction, the metal extraction potential might be limited by phytotoxicity problems [3]. For crops its resistance for excess metal content is of a low importance because of the short time of exposure (while chemical agents improving phytoextraction are applied shortly before harvest). The reported problems need further investigations.

Conclusions

1. Within the red beet, field pumpkin, chicory, common bean, white cabbage and parsnip the maximum Cd and Pb content was found in leaves.
2. The red beet was characterized by the highest cadmium concentration ratio (shoots/roots).
3. The red beet and common parsnip were characterized by the highest lead concentration ratios (shoots/roots).
4. The phytoremediation efficiency of the crops investigated depended on biomass production and the possibility of metal accumulation in harvestable organs.

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