# Phytoextraction of cadmium, copper, zinc and mercury by selected plants

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**ABSTRACT**

During the years 2006 and 2007 the phytoextraction ability of maize (*Zea mays*), willow-tree (*Salix smithiana*) and poplar (*Populus nigra* × *P. maximowiczii*) to accumulate cadmium, copper, mercury and zinc was investigated. Small scale field experiment was carried out on soil contaminated with chemicals from the waste incineration plant in Hradec Kralové (Czech Republic). Screening of this allotment showed very different contamination of all observed risk elements on places where the material intended to be burnt without safety of leakage into soil. Grown plants showed the different accumulation of observed elements in plant tissues as well as the influence of total content of the risk elements in soil. The highest Cd (1.5–1.73 mg/kg) and Zn (242–268 mg/kg) concentrations were found in willow-tree biomass mainly in the leaves. Cu and Hg were mostly accumulated by maize roots (14.6–15.8 mg Cu/kg and 1.3–7.4 mg Hg/kg) and lower amount was found out in willow-tree leaves again. In reference to total production of each plant the maximum Cd and Zn uptake by aboveground biomass was found in poplars (201 mg Cd/m$^2$ and 38 200 mg Zn/m$^2$) and maize, which showed high Zn uptake. The biggest amount of copper (2563 mg Cu/m$^2$) was accumulated by aboveground maize biomass on the collection point with the highest Cu concentration in soil and by poplar (2394 mg Cu/m$^2$) on the other collection point. The highest Hg uptake differs in reference to total Hg content in soil; willow-tree has the highest uptake on the place with lower Hg content in soil (44.6 mg Hg/m$^2$) and maize has the highest uptake on the place with higher Hg content in soil (92 mg Hg/m$^2$).

**Keywords**: cadmium; copper; zinc; mercury; maize; willow; poplar; accumulation; removal by plants

Heavy metal pollution is responsible for severe environmental problems and risks to human health, including decreased soil microbial activity and fertility, and yield losses (McGrath et al. 1995). Actually, large areas of land are contaminated with heavy metals deriving from urban activities (municipal sewage sludge and waste incinerators), agricultural practices (fertilisers and pesticides application) and industrial processing (metalliferous mining, smelting industry, printing factories and tanneries) (Lasat 2002). In contrast to organic pollutants heavy metals are not biodegradable, having ability to accumulate in organisms. The accumulation of heavy metals in the tissues of earthworms is a helpful indicator of environmental contamination. The degree of substrate contamination can be additionally evaluated on the basis of survivability, reproduction and body mass of earthworms (Lapinski and Rosciszewska 2008). For use of contaminated soils, however, elimination of elevated levels of risk elements is necessary.

Traditional remediation methods of such contaminated soils (for example soil excavation and dumping, vitrification, stabilization and soil washing/flushing) are generally cost-intensive and harmful to soil properties. Phytoextraction, the use of plants for extracting contaminants from soils, therefore presents currently an alternative for soils polluted with metals. However, the low mobility and bioavailability of some metallic elements (e.g.

Cr and Pb) limit the efficiency of the phytoextraction process (Blaylock et al. 1997). Studies on phytoextraction are mainly focused on metal hyperaccumulating plants, as they accumulate 100–1000 fold the levels commonly accumulated in plants, with no adverse effects on their growth (Reeves et al. 1999). In this context, plant species like *Salix viminalis* (taking large portion of Cd and Zn), *Brassica juncea* (Pb), *Lolium perenne* (Pb), *Zea mays* (Pb), *Helianthus annuus* (Pb, Cu), or others, are characterized by high content of heavy metals in biomass and good remediation capacity due to high biomass production (Schmidt 2003).

Several studies have shown the potential of willow for site reclamation and partial decontamination, as several species and clones of the genus *Salix* take up relatively high levels of heavy metals (Aronsson and Perttu 2001). For instance, up to 22 mg Cd/kg and 560 mg Zn/kg were found in *Salix viminalis* (Labrecque et al. 1995). Similar values were determined for poplar. Robinson et al. (2000) found up to 209 mg Cd/kg in leaves of *Populus trichocarpa* × *P. deltoides* growing on a contaminated site up to 300 mg Cd/kg in soil.

Recently, plants capable of forming an association with fungi, including maize (*Zea mays* L.), have been shown to accumulate considerable amounts of metals, such as Cu and Zn. Additionally, maize can be cultivated with high dry biomass production according to well established management (Requejo and Tena 2005).

The main objectives of our study were to assess and compare the heavy metals (Cd, Cu, Hg and Zn) phytoextraction potential of maize *(Zea mays)*, willow *(Salix smithiana)* and poplar *(Populus nigra × P. maximowiczii)* in soils contaminated with these elements and to recommend the most suitable measures for phytoextraction strategy at the particular contaminated site. Plants were grown for two periods in the small scale field experiment at industrially contaminated soil.

## MATERIALS AND METHODS

**Small scale field experiment**. The area of former waste incineration plant in the suburb of Hradec Kralové (Czech Republic) was chosen for growth of selected plants with a good ability to accumulate certain risk elements. This waste incineration plant functioned between 1993 and 2002. Hazardous waste containing oil substances, agrochemical waste, preservative agents, chemical process waste, percolation waste, degreasing waste containing solvents, waste containing metals, waste containing halogens, dyes, acid tar, waste containing sulphur, fertilizers, inorganic pesticides and many others were burnt there. Hazardous waste without protection was stored on the mentioned allotment during the running period of the incinerator.

Eleven sampling points were chosen on the site of 337 $m^2$ of total tract (Figure 1). These points were distant from each other to give us information about stocking rate of soil on the allotment (especially along the pavement where barrels with chemicals were stored). Collection points were located by GPS (Global Position System). At least eight subsamples were taken from 0–20 cm depth within the circle of 3 m diameter. Samples were homogenized, dried at the laboratory temperature (22°C) and passed through 2 mm sieve. Plant residues were removed before sieving.

Two areas with different scale and history of contamination were chosen out of the eleven collection points on the allotment. Two plots with the area of 3 × 3 m were prepared on these two areas. Basic characteristic of soil parameters are summarized in Table 1. Each plot was planted out and sowed with these experimental plants: willow *(Salix smithiana)*, poplar (*Populus nigra* × *P. maximowiczii*) and maize (*Zea mays* L.). Plants were treated ordinarily (watering, weeding) and fertilized by addition of 30 g/mg $NH_4NO_3$ for two vegetation periods. Then in autumn before senescence these plants were harvested aboveground biomass of fast growing trees and whole biomass of maize. Fresh plant

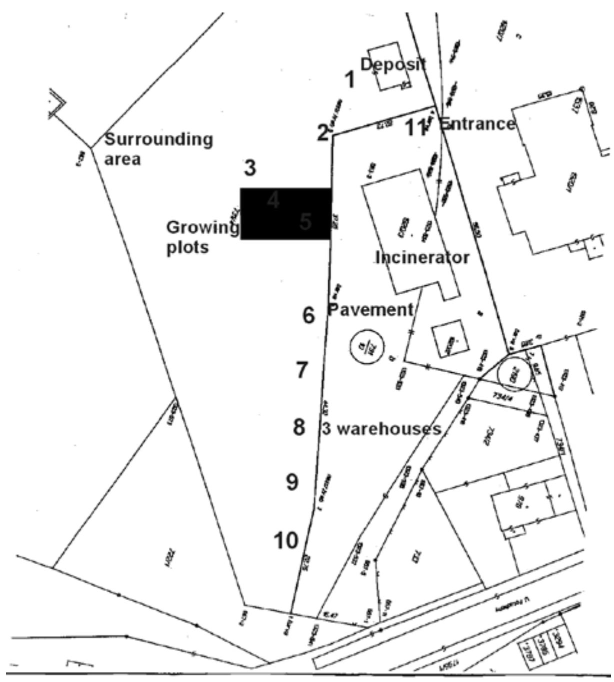


Figure 1. Description of sampling sites (1–11) at incinerator plant

Table 1. Physio-chemical characteristics of experimental soils

| Sampling point No. | pH ($CaCl_2$) | pH ($H_2O$) | $C_{ox}$ (%) | P (mg/kg)* | K (mg/kg)* | Mg (mg/kg)* |
|---|---|---|---|---|---|---|
| 1 | 6.85 | 7.67 | 1.8 | 109 | 203 | 325 |
| 2 | 7.08 | 7.98 | 1.4 | 128 | 233 | 345 |
| 3 | 7.41 | 8.23 | 1.9 | 133 | 219 | 375 |
| 4 | 7.45 | 8.21 | 1.6 | 118 | 189 | 435 |
| 5 | 6.09 | 6.66 | 7 | 1042 | 966 | 1416 |
| 6 | 7.53 | 8.39 | 1.2 | 177 | 112 | 450 |
| 7 | 7.12 | 7.88 | 2.3 | 170 | 205 | 443 |
| 8 | 7.72 | 8.12 | 2.3 | 172 | 226 | 408 |
| 9 | 7.44 | 8.12 | 1.6 | 263 | 572 | 394 |
| 10 | 7.82 | 8.59 | 1.2 | 177 | 345 | 545 |
| 11 | 6.94 | 7.48 | 3.5 | 335 | 544 | 388 |

*available nutrients according to Mehlich III. extraction procedure (Mehlich 1984)

biomass was weighed, separated to leaves and twigs (trees) and roots, leaves, stalks and seeds (maize), and after drying at the temperature of 60°C dry mass was measured.

**Analytical methods**. All the chemical analyses were provided in analytical laboratories of the Department of Agroenvironmental Chemistry and Plant Nutrition at Czech University of Life Sciences in Prague in order to determine the total contents of risk elements. Total element concentrations in soil were determined in digests obtained by two-step decomposition as follows: 0.5 g of sample was decomposed by dry ashing in a mixture of oxidizing gases ($O_2$ + $O_3$ + $NO_x$) in an Apion Dry Mode Mineralizer (Tessek, Czech Republic) at 400°C for 10 h; the ash was then decomposed in a mixture of $HNO_3$ + HF, evaporated to dryness at 160°C and dissolved in diluted aqua regia (Száková et al. 1999). Total contents of risk elements in soil samples are summarized in Table 1.

Plant samples were decomposed using the dry ashing procedure as follows: an aliquot (~ 1 g) of the dried and powdered aboveground biomass or roots were weighed to 1 mg into a borosilicate glass test-tube and decomposed in a mixture of oxidizing gases ($O_2$ + $O_3$ + $NO_x$) at 400°C for 10 h in Dry Mode Mineralizer Apion (Tessek, Czech Republic). The ash was dissolved in 20 ml of 1.5% $HNO_3$ (electronic grade purity, Analytika Ltd., Czech Republic) and was kept in glass tubes until the analysis (Miholová et al. 1993). Aliquots of the certified reference material RM NCS DC 73350 Poplar leaves (purchased from Analytika, Czech Republic) were mineralized under the same conditions for quality assurance of the total element contents in experimental plants. In this material, containing 0.32 ± 0.07 mg Cd/kg, 9.3 ± 1.0 mg Cu/kg and 26.3 ± 2.0 mg Zn/kg was determined 0.296 mg Cd/kg, 10.03 mg Cu/kg, and 26 mg Zn/kg were found out during the first year and 0.27 mg Cd/kg, 9 mg Cu/kg and 28.1 mg Zn/kg during the second one.

The total contents of Cd, Cu, and Zn in soil and plant digests were determined by optical emission spectroscopy with inductively coupled plasma (ICP-OES) with axial plasma configuration, Varian, VistaPro, equipped with autosampler SPS-5 (Australia). Measurement conditions for all lines were: power 1.2 kW, plasma flow 15.0 l/min, a uxillary flow 0.75 l/min, nebulizer flow 0.9 l/min. Hg content was determined by atomic absorption spectrometry by using single-purpose analyzer AMA-254 (Altec, Czech Republic). Exchangeable values of pH were measured in a 1:20 (w/v) 0.01 mol/l $CaCl_2$ soluble extract at 20 ± 1°C, and active pH values in water extract (ratio 1:3, v/w) at 20 ± 1°C. The used pH meter was WTW pH 340i set.

Certificated reference material RM NCS DC 73350 Poplar leaves that contains 0.32 ± 0.07 mg Cd/kg, 9.3 ± 1.0 mg Cu/kg and 26.3 ± 2.0 mg Zn/kg was used to check the quality of analyzed plant data. By analyzing the material 0.296 mg Cd/kg, 10.03 mg Cu/kg and 26 mg Zn/kg were found out during the first year and 0.27 mg Cd/kg, 9 mg Cu/kg and 28.1 mg Zn/kg during the second one. Hg content was determined with AMA-254 (Advanced Mercury Analyzer).

## RESULTS AND DISCUSSION

**Soil contamination**. Total average contents of chosen risk elements in soils are given in Table 2. Regulation N°13/1994 Collection of Laws of Ministry of the Environment of the Czech Republic provides maximum admissible risk element contents in soil as follows: 1 mg/kg Cd, 100 mg/kg Cu, 0.8 mg/kg Hg and 200 mg/kg Zn. Cadmium content in soil samples exceeded almost at all sampling points (except the points 1 and 6). The highest amounts are along the pavement (sampling points No. 2–5) and the eleventh point (behind the entrance to the grounds) where barrels with chemicals were stored. The highest load rate of this element can be found on location No. 5 where the limit rate is exceeded 6.8-fold. Copper content is exceeded only on location No. 5 and the limit rate is exceeded twice. The above-limit level of mercury was found on four locations but these are distant from each other so there is only point contamination. The highest contamination is on location No. 5 again where the maximum limit was exceeded fifteen-fold. High amount of zinc in soil can be observed almost in all sampling points. The highest contents were in contrast to preceding risk elements determined near closed chemical stocks not along the pavement. Evidently, contamination of this allotment is heterogeneous. In front of the incinerator building along the pavement there are areas with over-limit contents of almost all observed risk elements. On these places barrels with chemicals that were assigned to liquidation without security prevention of substance outflow into soil were stored. Biasioli et al. (2007) investigated urban soil load with risk elements in three big European cities (Ljubljana in Slovenia, Sevilla in Spain and Torino in Italy) and they found out high rates of Pb and Zn (average Zn rates are from 87 to 147 mg/kg). The research of soil load in China was done by Tang (2006) determining the average contents of heavy metals in vegetable-producing soils in Zhongquing city and their corresponding background; the value reported for Cd was 0.29 mg/kg, for Cu 23.0 mg/kg, for Hg 0.056 mg/kg and for Zn 82.3 mg/kg. In our experiment, substantially higher element contents were determined confirming high level of contamination of the investigated site.

Experimental plots for plant cultivation were set up on places with the highest concentration of observed risk elements and at the same time on places where the soil could be cultivated for growing. First of them was the point No. 4 with Cd and Zn concentration above limit value. The second plot was set in sampling point No. 5 where the unreasonably high concentrations of all observed risky elements (Cd, Cu, Zn and Hg) were found. Plot at sampling point No. 4 shows manifold less soil load with risky elements than the plot in sampling point No. 5 (4.4-fold lower Cd content, 11.6-fold lower Cu content, 22.8-fold higher Hg content and 4 times higher total Zn content). Heterogeneous load of risk elements as well as different agrochemical

Table 2. Total concentration of elements in soils on the individual sampling points (mg/kg)

| Sampling point No. | Cd | Cu | Hg | Zn |
|---|---|---|---|---|
| 1 | 0.361 ± 0.098 | 12.1 ± 0.4 | 2.57 ± 0.06 | 102 ± 4 |
| 2 | 5.85 ± 0.21 | 51.6 ± 17.8 | 0.153 ± 0.036 | 223 ± 39 |
| 3 | 2.00 ± 0.24 | 24.7 ± 4.8 | 0.149 ± 0.027 | 164 ± 11 |
| 4 | 1.55 ± 0.22 | 18.3 ± 0.9 | 0.522 ± 0.085 | 289 ± 18 |
| 5 | 6.8 ± 2.49 | 212 ± 19.0 | 11.9 ± 2.00 | 1160 ± 15 |
| 6 | 0.713 ± 0.292 | 34.4 ± 12.3 | 0.698 ± 0.092 | 188 ± 43 |
| 7 | 1.25 ± 0.29 | 26.1 ± 4.1 | 0.197 ± 0.011 | 225 ± 71 |
| 8 | 1.42 ± 0.04 | 18.1 ± 1.3 | 1.52 ± 0.19 | 181 ± 5 |
| 9 | 2.99 ± 0.04 | 93.4 ± 6.8 | 0.689 ± 0.207 | 2766 ± 111 |
| 10 | 1.15 ± 0.08 | 14.8 ± 3.3 | 0.664 ± 0.095 | 461 ± 19 |
| 11 | 5.19 ± 0.47 | 65.0 ± 2.1 | 1.73 ± 0.15 | 2067 ± 391 |

characteristics of soil samples can be observed on these two places. Soil pH of sampling point No. 4 is neutral to alkalic, on the other hand the results from sampling point No. 5 show acid pH. This place also shows high rates of oxidable carbon (7%, while plot No. 4 shows only 1.6%) and also substantially higher rates of all the determined nutrients.

Neutral soil pH was found almost on all places with the exception of sampling point No. 5 where the experimental plot shows acid soil reaction. This place also shows very high phosphorus content (according to regulation No. 275/1998 Collection of Laws of Ministry of Agriculture). It can be said that this allotment shows significant heterogeneity of oxidizable carbon content and individual nutrients on chosen sampling points. Values determined at plot No. 4 are in close relation to those at other plots and to soils nearby except contents of several metals. Plot No. 5 represents highly contaminated soil differing in other soil parameters not just in metals, confirming wide spectra of contaminants.

**The contents of Cd, Cu, Hg and Zn in experimental plants**. The total production of dry biomass of all three grown plants varied according to the sampling point characteristic, plant species and the vegetation period. The most significant difference was found among individual plant species. The biggest amount of aboveground biomass during two years was produced by poplar (429 g), slightly less by maize (396 g) and the lowest amount by willow-trees (88 g).

The highest average Cd contents were found in willow and higher concentration of this element was found in leaves in comparison with annual shoots (Table 3). Similarly, Vysloužilová et al. (2003b) found higher Cd and Zn concentration in leaves of willow than in its annual shoots. Higher cadmium content in willow leaves (1.73 mg/kg) was found on the plot with lower total content of this element in soil (sampling point No. 4) than on the sampling point No. 5 where the average amount of this element is 1.5 mg/kg. Unterbrunner et al. (2005) found 249 mg Cd/kg in the leaves of the same willow species in the soil with medium cadmium content. Vysloužilová et al. (2006) found out the largest metal concentrations in willow leaves (*Salix* × *rubens*) – 66.7 mg Cd/kg and 1090 mg Zn/kg. On the other hand the lowest Cd contents occurred in maize plants (Table 4) and the contents decreased in the following order: root > stalk > leaf > seed. Tlustoš et al. (1997) also found out that the highest Cd concentration was in cereal roots. However, the results were not significantly affected by cadmium level in soil. John et al. (2008) exposed *Lemna polyrrhiza* L. to different concentrations of Cd and found out that metals uptake was concentration and time dependent. Treatment with 1.10 and 20 mg/l of Cd showed synergistic relation while 30 and 40 mg/l treatments showed antagonistic relation during the metal uptake. Lower cadmium contents in aboveground biomass of poplars in comparison with willow are in agreement with results of Robinson et al. (2000). Cadmium and zinc concentrations are distinctively higher in aboveground biomass of willow and poplars compared to maize. Cui and Wang (2006) studied maize grown in pots in soil with added Cd up to 100 mg/kg and their results were that shoot biomass decreased with the application of Cd to the soil and the application of sulphur (50 mmol/kg) and Cd to soil led to an increasing accumulation of Cd in the shoots of maize. Similar results and similar Cd and Zn concentrations in the same plant species planted in soil with elevated metal concentration in average 9.7 mg Cd/kg dry soil, 1100 mg Zn/kg dry soil were found by Vandecasteele et al. (2006) (0.8–4.8 mg Cd/kg and 155–255 mg Zn/kg).

The highest copper concentrations (Table 4) were found in maize roots (14.6 mg/kg on the sampling point with the lowest concentration of this element in soil and 15.78 mg/kg on the sampling point No. 5). Within this plant the copper concentration decreases in following order: root > leaf > stalk > seed. Willow also shows its ability of copper accumulation into its leaves. On both sites the contents reached 12 mg/kg. Annual shoots of this woody plant show lower copper amount (Table 3).

Willow-trees accumulated the biggest amount of zinc (Table 3) more in leaves compared to the annual shoots (241 mg/kg on sampling point No. 4 where there is a lower content of this element than on sampling point No. 5 where the zinc content in leaves is 267 mg/kg). This finding is in contradiction with the results of research done by Greger et al. (2001). They found out higher Zn accumulations in roots and limited transport into aboveground biomass in willow-tree clones grown in contaminated soil compared to willow-tree clones grown in uncontaminated soil. Higher Zn content in leaves of this willow-tree species reported Unterbrunner et al. (2005) – 3270 mg Zn/kg. The findings that willow-trees are able to accumulate cadmium and zinc are in agreement with research results of Vysloužilová et al. (2003a). In poplar leaves we can find rates that are

Table 3. Average concentration of risk elements in fast growing trees (mg/kg dm*)

| Element | Plot No. | Poplar leaves | Twigs | Willow leaves | Twigs |
|---|---|---|---|---|---|
| Cd | 4 | 0.8 ± 0.35 | 0.55 ± 0.27 | 1.73 ± 0.27 | 0.98 ± 0.16 |
| Cd | 5 | 1.01 ± 0.14 | 0.76 ± 0.17 | 1.5 ± 0.49 | 0.94 ± 0.44 |
| Cu | 4 | 8.05 ± 2.25 | 8.78 ± 1.33 | 12.8 ± 5.25 | 9.13 ± 0.68 |
| Cu | 5 | 11.3 ± 2.89 | 10.5 ± 5.77 | 12.6 ± 5.49 | 7.6 ± 1.66 |
| Zn | 4 | 147 ± 95.7 | 73.9 ± 19.3 | 242 ± 16.9 | 80.1 ± 19.8 |
| Zn | 5 | 167 ± 47.5 | 71 ± 7.33 | 268 ± 130 | 103 ± 46.7 |
| Hg | 4 | 0.12 ± 0.09 | 0.07 ± 0.04 | 0.83 ± 0.78 | 0.13 ± 0.12 |
| Hg | 5 | 0.67 ± 0.55 | 0.16 ± 0.15 | 0.99 ± 0.93 | 0.67 ± 0.62 |

dm* – dry matter

about 100 mg/kg lower. Higher concentration of this element is in poplar leaves than in its annual shoots which are in agreement with the research results of other poplar clones of Sebastiani et al. (2004). Concerning maize the biggest amount of Zn element can be found in stalks while in roots and leaves the content is similar and lower (Table 4). These results are not in agreement with the results of Lubben and Sauberbeck (1991) who observed the highest zinc accumulation in roots of cereals in comparison with aboveground biomass. In aboveground biomass of poplars lower zinc concentration was found compared to willow-trees. However, it still shows the higher ability to accumulate this element than the aboveground biomass of maize.

The highest mercury concentrations were found in maize roots (1.3 mg/kg point No. 4 and 7.4 mg/kg point No. 5, Table 3) and in willow-tree leaves (0.8 mg/kg on sampling point No. 4 and 0.99 mg/kg on sampling point No. 5, Table 4). *Salix smithiana* applied in our experiment accumulated higher mercury concentration in aboveground biomass compared to *Salix viminalis* clones used by Wang and Greger (2004). Total mercury concentration in aboveground biomass of *S. viminalis* got the maximal rate of 0.36 mg/kg.

All the investigated risk elements (Cd, Zn, Cu, Hg) concentrations in particular maize parts decreased in the order roots > leaves > seeds. Comparable results were also presented by Nigam et al. (2001). The maximum concentrations of observed risk elements were found in willow-tree biomass comparing all the parts of observed plants. The main soil factors controlling metal solubility and bioavailability in soils are the total metal concentration, pH, soil sorption capacity and organic matter (Adriano 2001). Evidently, in our case higher concentrations of observed risk

Table 4. Average concentration of risk elements in maize (mg/kg dm*)

| Element | Plot No. | Roots | Stalks | Leaves | Seeds |
|---|---|---|---|---|---|
| Cd | 4 | 0.48 ± 0.11 | 0.18 ± 0.07 | 0.13 ± 0.08 | 0.09 ± 0.08 |
| Cd | 5 | 0.47 ± 0.18 | 0.23 ± 0.10 | 0.22 ± 0.04 | 0.12 ± 0.04 |
| Cu | 4 | 14.6 ± 3.32 | 6.96 ± 1.62 | 7.75 ± 0.52 | 3.67 ± 0.89 |
| Cu | 5 | 15.8 ± 2.51 | 7.08 ± 1.16 | 9.38 ± 4.21 | 3.45 ± 1.58 |
| Zn | 4 | 69.7 ± 7.03 | 107 ± 11.9 | 57.5 ± 28.8 | 37.7 ± 8.76 |
| Zn | 5 | 108 ± 54.3 | 180 ± 31.2 | 103 ± 23.2 | 43.3 ± 7.28 |
| Hg | 4 | 1.34 ± 1.1 | 0.05 ± 0.04 | 0.16 ± 0.11 | 0.01 ± 0.01 |
| Hg | 5 | 7.39 ± 2.87 | 0.25 ± 0.05 | 0.35 ± 0.26 | 0.09 ± 0.06 |

dm* – dry matter

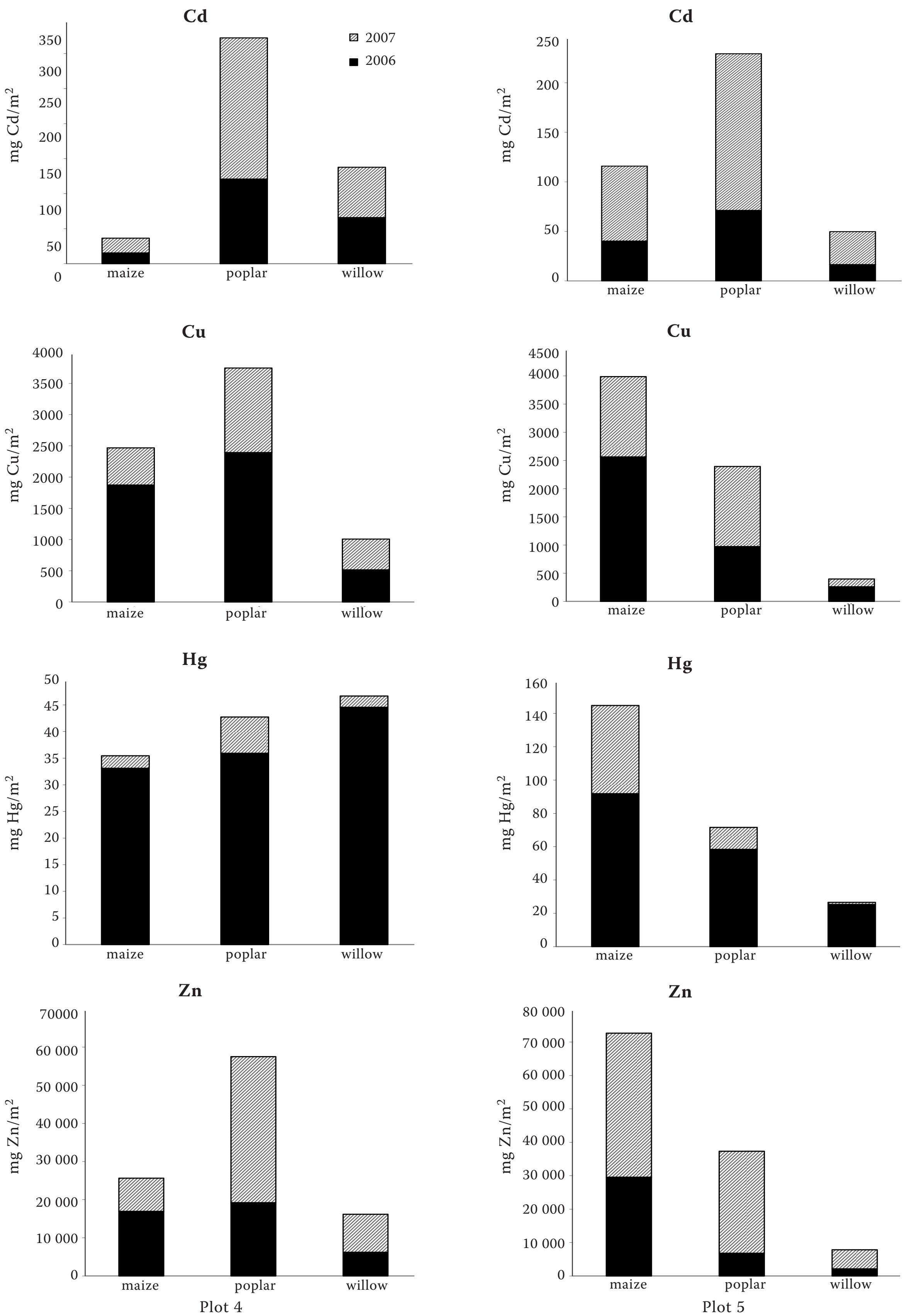


Figure 2. Average removal of individual elements by tested plant species

elements were found in plants grown on plot No. 5. It can be said that there is a relation to higher content of elements in soil, the higher accumulation in plants. Similarly, Greger et al. (2001) investigated differences in tolerance to an accumulation of heavy metals between different *Salix* clones, grown on heavy metal polluted and unpolluted areas. Clones from the polluted area had higher accumulations of Cd, Cu and Zn in their roots and a lower transport of heavy metals to the shoots than clones from the unpolluted area.

**Cd, Cu, Hg and Zn removal by plants**. The estimation of total accumulation capacity for individual plant and element is crucial parameter to observe total removal. Metal removal is influenced by two factors – the content of the element in particular above ground plant parts is the first one and the yield of aboveground dry biomass is the second one. The highest total removal rates were set out for zinc, lower ones for copper and cadmium and the lowest ones for mercury, which is in agreement with total soil element content.

From the comparison of the element removals by each plant (Figure 2) is clear that during two vegetation periods on both plots poplars have the highest cadmium uptake by aboveground biomass even though the highest average contents of this element were found in willow-trees. However, willow-trees showed lower yield of aboveground biomass on both places during two vegetation periods. Both woody plants showed higher Cd uptake from soil than maize. Willow-trees on two places with different cadmium load rate took up higher amount of this element during both years on the place with lower content of this element in soil. Our results of Cd uptake by willow differ from the results of Vysloužilová et al. (2003a) who found the highest Cd and Zn rates taken up by leaves of willow-tree grown in the most contaminated soil. These differences can be caused by a large variation among clones in their sensitivity to many heavy metals (Greger et al. 2001) or lower bioavailability at more contaminated site. The results of second year showed that Cd uptake is higher than during the first year with all the grown plant species.

The highest total copper uptake during two vegetation periods (Figure 2) differs according to individual sampling points. On sampling point No. 4 with lower Cu content in soil, poplars showed the highest uptake while on the highly contaminated site, maize was the dominant one. The highest Cu uptake relates with the fact that maize produced more biomass than willow-tree. Higher content of this element in soil was caused by higher uptake by aboveground maize biomass only during the first year. In relation to the assessment of elements uptake during two vegetation periods it is possible to say that Cu uptake on both places is higher in the first year than in the second one.

The mercury uptake seems to be affected by different characteristics and by load rate on the chosen growing places. On the place with lower Hg content in soil the highest uptake of this element was found by willow-tree. On sampling point No. 5 where the mercury content in soil is twenty-fourfold higher the highest Hg uptake from soil was observed at the aboveground maize biomass. This plant also produced the largest amount of biomass during both years of growing. Thus the mercury uptake was higher in soil with lower concentration of this element with all our plants during both years. The same results can also be concluded in assessment of average concentration of this element in individual plants. There is a significant Cu decrease during the second year with all our plants even though the amount of biomass with maize is approximately the same and with woody plants even higher.

Woody plants removed zinc in larger extent during the second year which depends on the fact that during the second year they produced bigger amount of aboveground biomass. Maize on the place with lower Zn content in soil produced much lower biomass during the second year compared to the first one; that is why the Zn uptake during the second year is significantly lower. As a whole we can say that poplar performed the highest zinc removal on both places during two years.

On the basis of our results the most suitable plant for uptake of all observed risk elements (Cd, Hg, Cu and Zn) is poplar. Only on soils contaminated with mercury the better result would be achieved by growing maize. Willow is not suitable for complex uptake of observed risk elements. Only in uptake of cadmium and zinc by woody plants, the positive dependence on amount of plant biomass can be seen.

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