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Accumulation of heavy metals in tree seedlings from soil amended with sewage sludge

Donatas Butkus,

Edita Baltrėnaitė

Department of Environmental Protection, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania
E-mail: edita@ap.vtu.lt

Interaction between plants and heavy metals (HM) is based on the ability of plants to either accumulate HMs or be resistant to huge amounts of HM in soil. Trees, due to their high biomass and long vegetation, are attractive for the extraction of HM from soil, but not all tree species are characterised by the same efficiency of HM accumulation, and the ability of many species to accumulate metals has not been widely analysed. This work aims at comparing the ability of three naturally growing tree species – pine (*Pinus sylvestris* L.), birch (*Betula pendula* Roth) and black alder (*Alnus glutinosa* (L.) Gaertn)) to accumulate Zn, Mn, Pb, Ni and Cu from sewage sludge. It has been noticed that the characteristics of the sludge (for example, pH, Al concentration), plant physiology (for example, the ageing processes in the pine needles every 4 years, possible HM transfer of into younger tissues) may influence HM transfer to trees growing on sludge-amended soil. HM accumulation in tree seedlings of different type and factors affecting the take-up of metals by seedlings are further discussed in the paper.

Key words: sewage sludge, heavy metals, transfer factor, translocation factor, *Pinus sylvestris*, *Betula pendula*, *Alnus glutinosa*

INTRODUCTION

Interaction between heavy metals (HM) and plants is based upon either HM extraction or exclusion by plants. Both processes are widely analysed, however, the uptake or the so-called phytoextraction seems more ecologically feasible because of HM accumulation and stabilization in plant biomass, preventing their further spread to deeper soil layers and groundwater. When plants are considered for phytoextraction of contaminants from soil, they are expected to do one or more of the following: take up contaminants from soil particles and/or soil solution into their roots; bind the contaminants into their root tissues, physically or/and chemically; transport the contaminants from the roots to the underground parts and prevent or inhibit the contaminants from leaching out of soil (Chaney et al., 1997; UNEP IETC, 2003). Phytoremediation methodologies are of high sustainability, require a low input of energy, manpower and low costs and offer recycling of materials and matter (Schröder et al., 2006).

Some plants phytostabilise HMs in the rhizosphere through root exudate immobilisation (Blaylock, Huang, 2000), while other species of plants incorporate metals into root tissues (Khan, 2001). Some plant species are able to transfer metals to their above-ground tissues, potentially allowing the soil to be decontaminated by harvesting the above-ground parts of the plants (Brun, 1998).

Among other plants, trees have a number of attributes (e. g., high biomass, economic value) which make them attractive for use in phytoremediation, but to be effective, they have to take up and tolerate high concentrations of HMs in their above-ground tissues (Pulford et al., 2001). There are some papers on the tree species which naturally colonize the investigated sites, for example, *Betula pendula*, *Alnus glutinosa*, *Salix viminalis*, *Pinus contorta*, ect. (Pulford et al., 2001; Rosselli et al., 2003; Maurice, Lagerkvist, 2000). The adaptation to local climate is one of the important criteria when selecting tree species for phytoremediation (Rosselli et al., 2003).

Betula is considered not a metal accumulator but only a metal-tolerant plant (Brown, Wilkins, 1985; Kozlov et al., 1995), however, high concentrations of Cu in *Betula* roots have been reported (Maurice, Lagerkvist, 2000). Some pine and black alder species were found to accumulate higher amounts of Zn in roots than in leaves and shoots, however, *Alnus glutinosa* showed a higher accumulation in leaves (Pulford et al., 2001). Cr was not taken up by *Betula pendula,* but was efficiently uptaken by *Pinus contorta* and *Alnus glutinosa* in hydroponic systems (Pulford et al., 2001). In the USA and Scandinavian countries, *Pinus sylvestris* stands are actively used for sewage sludge applications. The results showed an increased nitrogen amount and biomass of the stands, however, the content of HMs uptaken by trees needs to be examined on a broad scale (Norden, 2006). In a study of Rautio (2000) with *Pinus sylvestris* seedlings grown in soil containing elevated concentrations of Ni or Cu, Cu uptake by shoots was relatively low compared with the Ni uptake. Seedlings of *Pinus Sylvestris* may uptake and tolerate high concentrations of HMs if it is dry and the wet deposition of HMs is minimal. Therefore, differences in soil composition, e. g., content of humus and concentrations of available nutrients, may influence HM effects on trees (Ahonen-Jonnarth et al., 2004).

This study examines a potential use of three naturally colonized tree species – pine (*Pinus sylvestris* L., birch (*Betula pendula* Roth) and black alder (*Alnus glutinosa* (L.) Gaertn)) – for accumulation of industrial sewage sludge-derived metals Ni, Pb, Zn, Cu and Mn.

METHODOLOGY

In 1998, an experimental site was prepared in the woodcutting area of 2 ha in the Gilėnai forest in the Taruskos forestry located in Panevėžys region (Fig. 1), where 600 tons of industrial sewage sludge from the Panevėžys town were spread on the soil (the thickness of the layer was approximately 2–3 cm). In 1999, pine (*Pinus sylvestris* L.) and birch (*Betula pendula* Roth) seedlings were planted in this site, and black alders (*Alnus glutinosa* (L.) Gaertn) had grown there naturally.

Loam and sandy loam rocks, which make up the layer of 4–13 cm, are prevailing in the territory under investigation, and therefore forests in this area are turning into marshes. In the areas where marshes are widespread, the rocks are alkaline (pH > 8.0). The soil in the study territory consists of a 20–25 cm slightly decomposed forest floor in the higher parts of the forest and in the lower ones – of 0.75–0.5 m thick low mars-type slightly decomposed peat consisting of 70% of clayey fraction in the bottom part and of the forest floor and wood cuttings in the upper part (Katinas et al., 2002).

Wood and soil samples were taken in October 2005 from four places in the experimental site. In each place, pine, birch and black alder seedlings were pulled up with the roots. Pine, birch and black alder seedlings pulled up outside the boundaries of the experimental site (>200 m) were used as background trees that have grown in the soil not mixed with sludge. Tree seedlings were washed with water and left to dry at room temperature. All the needles and leaves were removed from each seedling, small branches were cut off and fine roots (Ø < 3 mm) were separated from large roots (Ø > 3 mm). Then all the parts of a tree were ground using a *Clatronic* grinder. Each sample of the roots, stem and branches was weighed and 0.5 g were taken, mixed with 8 ml HNO_3 (65%) and 2 ml H_2O_2 (30%), poured into special vessels and then placed into a *Milestone* ETHOS mineralizer and heated for 30 min. The solution was then poured into 50 ml flask and diluted with distilled water to reach the mark of 50 ml. Each sample of the needles / leaves was weighed and 0.5 g were taken, mixed with 7 ml HNO_3 (65%) and 2 ml H_2O_2 (30%) and then placed into the *Milestone* ETHOS digester and heated for 20 min. The solution was then poured into a 50 ml flask and diluted with distilled water to reach the mark of 50 ml.

Soil samples were taken from four places of the experimental site from a depth of 0–40 cm every 10 cm, 6 years after planting the trees. Three soil samples were taken from each place and mixed to form a composite sample. Before the drying process, the soil samples were kept at a temperature of +4 °C. Then they were dried at + 40 °C for two days, ground and sieved through a sieve whose mesh size was 2 mm. Each soil sample, weighing 0.2 g, was poured into mineralization vessels. 1.5 ml HNO_3 (65%) and 1.5 ml HCl (37%) were added, and everything was digested in the *Milestone* ETHOS digester for 31 min. The solution was then poured into a 50 ml flask and diluted with distilled water to reach the mark of 50 ml.

Soil characteristics in the habitats under investigation are presented in Table 1.

HM concentrations in the solutions were analysed using the *210 VGP* atomic absorption spectrophotometer of the company *Buck Scientific*, applying the flame method – flame atomic absorption spectroscopy (FAAS).

The transfer factors (TFs) were calculated by dividing the average HM concentrations in the stem by the average HM concentrations in the soil. The translocation factors (TcFs) were

Table 1. **Selected soil properties**

Soil properties	Soil amended with sewage sludge	Control soil
Soil pH	4.2 ± 0.38	6.6 ± 0.05
Dissolved organic carbon, mg • kg^{-1}	72.8 ± 16.8	25.9 ± 3.2
Mobile Al, mg • kg^{-1}	46.8 ± 28.8	6.2 ± 0.9

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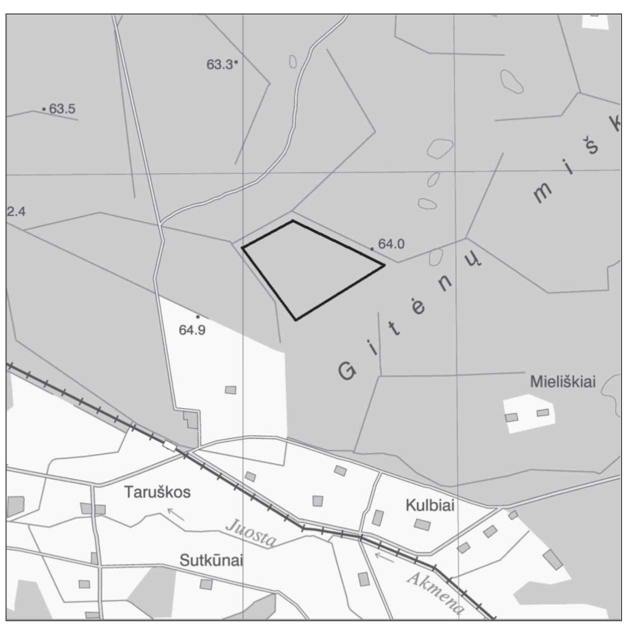

Fig. 1. Experimental site for industrial sewage sludge utilization in the Gilėnai forest of the Taruškos forestry located in Panevėžys region

calculated by dividing HM concentrations in leaves and needles by HM concentrations in fine roots.

RESULTS

HM concentration in the industrial sewage sludge and soil before spreading the sludge

According to HM concentration, the sewage sludge that has been spread in the woodcutting area in the Taruskos forestry is regulated by LAND 20–2005 and attributed to the category II of sludge. The sludge belonging to this category may be used in agriculture not more frequently than every three years for re-cultivating the damaged territories and for fertilising energy crops.

The concentration of HMs in the Panevėžys town sewage sludge that was spread in the woodcutting area in the Tarusku forestry in 1999 and the background concentration of HMs in the soil of the former woodcutting area are presented in Table 2. The concentration of HMs in the sewage sludge exceeded that of the background soil 4 to 90 times. The fact that the sludge comes from metal processing companies explains the especially high concentration of Pb, Zn and Cu in it. The most insignificant difference was observed in the case of Mn – its concentration in the sludge was higher than in the background soil only by 30%. The sewage sludge was highly heterogeneous, therefore the amounts of HMs in the soil and the tree samples were uneven. High contents of organic matter were found in the sludge (approximately 40%), as well as phosphorus (0.5%) and other nutrient substrances (Katinas et al., 2002) that promote the growth of plants.

The concentration of HMs in trees

All the tree species – pines (*Pinus sylvestris* L.), birches (*Betula pendula* Roth) and black alders (*Alnus glutinosa* (L.) Gaertn.) – were successfully growing in the soil fertilized by sludge, irrespective of the amounts of HMs that have been transferred to the above-ground tissues of the trees.

Zinc. The concentration of Zn in many parts of the trees that had grown on sludge was higher than that in the background trees, except for black alder branches, pine stem and needles (Fig. 2). The highest concentration of Zn was observed in the fine roots of pines that had grown on sludge (91 mg · kg^{-1}) and in black alder leaves (214 mg · kg^{-1}). Nearly in all cases (except for black alder), the concentration of Zn in large roots was lower than in fine roots. The black alders that have grown on sludge have accumulated about 2 times larger amounts of Zn in leaves than did control alders.

Manganese. In many cases (in pine fine roots, stems and needles, in birch fine roots, stem and leaves and almost in all parts of black alder, except leaves) the concentration of Mn was higher in the background trees than in those that had grown on sludge. The highest concentration of Mn was identified in the needles of pines (180 mg · kg^{-1}), birch large roots (166 mg · kg^{-1}) and black alder branches (146 mg · kg^{-1}) that had grown on sludge (Fig. 3). The concentration of Mn in large roots of pines

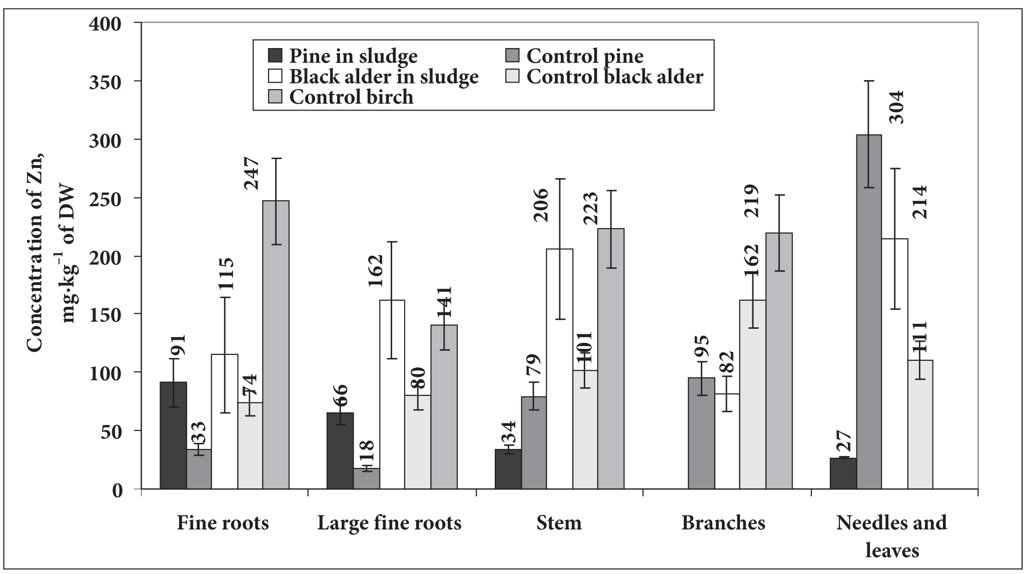

Fig. 2. Concentration of Zn in parts (fine roots Ø < 3 mm; large roots Ø > 3 mm, stem, branches and leaves and needles) of pine, birch and black alder that have grown in soil amended with sewage sludge (n = 4) and of control trees

Table 2. **Concentrations of heavy metals in industrial sewage sludge of Panevėžys region, soil amended with sewage sludge and control soil**

HMs	Industrial sewage sludge, mg · kg^{-1} (Katinas et al., 2002)	Soil amended with sewage sludge after 7 years, mg · kg^{-1}	Control soil, mg · kg^{-1}
Mn	224–572	108 ± 28	168 ± 11.8
Zn	383–538	114 ± 47	19.3 ± 3.6
Cu	118–161	25.3 ± 5.9	8.57 ± 0.41
Ni	33–45	29.7 ± 6.9	8.07 ± 0.59
Pb	597–1421	4.42 ± 1.33	13.7 ± 1.7

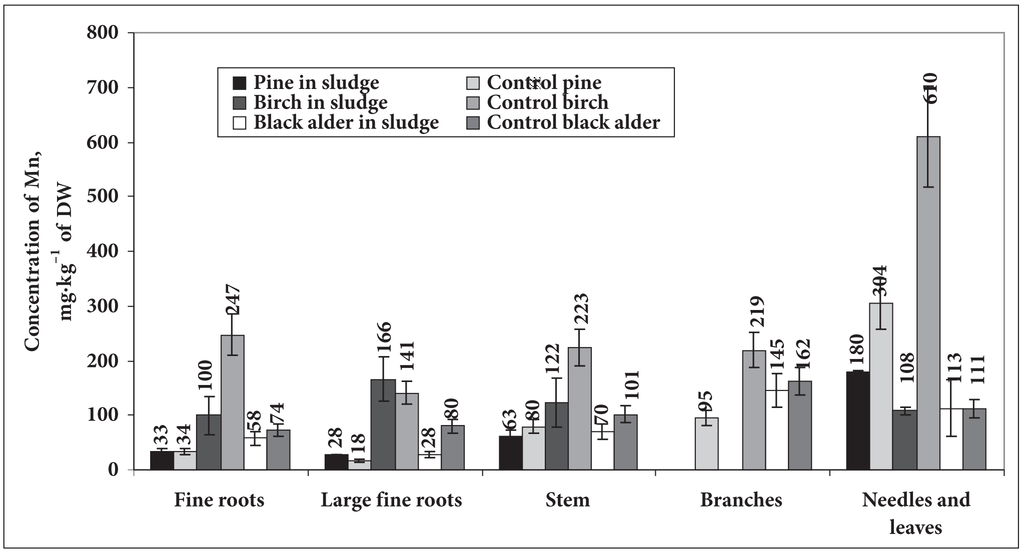

Fig. 3. Concentration of Mn in parts (fine roots Ø < 3 mm; large roots Ø > 3 mm, stem, branches and leaves and needles) of pine, birch and black alder that have grown in soil amended with sewage sludge (n = 4) and of control trees

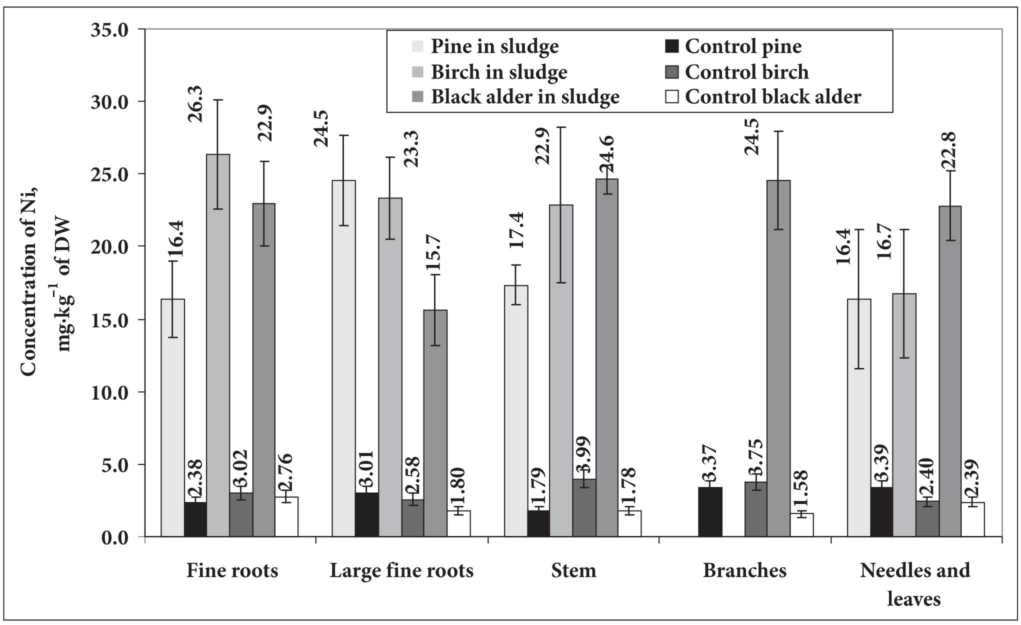

Fig. 4. Concentration of Ni in parts (fine roots Ø < 3 mm; large roots Ø > 3 mm, stem, branches and leaves and needles) of pine, birch and black alder that have grown in soil amended with sewage sludge (n = 4) and of control trees

and black alders that had grown on sludge was lower than that in fine roots (as distinct from birches).

Nickel. The concentration of Ni in all parts of the trees that had grown on sludge was higher than that in the background trees. Large roots of pines and fine roots of birches that had grown on sludge accumulated the largest amounts of Ni (respectively, 24.5 mg · kg^{-1} and 26.3 mg · kg^{-1}), and in the case of black alders – stems (24.6 mg · kg^{-1}), and the smallest amounts were accumulates by pine needles and fine roots (16.4 g · kg^{-1}), leaves of birches (16.4 mg · kg^{-1}), and large roots of black alders (15.7 mg · kg^{-1}) (Fig. 4). It was noted that the relationship between Ni concentration in the parts of background trees and the ones that had grown on sludge was very similar – 6–7 times (except for the branches). The concentration of Ni in branches of trees grown on sludge was found similar to that in leaves.

Copper. In most parts (except large roots of pine and black alder, branches of black alder and leaves, and needles of all investigated trees), the concentration of Cu was higher in trees grown on sludge than in the background trees. The highest concentration of Cu was found in the stems of pines and birches grown on sludge (9.63 mg · kg^{-1} for pine, 10.1 mg · kg^{-1} for birch and 13.1 mg · kg^{-1} for black alder). The lowest concentration of Cu was found in needles and leaves: in pines 1.77 mg · kg^{-1}, in birches 2.32 mg · kg^{-1}, and in black alders 2.75 mg · kg^{-1} (Fig. 5). The concentration of Cu in fine roots of all the trees grown on sludge was higher than that in large roots, and this difference made about two times for pines and black alders.

Lead. The concentration of Pb in all parts of the trees grown on sludge was higher than that of the background trees, except for pine stem, black alder branches and the leaves and needles

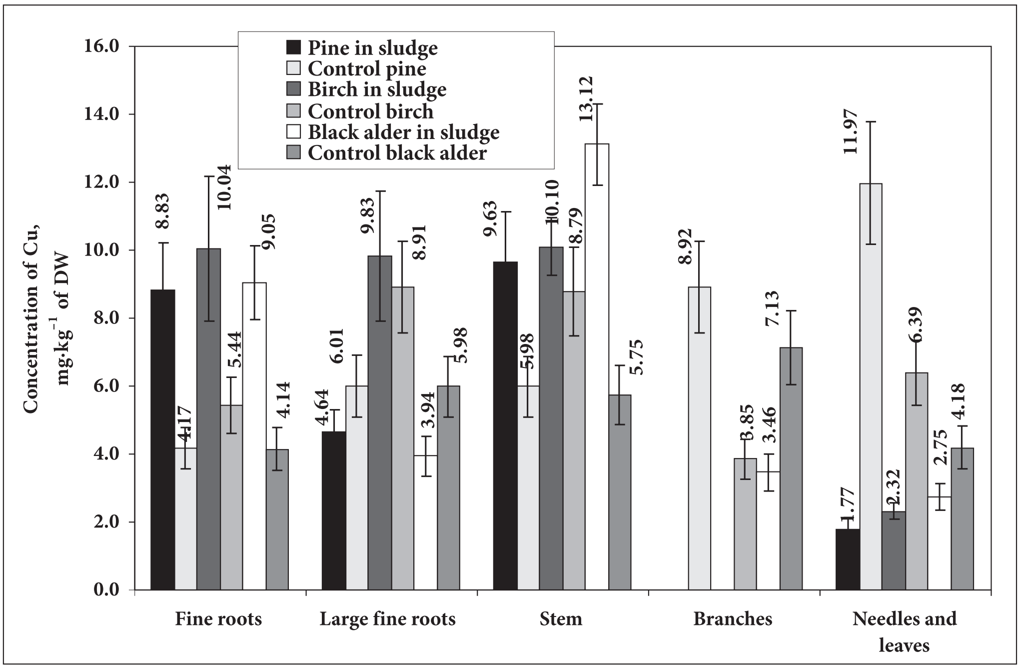

Fig. 5. Concentration of Cu in parts (fine roots Ø < 3 mm; large roots Ø > 3 mm, stem, branches and leaves and needles) of pine, birch and black alder that have grown in soil amended with sewage sludge (n = 4) and of control trees

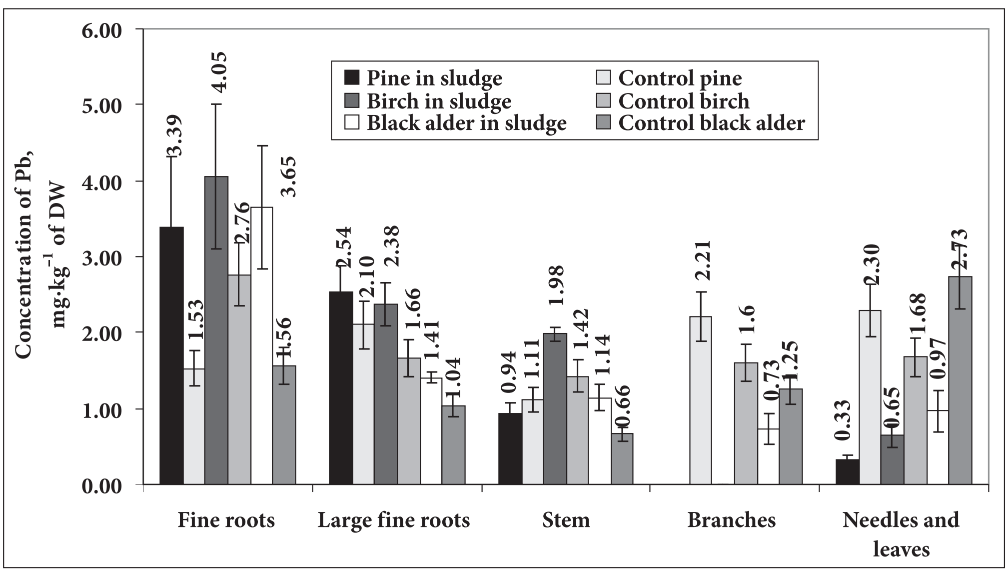

Fig. 6. Concentration of Pb in parts (fine roots Ø < 3 mm; large roots Ø > 3 mm, stem, branches and leaves and needles) of pine, birch and black alder that have grown in soil amended with sewage sludge (n = 4) and of control trees

of all the trees. Fine roots of pines and black alders (respectively 3.38 mg · kg^{-1} and 3.65 mg · kg^{-1}) as well as branches of birches (4.57 mg · kg^{-1}) accumulated the highest content of Pb. The lowest concentration of Pb was found in pine needles and in leaves of birches that have grown on sludge (respectively 0.33 mg · kg^{-1} and 0.65 mg · kg^{-1}) and in the case of black alders in the branches (0.73 mg · kg^{-1}) (Fig. 6). The concentration of Pb in fine roots of all the trees was lower than that in large roots.

Table 3 gives the sequence of parts of the tree seedlings following the increase of HM concentration. The distribution of HM concentration was uneven and varied in different parts of the same type of trees as well as in the same parts of different types of tree seedlings. There was a difference in HM concentrations in the above- and underground parts of tree seedlings. Lower concentration of Mn and Ni and higher concentrations of Pb and Cu were found in underground parts of tree seedlings. The largest concentrations in the underground parts were found for Zn, Ni and Pb in pine, for Mn and Ni in birch, and for Zn, Ni and Cu in black alder. The aboveground part of pines contained highest concentrations of Mn and Cu, of birch – Zn, Cu and Pb, and of black alder – of Zn, Ni and Cu.

The transfer factor (*TF*). The TF reveals the capacity of trees to extract HMs from soil. Taking into consideration the values of the TF, it is possible to select certain species of plants for remediation of the contaminated soil. The TF exceeding 1.0 was not identified in our study (Fig. 7). The TF values varied from 0.21

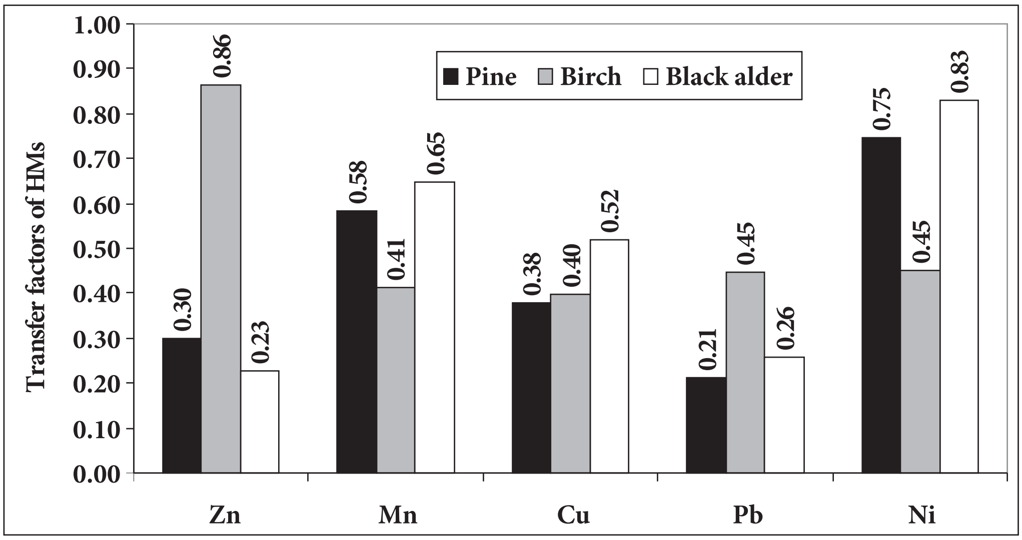

Fig. 7. Transfer factors of heavy metals (n = 4)

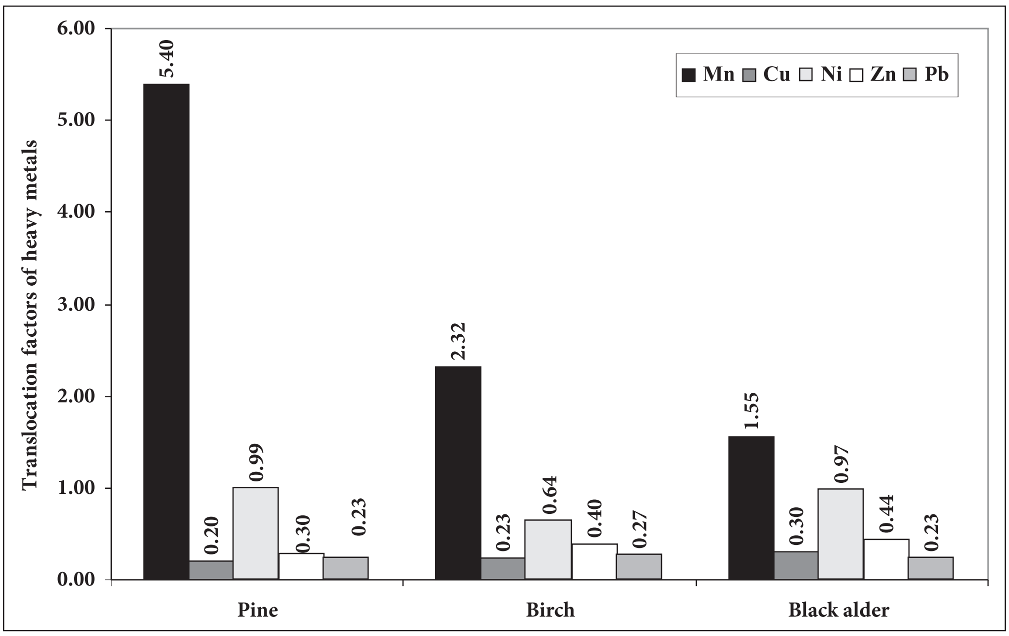

Fig. 8. Translocation factors of heavy metals (n = 4)

Table 3. **Sequence of tree seedling parts following an increase in HM concentration (parts in bold represent the underground parts of seedlings)**

HMs	Type of tree seedling	Sequence of tree parts following increase of HM concentrations
Zn	Pine	needles < stem < **large roots** < **fine roots**
	Birch	branches < **fine roots** < **large roots** < stem < leaves
	Black alder	**fine roots** < **large roots** < stem < leaves < branches
Mn	Pine	**fine roots** < **large roots** < stem < needles
	Birch	**fine roots** < leaves < stem < **large roots**
	Black alder	**large roots** < **fine roots** < stem < leaves < branches
Ni	Pine	**fine roots**, needles < stem, **large roots**
	Birch	leaves < **large roots** < stem < **fine roots**
	Black alder	**large roots** < **fine roots**, leaves < stem, branches
Cu	Pine	needles < **large roots** < **fine roots** < stem
	Birch	leaves < **large roots** < **fine roots**, stem
	Black alder	leaves < branches, **large roots** < **fine roots** < stem
Pb	Pine	needles < stem < **large roots** < **fine roots**
	Birch	leaves < stem < **large roots** < **fine roots**
	Black alder	branches, leaves < stem < **large roots** < **fine roots**

(Pb) to 0.75 (Ni) in pine, from 0.40 (Cu) to 0.86 (Zn) in birch, and from 0.23 (Zn) to 0.83 (Ni) in black alder. Pine and black alder had most efficiently uptaken Ni (respectively 0.75 and 0.83) and birch Zn (0.86). Higher than 0.5 values of the TF were found for Zn and Mn in pine and black alder, of Cu in black alder, and of Ni in all the trees. The average value of the TF reached 0.44 for pines, 0.51 for birches and 0.49 for black alder.

The HM translocation factor (TcF). The TcF of HMs from fine roots to leaves and needles of trees reflects the translocation of HMs from underground to aboveground tissues, or, in other words, the capacity of trees to transfer HMs up with the transpiration flow. The highest TcF, exceeding 1.0, was observed in the case of Mn (Fig. 8). Its TcF from fine roots to needles and leaves was the highest (TcF = 1.55–5.40). The TcF values of other HMs did not exceed 1.0 and could be presented in the following order: Pb, Cu < Zn < Ni. If we compare the translocation of HMs in different tree species, Mn and Ni are the most efficiently transferred metals in pines, whereas Mn, Ni, Zn in birches and black alders. TcF alues exceeding 0.5 were typical of Mn and Ni in all the trees (Fig. 8).

DISCUSSION

Because of the very heterogeneous composition of the sludge, an especially a high diversity of HM concentrations in the soil and in trees was found in the present study. Moreover, the distribution of HMs was uneven not only in the case of different tree species, but also among trees belonging to the same species.

Visually, no morphological changes in the trees were identified, although the mean concentrations of Zn and Mn were close to excess values for plants (Kabata-Pendias and Pendias, 1992). For other HMs (Ni, Pb and Cu) the concentrations were similar to natural levels (Kabata-Pendias, Pendias, 1992).

Higher concentrations of Zn in the leaves and needles of the background pines than in those grown on sludge support data of previous researches (Kabata-Pendias, Pendias, 1992; Mertens et al., 2001; Nissen, Lepp, 1997) and might be caused by a process during which a tree strives to remove Zn from its body with the leaves or needles (Dahmani-Muller et al., 2000). On the other hand, such difference might occur because of a lower content of water in needles contaminated with HMs and differences in senescence processes in the contaminated and the background sites. Due to the senescence processes ongoing in needles, the content of water, as well as the concentrations of N and K in them decrease (Giertych et al., 1997; Zelawski, 1967; Helmisaari, 1990, 1992). Higher concentrations of Zn in control pine stems, branches of black alder and pine needles can be explained by the fact that the environment became more acidic after the spread of the sludge (pH 4.2), if compared with the control site (pH 6.6). As a result, the amounts of bioavailable Al have increased thus limiting bioavailability of other macro-elements and certain micro-elements (Reich et al., 1994; Kabata-Pendias and Pendias, 1992). The concentrations of Al in the woodcutting area were 15–133 mg · kg^{-1} and in the control site only 6.2 mg · kg^{-1}.

The distribution of Mn concentration in the trees was uneven. The concentration exceeding 600 mg · kg^{-1} had no visible impact on the growth of the trees. It is already known that the conifers growning in forests can be resistant to the concentrations of Mn in the crown amounting to 400 mg · kg^{-1}, although there are evidences illustrating that conifers were affected even in the presence of lower concentrations of Mn (Stone, 1968). In our research, pines were not affected by Mn concentrations in their needles exceeding 180 mg · kg^{-1}, birches by approximately 600 mg · kg^{-1}, and black alders 113 mg · kg^{-1}. Larger amounts of Mn in many parts of the control trees, if compared with those grown on sludge, may be related to Al in the sludge concentrations about 7 times higher in the experimental site than in the control site. It is believed that huge amounts of Al in soil can reduce the absorption of other cations, especially of Mn (Oleksyn et al., 1996). Despite the opinion that more acidic soil can be the reason for a greater Mn uptake by trees, there are tree genotypes that are resistant to the toxic effect of Mn when the pH is low or which can accumulate Mn when the pH is high.

Ni is attributed to mobile elements (Helmisaari, 1990; Kabata-Pendias, Pendias, 1992). The results of our research confirmed this opinion. It has been established that Ni accumulation was very similar in all the examined trees and it did not exceed the level of 27 mg · kg^{-1}. In the presence of a high amount of bioavailable Ni in soil, trees of different species accumulated similar amounts of Ni if compared with other metals (e. g., Mn, Zn, Cu) that are more required for metabolism, enzymatic activity and the normal growth of trees.

The concentration of Cu in trees that had grown on sludge and in the control site in many cases was very similar and close to natural concentrations of Cu in plants (Kabata Pendias, Pendias, 1992). Cu is not actively transferred to trees because it is strongly bound with soil particles (Turner, Dickinson, 1993), but there are data illustrating high values of Cu biological uptake (Kloke et al., 1984). On the other hand, insignificant differences among Cu values in separate parts of trees can be explained by stabilization of Cu in wood (Lepp, 1981; Nissen, Lepp, 1997). Only slightly higher concentrations of Cu in the stems and lower in leaves of birches than in the underground part confirm the presumption that Cu is more abundantly accumulated in roots (especially in fine ones) of *Betula pendula* (Khan, 2001; Marschner, 1995). Higher concentrations of Cu in the leaves and needles of control trees, if compared with those of trees grown on sludge, may be related to a less efficient transfer of Cu because of a higher concentration of Al in the contaminated soil than in the control one, as it is known that increased Al concentrations limit the absorption of other micro-elements by plants.

The concentrations of Pb in the trees that have grown on sludge and in the control site did not exceed the natural concentrations of Pb in plants (Kabata Pendias and Pendias, 1992) (Fig. 7). Thus, Pb is not actively uptaken by the study trees. This is confirmed also by other researchers – Korentejar (1991) and Henning et al. (2000). Greater concentrations of Pb in pine stems, black alder branches and the needles and leaves of all trees grown on sludge, if compared with those of trees grown in the control site, could have been uptaken from higher concentrations of Pb in the natural forest soil where Pb is concentrated on the surface humus layer (Butkus et al., 2002). Pb of anthropogenic nature is more mobile in the soil, and therefore it was more difficult for trees growing on sludge to accumulate it.

The Fs of all HM by the examined trees were not the same. Zn and Ni (TF > 0.7) were the most efficiently uptaken metals, whereas the TF for Mn, Cu and Pb varied from 0.4 to 0.7. The values of the TF of certain metals were higher in trees grown on sludge than in naturally grown trees: Pb, Cu – 0.01–0.05; Zn – 1–2 (Korentejar, 1991; Butkus et al., 2007), and this means that the tree species studied may be successfully planted in soils fertilised with sewage sludge. In many cases, the environment of the soil and the concentration of other elements were important for HM transfer: the acidic environment of soil (pH 4.0–5.0) may promote a more active transfer of HMs to trees and may be hindered by the presence of large amounts of Al. As regards the tree species, a slightly greater uptake of HMs is more characteristic of birches and black alders than of pines. This confirms the statements that *Betula*, although not attributed to hyper-accumulators, may be efficiently used for removing HMs from contaminated soils (Rosselli et al., 2003). *Alnus glutinosa* is attributed to tree species that can accumulate Zn (Pulford et al., 2001) as well as Mn and Ni.

The highest TcF (over 1.5) has been established in the case of Mn, and the most active transfer of Mn goes in the direction from the roots of a pine to its needles. Other researches also claim that the amount of Mn in leaves increases with the growth and maturity of trees (Ulrich, 1983; Kavvadias, 1999) as Mn is actively transferred from roots to leaves. According to tree species, higher TcFs of Mn and Ni are typical of pines, whereas higher levels of Zn, Cu and Pb are found in birches, possibly because of an active transfer of metals to younger tissues, especially in pines (Jarvis, Jarvis, 1963).

The heterogeneous composition of the sludge determined the uneven distribution of HMs in the underground and above-ground parts of tree seedlings. It was determined that more Pb was more accumulated in fine roots whereas Cu in stems of seedlings, possibly because of a more intensive Cu accumulation in wood tissues and a low translocation of Pb.

CONCLUSIONS

1. Phototoxic concentrations of HMs, referred to in the literature, not always specify the levels upon reaching which a tree becomes apparently vulnerable. It is probable that the impact of phytotoxic concentrations of HMs is either strengthened or weakened by a tree habitat: soil characteristics, plant species, a lack of nutrient materials, etc.

2. It was suggested that the characteristics of the sludge (e. g., pH, Al concentration), plant physiology (e. g., the ageing processes in the pine needles every 4 years, possible HM transfer into younger tissues, striving of the trees to remove certain HMs through leaves, etc.) might influence the HM transfer to the trees growing on sludge.

3. The examined trees most efficiently took up Zn and Ni (the TF values were >0.7) and slightly less efficiently Mn, Cu and Pb (the TF values varied from 0.4 to 0.7). Slightly higher amounts of HMs were taken up by birches and black alders.

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Donatas Butkus, Edita Baltrėnaitė

SUNKIŲJŲ METALŲ KAUPIMASIS MEDŽIŲ SODINUKUOSE TRĘŠIANT DIRVĄ NUOTEKŲ DUMBLU

Santrauka

Augalų ir sunkiųjų metalų ryšys pagrįstas augalų geba pasisavinti sunkiuosius metalus arba trukdyti jiems pasišalinti iš dirvožemio. Medžiai dėl didelės biomasės ir ilgo vegetacijos laiko yra patrauklūs sunkiųjų metalų pašalinimui iš dirvožemio, tačiau ne visų rūšių medžiai vienodu efektyvumu kaupia sunkiuosius metalus, o skirtingų medžių geba kaupti sunkiuosius metalus dar nėra plačiai išnagrinėta.

Šio darbo tikslas – palyginti trijų natūraliai augusių medžių – paprastosios pušies (*Pinus sylvestris* L.), karpotojo beržo (*Betula pendula* Roth) ir juodalksnio (*Alnus glutinosa* (L.) Gaertn) – gebą kaupti iš nuotekų dumblo Zn, Mn, Ni, Pb ir Cu. Pastebėta, kad dumblo savybės (pvz., pH ir Al koncentracija), augalų fiziologija (pvz., senėjimo procesai pušies spygliuose kas 4 metai, galima sunkiųjų metalų pernaša į jaunesnius audinius) gali turėti įtakos sunkiųjų metalų pernašai iš nuotekų dumblu patręšto dirvožemio į medžio sodinukus. Aptariama skirtingų sodinukų geba kaupti sunkiuosius metalus ir veiksniai, galintys turėti įtakos sunkiųjų metalų pernašai.

Raktažodžiai: nuotekų dumblas, sunkieji metalai, pernašos faktorius, translokacijos faktorius, *Pinus sylvestris*, *Betula pendula*, *Alnus glutinosa*