Journal of Soil Science and Plant Nutrition
https://doi.org/10.1007/s42729-024-01652-w

ORIGINAL PAPER

Organic Amendments to Short Rotation Coppice (SRC) Plantation Affect Species Richness and Metal Accumulation of Spontaneously Growing Herbaceous Plants

Michael O. Asare[1] · **Elisa Pellegrini**[2] · **Jiřina Száková**[1] · **Johanna Ruth Blöcher**[3] · **Jana Najmanová**[1] · **Pavel Tlustoš**[1] · **Marco Contin**[2]

Received: 20 June 2023 / Accepted: 29 January 2024

Abstract

Excess potentially toxic metals (PTMs) in soils require ad hoc approaches to salvage. Hence, this study explored the shoot accumulation of cadmium (Cd), lead (Pb), and zinc (Zn) by herbaceous plants growing under previously established *Salix* and *Populus* clones Short Rotation Coppice (SRC) with compost and sewage sludge applications in an abandoned metallurgical site, Podlesí, Czech Republic; PTM decontamination of soils. Soils within the SRC experimental site and outside considered as control were analyzed for their chemical properties by multi-analytical techniques. Shoots of spontaneously growing herbaceous plants under trees in the site and without trees in control were determined for pseudo-total Cd, Pb, and Zn contents. Moderately to slightly acid soils, high cation exchange capacity, and C/N ratio supported mineralization and relative mobility of total Cd (7.7–9.76), Pb (1541–1929), and Zn (245–320 mg kg^{-1}) in soils. Although soil amendments improved chemical properties, compost application supported higher species richness than sewage sludge. Over 95% of plants accumulated Cd and Zn above the WHO threshold and green fodder in the Czech Republic, with 36% Pb above the regional limit (40 mg kg^{-1}). Approximately 100, 50, and 6% of herbaceous species had Cd, Pb, and Zn accumulation, respectively, higher than published average upper limits in plants (0.2 Cd, 10 Pb, and 150 Zn mg kg^{-1}). Dicots recorded higher Cd content, *Tenacetum vulgare* (L.), *Hypericum maculatum* (Crantz), and *Cirsium arvense* (L.); *Stachys palustris* (L.), *Lamium perpereum* (L.), and *Campanula patula* (L.) for Pb; *Glechoma hederaceae* (L.), *C. patula*, and *C. arvense* for Zn in all treatments. Appropriate soil amelioration of SRC-supported PTM mobility and excess herbaceous species shoot accumulation, growth, and richness.

Keywords Compost · Dicot · Potentially toxic metals · Sewage sludge · Shoot accumulation · Soil chemical properties

1 Introduction

Soil contamination by potentially toxic metals (PTMs), typically lead (Pb) and cadmium (Cd), is a widespread problem. For example, Pb is one of the most toxic elements whose extensive use from anthropogenic interferences, ore mining, smelting, and tailings, has caused environmental (Gupta et al. 2019; Kushwaha et al. 2018) and health-related issues (Han et al. 2020; Varrica et al. 2018). Only in the Czech Republic, there are over 800 ore deposits, with a similar number of known metalliferous mineral occurrences (Bufka et al. 2005). Therefore, strict measures are required with the increasing trends in metal production (U.S. Geological Survey 2020; Shahabi-Ghahfarokhi et al. 2021), especially in Europe (Bertrand et al. 2016).

Various biological, chemical, and physical techniques to eliminate PTMs in soils are commonly used (Aparicio et al.

✉ Michael O. Asare
asare@fzp.czu.cz

[1] Department of Agro-Environmental Chemistry and Plant Nutrition, Faculty of Agrobiology, Food, and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129Prague 6, 16500 Suchdol, Czech Republic

[2] Department of Agricultural, Food, Environmental, and Animal Sciences, University of Udine, Via Delle Scienze 206, 33100 Udine, Italy

[3] Department of Water Resources and Environmental Modeling, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, 16500 Prague, Suchdol, Czech Republic

2021; Ashraf et al. 2018). Conventional strategies for cleaning PTM-contaminated lands, e.g., soil washing (Shen et al. 2019), solidification (Matec Industries 2021), and vitrification (Liu et al. 2018), are often ex situ and require high treatment costs. These approaches can result in the loss of soil fertility and biodiversity (Eissa and Almaroai 2019; FAO 2017; Liu et al. 2019). Meanwhile, using phytoremediation (plant-based approach) to remove PTMs in contaminated soils outscores the demerits of conventional methodologies (Reeves 2006; Tonelli et al. 2020; van der Ent et al. 2003). During the selection process for tolerant plants for effective PTM removal, it is vital to consider species capable of recovering soil health, e.g., perennial herbaceous plants (Chamberlain et al. 2022).

Several factors affect the mobility, immobilization, and uptake of PTM in soils, e.g., pH, element content, root architecture, and organic matter (Borah et al. 2018; Zeng et al. 2011). Although organic amendment, including the application of compost and sewage sludge, improves soil fertility for plant growth, it contributes to microbial count and diversity in soils capable of solubilizing PTMs for plant accessibility. Moreover, the addition of organic matter can influence the number of plant species (Moreno-Peñaranda et al. 2004). As metal-contaminated soils are not suitable for the cultivation of crops, a cleanup campaign becomes pertinent.

According to agricultural and environmental legislation, PTM-contaminated soils are not suitable for the cultivation of food crops and herbage and should undergo extensive remediation actions, a condition that makes the management of polluted sites often not sustainable. In contrast, the use of PTM-polluted soils to grow high biomass woody plants managed as Short Rotation Coppice (SRC) allows for reduced environmental mobility of PTM and produces polluted woody biomass (Zárubová et al. 2015), thus representing an option to reduce both the environmental impact of PTM-polluted soils and produce income from the use produced biomass. Fast-growing species of *Salix* and *Populus* spp. SRC have shown high extraction of PTMs in contaminated soils (Goliński et al. 2015; Hassinen et al. 2009) and produce large amounts of biomass in rotations of 3 to 10 years (Šlapokas and Granhall 1991). It has been widely reported that phytomanagement of PTM-polluted soils with SRC of fast-growing plants (e.g., willow and poplar) allows for restoration of soil physical and chemical fertility (Courchesne et al. 2017) and microbial diversity and activity, especially if aided by the use of soil ameliorants. Meanwhile, the diversity and PTMs accumulation potency of herbaceous species (plants without persistent woody stem above ground) in polluted soils is still not well-understood, especially in the case of perennial species. Studies have been carried out on short-lived herbaceous species or plants characterized by low-biomass (e.g., Chen et al. 2014; Wei et al. 2006), and plant species such as *Lolium perenne* (L.) and *Poa pratensis* (L.) were used to remove copper (Cu), Cd, and Pb from sewage water (Liu et al. 2019).

Selecting resistant herbaceous plants for PTM removal can offer an even more cost-effective and time-saving approach to improve the phytomanagement of PTM polluted soils and also improve the self-sustenance of SRC phytomanagement interventions (Licinio et al. 2023).

The study focussed on herbaceous plant growth and their ability to accumulate PTMs from contaminated soil under SRC of *Salix* and *Populus* species after different organic treatments. The field trial was established in 2008 (Zárubová et al. 2015).

The study aimed to evaluate the following aspects of herbaceous plant species: (i) the composition of the herbaceous plant species community and the effects of compost and sewage sludge on species count and (ii) the accumulation potential of PTMs of the detected species and the eventual effects of compost and sewage sludge. To our knowledge, this is the first study to focus on the potential of herbaceous plants to accumulate PTMs in the presence of fast-growing woody plants and may help improve the phytomanagement of metal-polluted soils.

2 Materials and Methods

2.1 Study Site and Field Experiment

The study occurred in Podlesí (49° 42′ 24″ N, 13° 58′ 32″ E), near the ancient mining and smelting town Příbram, 58 km south of Prague, Czech Republic. The site represents moderately Cd, Pb, and Zn-contaminated agricultural soil, predominantly from atmospheric deposition due to its proximity to an abandoned smelter (approximately 200 m).

The elevation of the study area is 500 m above sea level (asl), with mean annual precipitation and temperature of 700 mm and 6.5 °C, respectively. The site characterizes modal Cambisols (syn. *modální* Kambizem) with geological substrates formed mainly by schists, sandstones, graywackes, and quartz (Czech Geological Survey 2012; Němeček and Kozák 2005).

Minerals rich in PTM include galenite (PbS), sphalerite (ZnS), boulangerite ($Pb_5Sb_4S_{11}$), and antimonite (Sb_2S_3) throughout the study area. The levels of these minerals also cause natural increases in the content of PTMs in the soil (Borůvka and Vacha 2006).

To cover the variability of soil and herbaceous plant samples, we took advantage of the experimental design of the *Salix* and *Populus* clones SRC in the site (see Zárubová et al. 2015 for a detailed description of the experimental design). The SRC consisted of two *Salix* clones, allochthonous (*Salix schwerinii* × *Salix viminalis*) × *S. viminalis*) hybrid Tordis and autochthonous *Salix* × *smithiana* clone S-218. Among

Populus clones consisted of the most widely planted hybrid clone in the Czech Republic, *Populus maximowiczii* × *Populus nigra* J-105, also known as the Max-4 and *P. nigra* clone Wolterson. Shoots were harvested after four seasons in 2012 and then after two more seasons in 2014.

The *Salix* and *Populus* clones appear in four split-plot randomized blocks with the application of compost (co), sewage sludge (ss), and control (*k*) without any treatment. The ratio of compost and sewage sludge to spoil material was estimated to give an appropriate range of contents as follows: compost composition, 59.9% dry matter, nitrogen (N) 16 kg/t, 20 t/ha dry compost, and 33.4 t/ha with an application of 100 kg/plot with the content of elements given in Table S1 (Kubátová et al. 2016); sewage sludge, 20.4% dry matter, N 46 kg/t dry matter, 6.96 t/ha sludge dry matter, 34.8 t/ha of fresh sludge on a plot size of 29.25 m^2. The application of sewage sludge was 100 kg/plot applied in 2012. An exact description shows that *Salix* clones accumulated up to 55 Cd, 29 Pb, and 506 Zn mg kg^{-1} in dry-weight biomass compared to 25 Cd, 30 Pb, and 206 Zn mg kg^{-1} in *Populus* at the phytoremediation experimental site (Kubátová et al. 2016).

2.2 Soil Sampling and Preparation

In the experimental site, soil samples were randomly collected from the randomized blocks of *Salix* and *Populus* clones from *k*, co, and ss, according to the intra-row distance of 0.25 m. For each treatment, soil sampling involved random collection around the same tree species on one block (7.5 × 1.3 m) to avoid lateral mixing of adjacent soils. The total size of the experimental site represents approximately 100 m^2. Each randomized block of different treatments was represented by nine replicates of soil samples.

Additionally, soil samples were randomly collected outside the experimental site, without trees, as control (*c*) with the same soil and parent bedrock. At *c*, the sampling covered nine soil samples taken randomly within an area < 100 m^2, according to the distribution of the herbaceous plant species. In this case, soil samples are collected around locations with herbaceous plants to detect the direct effect of the physicochemical properties of the soil.

Each soil sample consisted of five subsamples randomly taken from the arable layers (upper 30 cm) with a soil probe (Purchhauer type, core diameter: 30 mm). In total, 36 mixed soil samples (9 replicates × 4 treatments) were collected as an acceptable method to average out short-range variation, making the results and generalization more reliable (Asare et al. 2020). Samples of each soil were air-dried, disaggregated, and passed through a 2-mm mesh sieved to homogeneity for subsequent chemical analysis. Each representative soil sample was prepared into three replicates.

2.3 Determination of Soil Chemical Properties

The pH of all soil samples followed the measurement by a 1/2.5 (w/v) suspension of soil and 0.01 M calcium chloride ($CaCl_2$). Carbonates were determined volumetrically following the method proposed by Kalra and Maynard (1991).

The total carbon in soil samples again was determined according to automated thermal analyses in which carbon is converted to carbon dioxide (CO_2) by flash combustion at 1080 °C (Costech Instruments Elemental Combustion 102 System elemental analyzer, Thermo Scientific 103 Delta V Advantage). Carbonates were previously removed from 10 mg of soil by treatment with hydrogen chloride (HCl) in silver capsules. The total N content was determined from 50 mg of soil using the modified Dumas combustion method at 960 °C with a CNS elemental analyzer (Vario MACRO cube CNS; Elementar Analysensysteme GmbH, Langenselbold, Germany). The cation exchange capacity (CEC) was determined by ISO 11260 (1994).

The total contents of soil PTM (Cd, Pb, and Zn) and sulfur (S) in the soils were extracted using the USEPA 3052 extraction procedure (International Organization for Standardization, USEPA 1996) with an extraction mixture of 65% nitric (HNO_3), 36% hydrochloric (HCl), and 38% hydrofluoric (HF) acids. The total element content in soil digest was determined by inductively coupled plasma-optical emission spectrometry (ICP-OES, Agilent 720, Agilent Technologies Inc., USA), equipped with a two-channel peristaltic pump, a Struman-Masters spray chamber, and a V-groove pneumatic nebulizer made of inert material (experimental conditions, power of 1.2 kW, plasma flow of 15.0 $Lmin^{-1}$, auxiliary flow of 0.75 $Lmin^{-1}$, nebulizer flow of 0.9 $Lmin^{-1}$).

2.4 Plant Sampling, Classification, and Preparation

A comprehensive identification campaign and sampling of herbaceous plant species were well-performed following a systematic characterization of mature plant species. The geobotanical description of the herbaceous species was carried out in situ following the methodology and traditional techniques adopted in Plant Taxonomy. The nomenclature of the taxa used followed that adopted in Angiosperm Phylogeny Group (APG) IV (https://www.gbif.org/species/3106).

Plant materials collected were whole green biomass (shoot above the soil surface) of mature herbaceous plant species in all four sampled locations. The samples were washed with deionized water (H_2O) to remove ions transported from environmental dust. Next, we dried all the samples in an electric oven (SLW 53 STD, Pol-Eko, Wodzisław Śląski, Poland) at 60 °C for 48 h and then cut them in a stainless steel Retsch friction mill (Retsch, Haan, Germany; particle size 0–1 mm) to obtain homogenized-powdered samples.

2.5 Determination of PTMs in Plant Samples

Powdered samples of each dry weigh plant species were further analyzed for PTM following the microwave-assisted acid approach (USEPA 3051 1994), with contents determined by the same ICP-OES (Agilent 720, Agilent Technologies Inc., USA).

2.5.1 Analytical Protocol

An aliquot (~ 500 mg of dry matter) of the plant sample was weighed in a digestion vessel for elemental content in the determination of the plant biomass. Concentrated HNO_3 acid of 8.0 mL and 30% peroxide (H_2O_2) (2.0 mL) (Analytika Ltd., Czech Republic) were added. The mixture was heated in an Ethos 1 (MLS GmbH, Germany) microwave-assisted wet digestion system for 30 min at 220 °C. After cooling, we quantitatively transferred the plant digests into a 20-mL glass tube, topped with deionized H_2O and kept them at laboratory temperature until the determination of the contents of PTM.

For quality assurance of the analytical data, a standard reference material (NIST SRM tomato leaves 1573) certified for the determination of total contents of arsenic (As), Cd, Cu, and Zn in plant biomass was used (http://www.nist.gov/srm) and contents of PTMs determined by same ICP-OES. ICP-OES has previously been used for the determination of the total Pb content in dried-weight plant samples (Gonçalves et al. 2019; Yener 2019). The results of the control elements (Cd and Zn) revealed a recovery (R) of 90% with an obtained SRM value of 0.061 ± 0.01 Cd and 80.4 Zn mg kg^{-1} to original values—0.068 ± 0.012 Cd and 82.3 ± 3.9 Zn mg kg^{-1}, respectively (Magnusson and Örnemark 2014).

$$R = (\text{mean value of element} \div \text{mean reference value}) \times 100 \quad (1)$$

According to the obtained results, the precision of the analytical method was adequate for this study.

2.6 Estimation of Bioaccumulation Factor (BAF)

The *BAF* (soil-shoot quotient) explains the ability of a plant to translocate the metal from the soil to shoot. The use of *BAF* is a vital parameter when associated with the permissible limits of PTMs in plants. The estimation of *BAF* follows the equation of Baker (1981) and Vondráčková et al. (2015).

$$BAF = \frac{Content\ of\ PTM\ in\ shoot}{content\ of\ PTM\ in\ soil} \quad (2)$$

The accumulation of PTMs in the studied plant species was evaluated against the regulatory limits of plant-origin animal feed raw materials, following the Czech Republic Regulation (Commission Directive 2010/6/EU), WHO (1996), and the average values expected in plant biomass by Kabata-Pendias (2011).

2.7 Statistical Analysis

For data generated from field and laboratory, we checked for homogeneity of variance and normality with the Levene and Shapiro–Wilk tests, respectively. Data for soil chemical properties met assumptions for the use of parametric tests. In that case, the analysis of variance (ANOVA) model with Tukey's honestly significant difference (HSD) post hoc test for significant ANOVA results was applied to determine significant differences in soil properties in all treatments. Differences between treatments were considered significant at $p < 0.05$. Principal component analysis was used to show the variability among herbaceous plants according to monocot/dicot and botanical families.

In the case of PTM data of plants for each treatment, the Kruskal–Wallis analysis of variance model was applied to determine the significant differences since there was no normality. We evaluated the relationships between soil chemical properties using Pearson's correlation (r). Data for soil and plant samples were statistically analyzed using R software version 4.1.3 with "data.table," "ggplot2," and "factoextra" (R Development Core Team 2010).

3 Results

3.1 Soil Chemical Properties

There was a significant effect of the content of Cd, Pb, and Zn between treatments (Table 1). The PTM content in the soil ranged from 7.7 to 9.8 mg Cd kg^{-1}, 1541–1929 mg Pb kg^{-1}, and 245–320 mg Zn kg^{-1} in all treatments (Table 1) compared to global (0.3 Cd, 100 Pb, and 200 Zn mg kg^{-1}) and regional regulatory limits (0.5 Cd, 60 Pb, and 150 Zn mg kg^{-1}) (Decree of the Ministry of Environment No. 153/2016 Coll., Czech Republic) limits for agricultural soils. Soil pH, contents of total C, N, S, CEC, and C/N ratio corresponded to the range of values characteristic of soils of the temperate climate zones (Antisari et al. 2021) with notable heterogeneity (Fig. 1). A $pH_{[CaCl2]}$ range of 5.2–5.8 (moderate to slight acidity) can support relative solubility of Cd, Pb, and Zn (Fig. 1a). Compared to co (pH 5.8) in all treatments, the effect of compost application resulted in a reduction of soil acidity.

Treatments with ameliorants increased the amount of organic matter, indicated by the significantly high contents of total C, N, and S (Fig. 1b, c, e) and a suitable C/N ratio (Fig. 1d) for mineralization of nutrients.

The application of organic matter also relates to the significant increase in CEC (Fig. 1f). The release of positive

Table 1 Mean content (±SD) of total Cd, Pb, and Zn under different treatment of soils in the SRC experimental site and control without trees

Treatment mg kg^{-1}	Cd	Pb	Zn
c	8.04 ± 2.12ab	1872 ± 346b	278 ± 35.6c
co	9.76 ± 0.71a	1929 ± 210a	320 ± 23.7a
k	7.7 ± 1.7b	1541 ± 255.3d	245 ± 28.8d
ss	7.73 ± 1.91b	1695 ± 413c	290 ± 66.6b
p-value	0.002	0.001	0.001

The *p*-values were obtained by one-way ANOVA Test. Using the Tukey post hoc test, the mean contents of each potentially toxic metal (PTM—Cd, Pb, and Zn) in each treatment with different letters are significantly different.

SD standard deviation, *SRC* Short Rotation Coppice, *c* control without trees, *co* treatment with compost application, *k* no organic matter treatment in the experimental site, and *ss* treatment with sewage sludge

ions (H^+) in the acid soil reaction in the case of compost application can contribute to the comparatively high CEC. The correlations between soil chemical properties for each treatment are shown in Table 2. There was a negative correlation between pH and all soil chemical properties in *k* ($r = -0.84$ to -0.98) and vice versa for the other treatments except for pH and N (in *c)* and S (in co). The possibility of sorption is well-indicated by the relationship between C and N in both co and ss treatments, while the pH and S in the application of compost were negative ($r = -0.3$).

3.2 Description of Herbaceous Species Richness and Diversity

Different treatments resulted in varied counts of perennial herbaceous species, botanical families, and monocot/dicot (Tables S2 – S4). Exactly 53 herbaceous plants were recorded, with 58% and 51% for the *c* and co treatments,

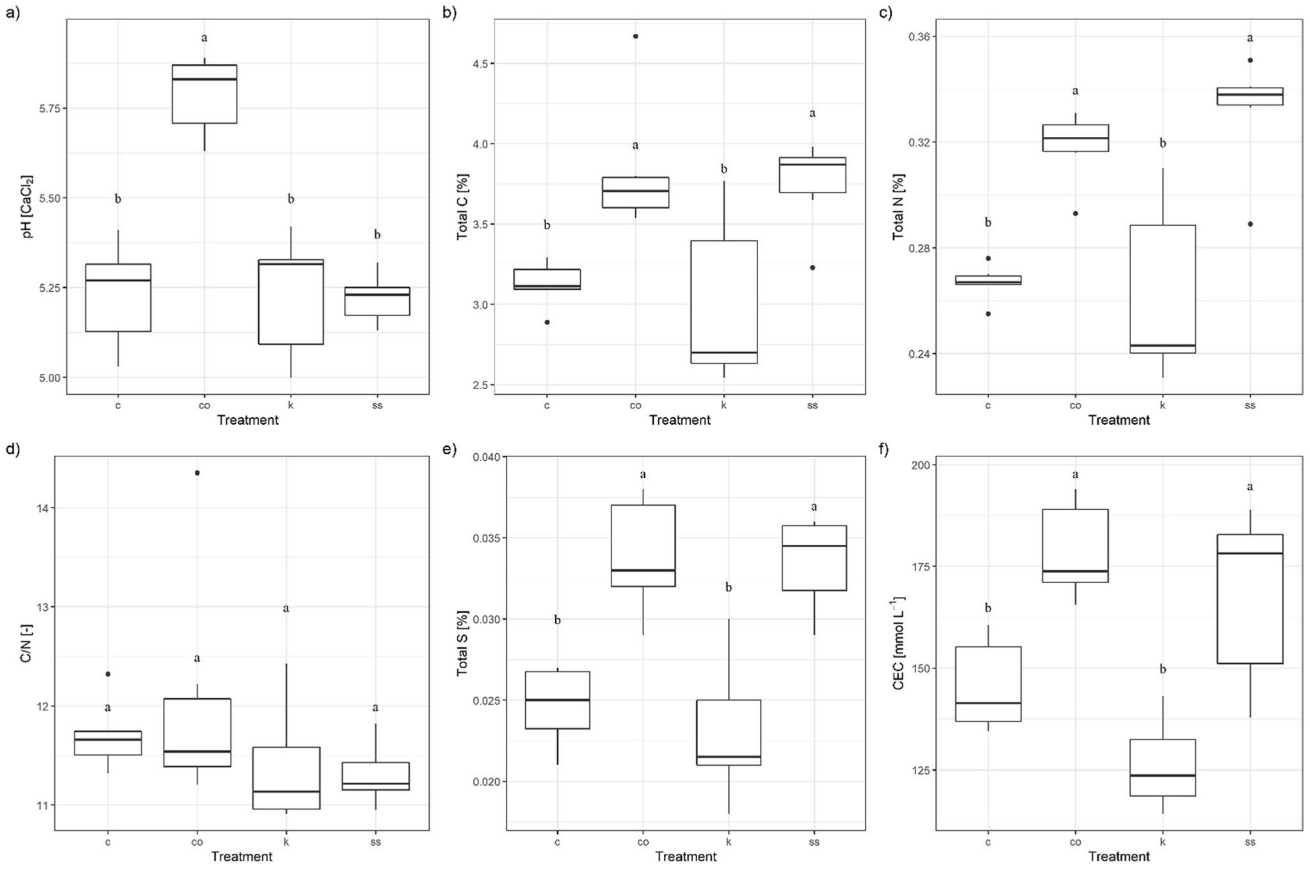

Fig. 1 Effect of different soil treatments on **a** pH and content of **b** total C, **c** total N, **d** C/N ratio, **e** total S, and **f** CEC. Mean values with different letters significantly differ using the Tukey HSD post hoc test. *p*-value (one-way ANOVA) was significant at < 0.05. Error bars indicate standard deviation. Abbreviations: *c*, control without trees; co, treatment with compost application; *k*, no organic matter application in the experimental site; and ss, treatment with sewage sludge application

Table 2 Correlations between chemical properties of soils at different treatments

	pH	CEC	Tot C	Tot N	Tot S	C/N ratio
c						
pH		0.51*	0.3	−0.01	0.63*	0.47
CEC			0.38	−0.07	0.65*	0.68*
Tot C				0.80*	0.86*	0.85*
Tot N					0.62*	0.36
Total S						0.80*
C/N ratio						
co						
pH		0.68*	0.34	0.40	−0.3	0.01
CEC			−0.17	0.41	−0.39	−0.36
Tot C				0.4	0.42	0.92*
Tot N					0.1	0.01
S						0.41
C/N ratio						
k						
pH		−0.86*	−0.98*	−0.96*	−0.84*	−0.91*
CEC			0.88*	0.93*	0.93*	0.65*
Tot C				0.99*	0.89*	0.93*
Tot N					0.95*	0.86*
S						0.69*
C/N ratio						
ss						
pH		0.78*	0.06	0.34	0.80*	−0.65*
CEC			0.50*	0.70*	0.97*	−0.33
Tot C				0.93*	0.57*	0.51*
Tot N					0.74*	0.17
S						−0.22
C/N ratio						

Tot total, *c* control without trees, *co* treatment with compost application, *k* no organic matter treatment in the experimental site, and *ss* treatment with sewage sludge application. Locations with an asterisk (*) indicate a moderate ($r = -0.5/0.5$ to $-0.7/0.7$) to strong significant correlation ($r = -0.8/0.8$ to $-0.98/0.99$) at $p < 0.05$

Table 3 Characteristics of biomass under different treatments

Treatment	No. of species	No. of monocot	No. of dicot	No. of Families
c	31	21	10	13
co	27	23	8	15
k	24	15	10	14
ss	24	15	9	9

No. number, *c* control without trees, *co* treatment with compost application, *k* no organic matter application in the experimental site, and *ss* treatment with sewage sludge application

respectively, and 45% each for *k* and ss (Table 3). Although organic matter application plays a significant role in species richness, the quality of the materials and conditions of preparation is vital (Weisser et al. 2017). The application of sewage sludge supported the nutrient status of the soil and plant species but not the richness. The botanical families and monocot/dicot showed 47.2 and 31.7% variability in the first and second axes of the ordination diagrams (Fig. 2a, b). In all fields, we recorded 20 botanical families with a high prevalence of species in Poaceae, Asteraceae, Fabaceae, and Rubiaceae (Fig. 2a).

3.3 PTM Accumulation by Herbaceous Plants and Bioaccumulation Factor (BAF)

The contents of PTMs accumulated by each herbaceous plant species and monocots/dicots under different treatments are shown in Figs. 3, 4, 5 and 6. The contents of Cd in *c*, co, *k*, and ss treatments ranged from 0.51 to 16.5 mg kg^{-1} in *Lathyrus pratensis* (L.) and *Tanacetum vulgare* (L.), 0.22–29.6 mg kg^{-1} in *Urtica dioica* (L.)

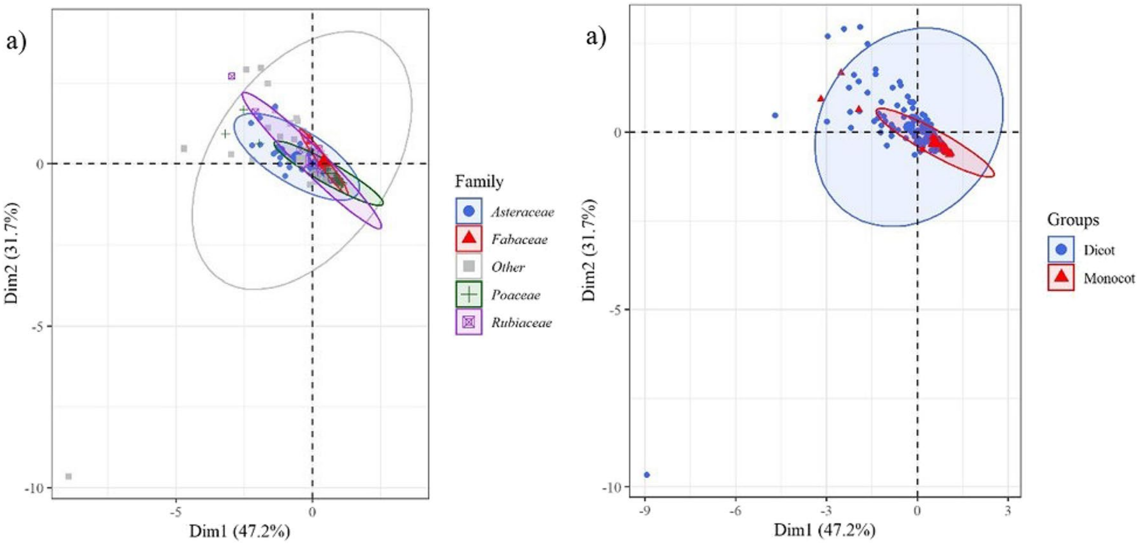

Fig. 2 Ordination diagram of the first and second axis of the distribution and variability of **a** botanical families and **b** taxa (monocot and dicot) of studied herbaceous plant species

and *Hypericum maculatum* (Crantz), 0.23–43.7 mg kg^{-1} in *Holcus lanatus* (L.) and *H. maculatum*, and finally 0.23–19 mg kg^{-1} in *Elymus repens* (L.) and *Cirsium arvense* (L.), respectively (Fig. 3a–d).

The mean accumulation of Cd by plants in all treatments was 4.29 in *c*, 4.52 in co, 4.77 in *k*, and 3.22 mg kg^{-1} for ss. *H. lanatus* recorded the overall highest accumulation of Cd in all treatments. The accumulation of Cd by plants in all treatments was above published average upper limits in plants (0.2 mg Cd kg^{-1}) given by Kabata-Pendias (2011).

The lowest Pb content in the c treatment was 4 mg kg^{-1} in *Alopeculus pratensis* L. and the highest was 70 mg kg^{-1}in Stachys *palustris* (L.) (Fig. 4a). Furthermore, the content of Pb in co, *k*, and ss treatments ranged from 5.7 to 61 mg kg^{-1} in *Crepis biennis* (L.) and *Lamium purpureum* (L.), 2.33–33 mg kg^{-1} in *Poa* sp. and *C. patula*, and 4.9–30 mg kg^{-1} in *Trifolium* sp. and *S. palustris*, respectively (Fig. 4b–d). The mean Pb accumulation by plants in all treatments was 19.7 in *c*, 18.4 in co, 11.8 in *k*, and 13.3 mg kg^{-1} for ss. Exactly 19 (61%), 21 (78%), 10 (42%), and 12 (50%) herbaceous species from *c*, co, *k* and ss treatment accumulated a Pb content above the published upper limits in plants—10 mg Pb kg^{-1} (Kabata-Pendias 2011).

The content of Zn was above the average upper limits in plants—150 mg kg^{-1} Zn—according to Kabata-Pendias (2011), only in *Glochoma hederacea* (L.), *Campanula patula* (L.), and *C. arvense*. The Zn content in *c* treatment ranged from 20.9 to 185 mg kg^{-1} in *Calamagrostid epigejos* (L.) and *Glochoma hederacea* L., respectively (Fig. 5a).

Similarly, for co, *k* and ss treatments, the Zn content ranged from 30 to 162 mg kg^{-1} in *C. biennis* and *Campanula patula* (L), 18.9 to 164 mg kg^{-1} in *H. lanatus* and *C. patula* and 25 to 167 mg kg^{-1} in *Cardus acanthiodes* (L) and *C. arvense,* respectively (Fig. 5b–d). Mean Zn accumulation in the herbaceous plants ranged from 56 to 71 mg kg^{-1} in treatments *k* and co, respectively.

Accumulation of Cd, Pb, and Zn by monocot/dicot under different treatments is in Fig. 6. Generally, there was the highest accumulation of PTMs in dicots compared to monocots (Fig. 6). Compared to 245–320 mg Zn kg^{-1} in the soils, all the plants accumulated lesser in each treatment. There were high accumulations of Cd ($BAF > 1$) visible among 11 herbaceous species under different treatments (Table 4). The *BAF* of Pb and Zn for all the plants studied was below 1 ($BAF < 1$) as no plant accumulated PTM above the content of the soil (Table S6).

4 Discussion

The current study demonstrated the potential of herbaceous plants growing under phytoremediation scheme of *Salix* and *Populus* SRC plantation to accumulate Cd, Pb, and Zn from contaminated soil in varying contents in their shoots. Some plants possess the ability to persist in PTM-contaminated soils via accumulation (Sun et al. 2006) of excess PTMs (Dalvi and Bhalerao 2013) into the aerial parts. Identification of these herbaceous plants (common weeds) in contaminated soils and accumulation is a prerequisite for the bioindication of soil pollution and the availability of metals to plants and crops (Pietrelli et al. 2022).

Studies have shown that herbaceous species including *Artemisia vulgaris* L., *Heracleum sphondylium* L., and

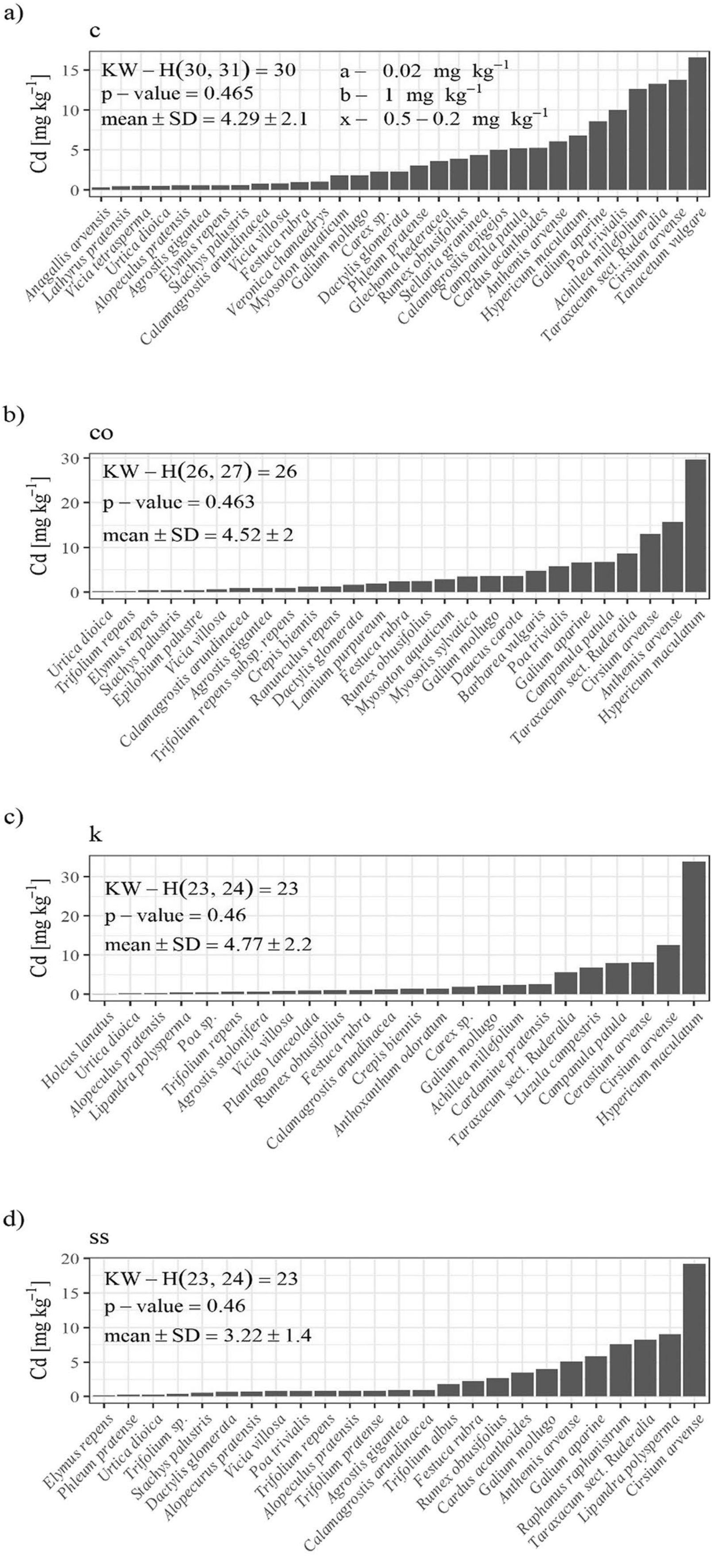

Fig. 3 The mean content of Cd in shoots of herbaceous plant species under different soil treatments **a** *c*, **b** co, **c** *k*, and **d** ss. The *p*-value was obtained by the Kruskal–Wallis analysis of variance (ANOVA). Abbreviations: *c*, control without trees outside the Short Rotation Coppice (SRC) experimental site; co, treatment with compost application; *k*, no organic matter application in the experimental site; and ss, treatment with sewage sludge application. *a*, WHO limit; *b*, green fodder (Czech legislation); *x*, normal level according to Kabata-Pendias (2011). SD, standard deviation

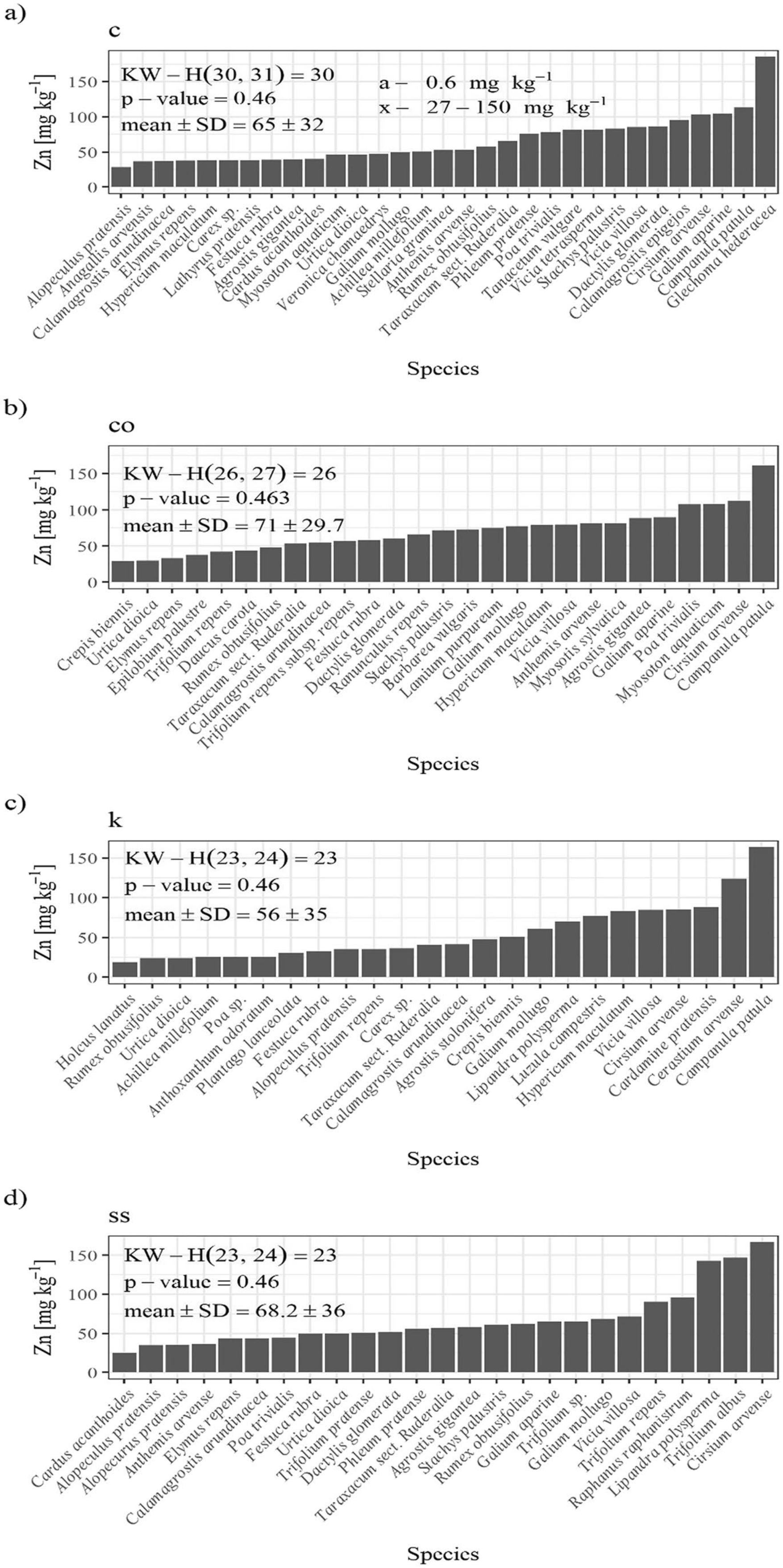

Fig. 4 The mean content of Pb in shoots of herbaceous plant species under different soil treatments **a** *c*, **b** co, **c** *k*, and **d** ss. The *p*-value was obtained by the Kruskal–Wallis analysis of variance (ANOVA). Abbreviations: *c*, control without trees outside the Short Rotation Coppice (SRC) experimental site; co, treatment with compost application; *k*, no organic matter application in the experimental site; and ss, treatment with sewage sludge application. *a*, WHO limit; *b*, green fodder (Czech legislation); *x*, normal level according to Kabata-Pendias (2011). SD, standard deviation

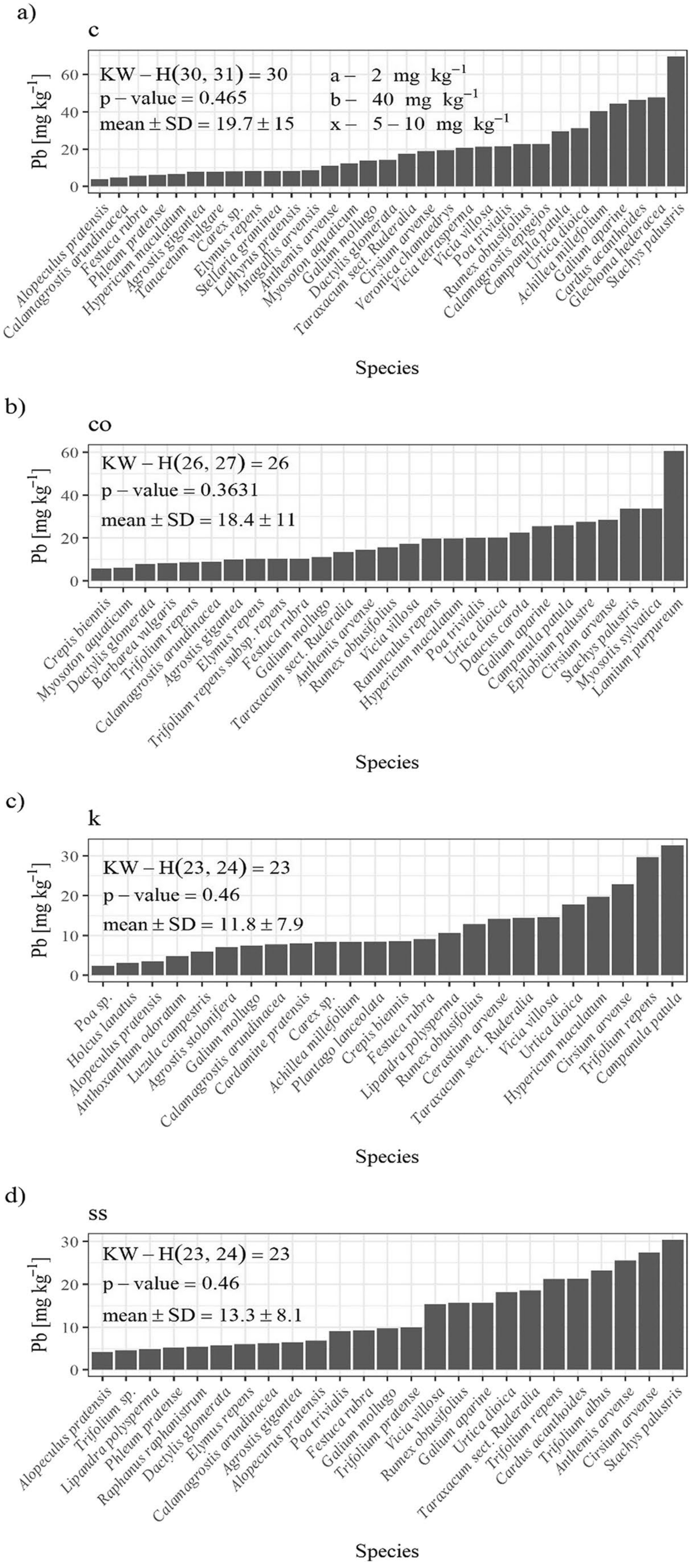

Fig. 5 The mean content of Pb in shoots of herbaceous plant species under different soil treatments **a** *c*, **b** co, **c** *k*, and **d** ss. The *p*-value was obtained by the Kruskal–Wallis analysis of variance (ANOVA). Abbreviations: *c*, control without trees outside the Short Rotation Coppice (SRC) experimental site; co, treatment with compost application; *k*, no organic matter application in the experimental site; and ss, treatment with sewage sludge application. *a*, WHO limit; *b*, green fodder (Czech legislation); *x*, normal level according to Kabata-Pendias (2011). SD, standard deviation

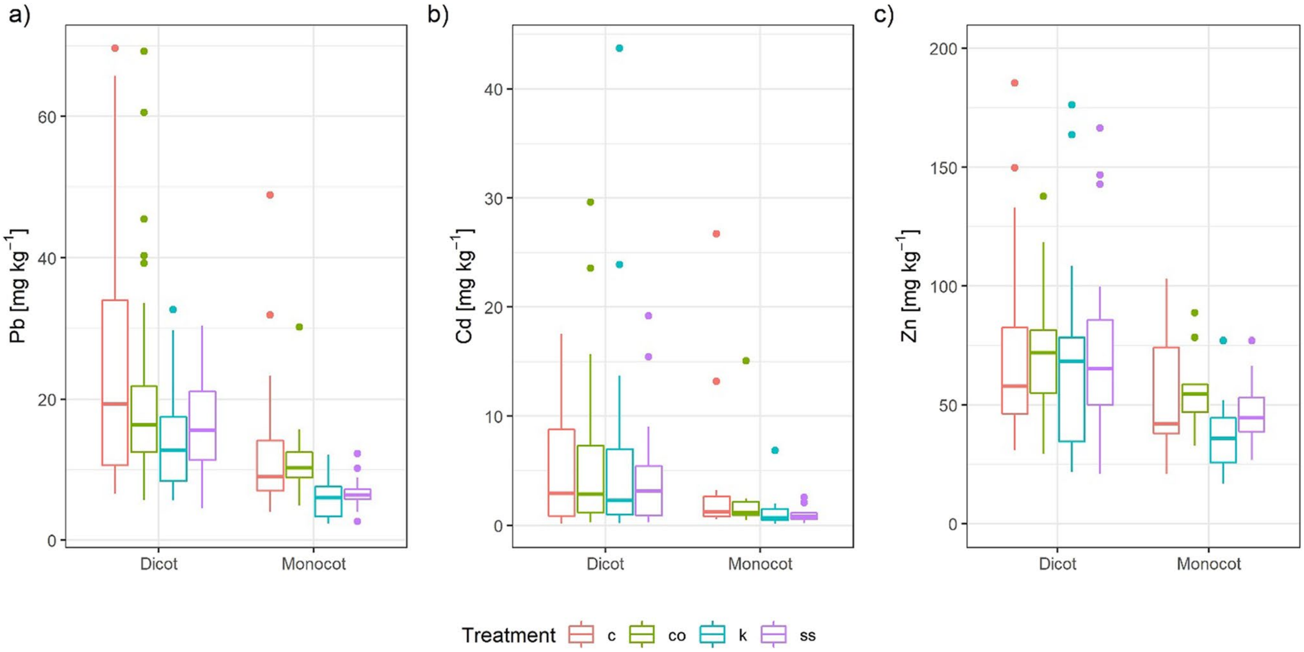

Fig. 6 Effect of different soil treatments on the mean content of **a** Cd, **b** Pb, and **c** Zn in monocots and dicots. Error bars and dots indicate ± SD (standard deviation) and outliers, respectively. Abbreviations: *c*, control without trees outside the Short Rotation Coppice (SRC) experimental site; co, treatment with compost application, *k*, no organic matter application in the experimental site; and ss, treatment with sewage sludge application

Bistorta officinalis L. exhibit marked accumulation of Zn, Cu, Mn, Ni, As, Pb, and Cr in their tissues (Nworie et al. 2019). Thus, such sites remain unsuitable for agricultural production as metals will pose a risk to food crops. Moreover, spontaneous growth of native species *A. vulgaris* and *Trifolium repens* L. growing on Ni, Cr, Cd, Pb, Zn, and Cu contaminated soils along the Spreča river valley (the north-east region of Bosnia and Herzegovina) were consider more suitable for aerial accumulation of metals than *L. perenne*, *Urtica dioica* L., *Mentha arvensis* L., *Medicago sativa* L., *Urtica urens* L., and *Achillea millefolium* L. (Murtić et al. 2021).

Table 4 Bioaccumulation factor of herbaceous plants from different treatments

Species (family) Cd	*c*	co	*k*	ss
Achillea millefolium (Asteraceae)	1.6	-	-	-
Anthemis arvense (Asteraceae)	-	1.6	-	-
Calamagrostis epigejos (Poaceae)	1.6	-	1.03	-
Campanula patula (Campanulaceae)	-	1.2	-	1.2
Cerastium arvense (Caryophyllaceae)	-	1.3	1.6	2.5
Cirsium arvense (Asteraceae)	-	1.3	-	-
Galium aparine (Rubiaceae)	1.1	-	-	-
Hypericum maculatum (Hypericaceae)	-	3	-	-
Lipandra polysperma (Amaranthaceae)	-	-	-	1.1
Poa trivallis (Poaceae)	1.2	-	-	
Taraxacum sect. Ruderalia (Asteraceae)	1.7	-	-	1.1

c control without trees outside the Short Rotation Coppice (SRC) experimental site, *co* treatment with compost application, *k* no organic matter application in the experimental site, and *ss* treatment with sewage sludge application. Only bioaccumulation factor (BAF) > 1 was presented

The current research considered the cutting of aerial parts of plants to allow roots to regenerate shoots for continuous above-ground accumulation—this method is a permanent approach to Cd, Pb, and Zn removal from contaminated soils. The shoot system periodically requires harvesting to avoid continuous drop in biomass.

Increasing the time cycles of the SRC allows biodiversity to develop in the coppice. The older the planted crop, the shadier the conditions for the ground vegetation, which is associated with a shift from annual to perennial and from light-demanding to shade-tolerant species (Baum et al. 2009). Studies have shown that SRC willow plantation supports high plant species richness and abundance compared to arable lands. For example, a study found 27% higher cover of plant species richness in SRC willow plantation compared to neighboring arable land (Kwapong 2023). Meanwhile, the condition of organic amelioration can support the mobility and accumulation of PTMs by plant species, enhance diversity, and richness (Niroshika et al. 2020). Under 65 °C thermal conditions, microbes in the compost during preparation can undergo aerobic respiration, which maintains the decomposition process that produces high quality compost, resulting in spore germination to increase plant species and growth (Chen et al. 2020). Under field conditions, the control environment (*c*) exhibited species richness considering the chemical characteristics of the soil, which partly support the release of elements for relatively easy plant uptake and from minimal or no competition for resources compared to locations with tree canopies (Vetaas et al. 2020). Although the number of species in the treatment *k* was the same in the application of sewage sludge, it could not yet match the species count in the compost application. The differences in the level of plant accumulation of PTMs also relate to plant and other extrinsic characteristics, e.g., microbial activities in the root rhizosphere, which could lead to the solubility of PTMs.

The relationship between soil parameters has implications on the metal content in plants. For example, Adams et al. (2004) predicted the Cd content in wheat grains based on the relationship between the soil Cd content and pH. For example, acidic pH supports the solubility of elements, e.g., PTMs, in soils (Matsumoto et al. 2017). In this study, positive ions from pH, CEC, Cd^{2+}, Pb^{2+}, and Zn^{2+} cannot fully participate in chemical reactions that involve bonding and adsorption on surfaces (Strawn 2021), supported by the relatively weak correlation between pH and C and N (organic matter components). The positive impact of organic ameliorants includes the comparatively high contents of nutrients (N, C, and S) and the improved physical state of plants during the field study. Increased acidity resulting from the application of the sewage sludge contributed to the high release of H^+, which can reduce the mobility of PTMs and uptake due to adsorption by negative charges of the organic material—evident in the comparatively low mean accumulation of studied PTMs to those in co.

Lesser species count can result from competition. For example, the prevalence of *Rumex obtusifolius* L. (Polygonaceae) with broad leaves may obscure the emergence of less competitive species. For example, decreased species diversity resulted from the colonization by *Rumex alpinus* L., in the alps of Austria, Italy, and the Gaint Mountains of Czech Republic (Jungová et al. 2022).

Competition has an additional selection for species that maintain high roots and densities (Craine and Dybzinski 2013; Jungová et al. 2022). Although these dynamics are pertinent, different plants show varying uptake and aerial accumulation mechanisms (Matanzas et al. 2021) due to their genotypes and susceptibility to specific PTMs. For instance, *A. millefolium*, (Asteraceae), *Anthemis arvense* L. (Asteraceae), *Calamagrostis epigejos* L. (Poaceae), *C. patula* (Campalunaceae), *Cerastium arvense* L. (Caryophyllaceae), *C. arvense* (Asteraceae), *Galium asparine* L. (Rubiaceae), *Hypericum maculatum* Crantz (Hypericaceae), *Lipandra polysperma* L. (Amaranthaceae), *P. triviallis*, and *Taraxacum sect. Ruderalia* (Asteraceae) exhibited a high shoot accumulation of Cd. Meanwhile, by the conventional standard of classifying plant hyperaccumulators, according to Reeve et al. (2006) and van der Ent et al. (2003), all the plant species were below the expected contents. Although *Salix* and *Populus* sp. are nonhyperaccumulators, these species accumulate 250 mg Cd kg^{-1} and 3300 mg Zn kg^{-1} with high biomass growth (Wieshammer et al. 2007). Thus, considerable attention to plant shoot accumulation is vital. However, some plants usually exclude (root accumulators—phytostabilization) Pb uptake due to restricted translocation by apoplastic barriers in the root, e.g., Casparian strips (Collin et al. 2022). Hence, plants with an above-ground Pb content greater than regulatory limits are considered suitable for phytomanagement. For example, species—*A. millefolium*, *Galium aparine*, *C. acanthoides*, *G. hederacea*, and *S. Palustris* in treatment *c* and only *L. purpureum* in co—recorded Pb above the permissible limits of raw materials of plant origin/animal feed (40 mg Pb kg^{-1}), according to Directive 2010/6/EU of the Commission.

Meanwhile, Pb shoot accumulation in all the studied plants was above WHO limit (2 mg Pb kg^{-1}). Cai et al. (2020) suggested that *Rudbeckia hirta* L. has restoration potential and its accumulation of Pb in the shoot when the content was up to 1000 mg kg^{-1} compared to the lower contents of *Polygonum lapathifolium* L., *Medicago sativa* L., *Talinum paniculatum* (jacq.), *Capsicum annuum* cv., and *Trifolium repens* L.

Herbaceous species usually colonize on contaminated soils with potential use in phytoremediation of metals (Mongkhonsin et al. 2019). The advantage of using these herbaceous plants is associated with their often annual, biennial, or perennial nature, which indicates accumulation can be continual and fast growth of new species. According to WHO limit for Cd, Pb, and Zn many of the studied plants and their potential bioactive substances may lose their medicinal potency (Asare et al. 2022).

During phytoextraction, many plant species are considered according to their high biomass production (Zárubová et al. 2015). In this study, dicots recorded the highest contents of PTMs in all the treatments—for Cd (C, *Tenacetum vulgare*), *H. maculatum* for both co and *k*, and again *C. arvense* for ss with *H. maculatum* accumulating > 100% in co. Again, dicots with BAF > 1 were greater than monocots in the accumulation of Cd. Furthermore, under different treatments, Pb (*S. palustris*, *L. perpereum*, and *C. patula*) and Zn (*G. hederaceae*, *C. patula*, and *C. arvense*) were highest in all dicots. Since most of the studied plants (e.g., *S. palustris* and *C. arvense*) have consumable parts and products (European Medicine Agency 2016), it is paramount to consider a low threshold, e.g., WHO, to avoid health-related issues.

Phytomanagement of PTM-contaminated soils should consider occupying an entire contaminated surface for all seasons and employ herbaceous plants with high accumulation potential. The impact of soil contamination on PTM uptake by plants requires field studies to select more effective species that can withstand varied environmental conditions.

5 Conclusions

The Short Rotation Coppice (SRC) of hybrid *Salix* and *Populus* clones resulted in the growth of multiple understorey herbaceous species. Meanwhile, the application of suitable organic ameliorants increases the number of herbaceous species and shoot accumulation of soil cadmium (Cd), lead (Pb), and zinc (Zn), especially compost treatment.

The study further indicated that herbaceous plant species (common weeds) accumulate potentially toxic metals (PTMs)—Cd, Pb, and Zn in their shoots from contaminated soils and can be considered a more cost-effective approach for the phytomanagement of PTM contaminated sites.

The accumulation of PTM by herbaceous plants is an indication of their availability to crops that make such fields not suitable for arable purposes. The conditions of the chemical properties of natural soils partly influence the accumulation of PTMs by herbaceous plants. Changes in the diversity of vegetation can serve as an indicator of the progress of clean-up process using phytoremediation with SRC.

Furthermore, dicots exhibited supremacy in the accumulation of Cd (*Tanacetum vulgare* L., *Hypericum maculatum* Crantz, and *Cirsium arvense* L.), Pb (*Stachys palustris* L., *Lamium Purpureum* L., and *Campanula patula* L.), and Zn (*Glechoma hederaceae* L., *C. patula*, and *C. arvense*) and best suited in the cleaning Cd/Zn/Pb-contaminated soils due to their biomass comparatively higher than monocots.

SRC plantation resulted in the growth of tolerant herbaceous plants suitable for phyto-management of Cd/Pb/Zn-contaminated sites, according to the level of contamination, while the condition of organic ameliorants can foster nutrient enrichment to soils and improves species richness.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42729-024-01652-w.

Author Contribution Conceptualization: M.O.A., J.S., P.T., M.C., E.P.; data curation: M.O.A, J.N., J.S., E.P. J.R.B.; formal analysis: M.O.A., J.S., P.T.; funding acquisition: J.S., P.T.; methodology: M.O.A., J.S., P.T.; project administration: J.S., P.T.; resources: J.S., P.T.; supervision: J.S., P.T., M.C.; validation: J.S., P.T., M. C.; writing—original draft: M.O.A., J.S.; writing—review and editing: M.O.A., J.S., P.T.

Funding Open access publishing supported by the National Technical Library in Prague. This research received support from the Nutrisk project (European Regional Development Fund—Project No. CZ.02.1.01/0.0/0.0/ 16_019/0000845).

Declarations

Competing interests The authors declare no competing interests.

References

Adams ML, Zhao FJ, McGrath SP, Nicholson FA, Chambers BJ (2004) Predicting cadmium concentrations in wheat and barley grain using soil properties. J Environ Qual 33:532–541. https://doi.org/10.2134/jeq2004.532

Antisari VL, Ferronato C, De Feudis M, Natali C, Bianchini G, Falsone G (2021) Soil biochemical indicators and biological fertility in agricultural soils: a case study from Northern Italy. Miner 11:219. https://doi.org/10.3390/min11020219

Aparicio JD, Lacalle RG, Artetxe U, Urionabarrenetxea E, Becerril JM, Polti MA, Garbisu C, Soto M (2021) Successful remediation of soils with mixed contamination of chromium and lindane: integration of biological and physicochemical strategies. Environ Res 194:110666. https://doi.org/10.1016/j.envres.2020.110666

Asare MO, Horák J, Šmejda L, Janovský M, Hejcman M (2020) A medieval hillfort as an island of extraordinary fertile Archaeological Dark Earth soil in the Czech Republic. Eur J Soil Sci 72:98–113. https://doi.org/10.1111/ejss.12965

Asare MO, Száková J,Tlustoš P (2022) The fate of secondary metabolites in plants growing on Cd-, As-, and Pb- contaminated soils-a comprehensive review. Environm Sci Pollut Res 30:11378–11398. https://doi.org/10.1007/s11356-022-24776-x

Ashraf S, Afzal M, Naveed M, Shahid M, Zahir ZA (2018) Endophytic bacteria enhance remediation of tannery effluent in constructed wetlands vegetated with *Leptochloa fusca*. Inter J Phytoremediation 20:2. https://doi.org/10.1080/15226514.2017.1337072

Baker AJM (1981) Accumulators and excluders strategies in response of plants to heavy metals. J Plant Nutr 3:643–654. https://doi.org/10.1080/01904168109362867

Baum S, Weih M, Busch G, Kroiher F, Bolte A (2009) The impact of Short Rotation Coppice plantations on phytodiversity. Landbauforschung Volkenrode 59:163–170

Bertrand G, Cassard D, Arvanitidis N, Stanley G (2016) EuroGeo Survey Mineral Resources Expert Group. Map of critical raw material deposits in Europe. Energy Procedia 97:44–50

Borah P, Singh P, Rangan L, Karak T, Mitra S (2018) Mobility, bioavailability and ecological risk assessment of cadmium and chromium in soils contaminated by paper mill wastes.

Groundw Sustain Dev 6:189–199. https://doi.org/10.1016/j.gsd.2018.01.002

Borůvka L, Vacha R (2006) Litavka River alluvium as a model area heavily polluted with potentially risk elements. In: Morel, JL, Echevarria G, Goncharova N (eds) *Phytoremediation of metal-contaminated soils*. NATO Science Series, Springer, Dordrecht. https://doi.org/10.1007/1-4020-4688-X_9

Bufka A, Přibil M, Velebil D, Vaněk V (2005) Historical subsurface mining works in the Czech Republic as technical monuments. Retrieved from http://www.velebil.net/en/czech-mines/. Assessed 17 Sept 2023

Cai X, Yu X, Lei L, Xuan B, Wang J, Zhang L, Zhao S (2020) Comparison of lead tolerance and accumulation characteristics of fourteen herbaceous plants environment and pollution technology An International Quarterly Scientific Journal 19:1547–1555. https://doi.org/10.46488/NEPT.2020.v19i04.021

ChamberlainL A, Aguayo T, Zerega NJC, Dybzinski R, Egerton-Warburton LM (2022) Rapid improvement in soil health following the conversion of abandoned farm fields to annual or perennial agroecosystems. Front Sustain Food Syst 6:1010298. https://doi.org/10.3389/fsufs.2022.1010298

Chen B, Zhang Y, Rafiq MT, Khan KY, Pan F, Yang X, Feng Y (2014) Improvement of cadmium uptake and accumulation in *Sedum alfredii* by endophytic bacteria *Sphingomonas Sa*MR12: effects on plant growth and root exudates. Chemosphere 117:367–373. https://doi.org/10.1016/j.chemosphere.2014.07.078

Chen T, Zhang S, Yuan Z (2020) Adoption of solid organic waste composting products: a critical review. J Clean Prod 272:122712. https://doi.org/10.1016/j.jclepro.2020.122712

Collin S, Baskar A, Geevarghese DM, Ali MNVS, Bahubali P, Choudhary R, Lvov V, Tovar GI, Senatov F, Koppala S, Swamiappan S (2022) Bioaccumulation of lead (Pb) and its effects in plants: a review. J Hazard Mater Letters 3:100064. https://doi.org/10.1016/j.hazl.2022.100064

Courchesne F, Turmel MC, Cloutier-Hurteau B, Constantineau S, Munro L, Labrecque M (2017) Phytoextraction of soil trace elements by willow during a phytoremediation trial in Southern Québec. Canada Inter J Phytoremediation 19:545–554. https://doi.org/10.1080/15226514.2016.1267700

Craine JM, Dybzinski R (2013) Mechanisms of plant competition for nutrients, water, and light. Funct Ecol. https://doi.org/10.1111/1365-2435.12081

Czech Geological Survey (2012) Geological map of the Czech Republic. Retrieved from http://www.geology.cz/extranet-eng/publications. Assessed 12 Oct 2022

Dalvi AA, Bhalerao SA (2013) Response of plants towards heavy metal toxicity: an overview of avoidance, tolerance, and uptake mechanism. Ann Plant Sci 2:362–368

Eissa MA, Almaroai YA (2019) Phytoremediation capacity of some forage plants grown on a metals-contaminated soil. Soil Sediment Contam 28:569–581. https://doi.org/10.1080/15320383.2019.1634674

European Medicine Agency (2016) Assessment report on *Equisetum arvense* L., herba. https://www.ema.europa.eu/en/documents/herbal-report/final-assessment-report-equisetum-arvense-l-herba_en.pdf. Accessed 31 Aug 2022

Food and Agriculture Organization [FAO] (2017). Voluntary guidelines for sustainable soil management. http://www.fao.org/documents/card/en/c/5544358d-f11f-4e9f-90ef-a37c3bf52db7/. Accessed 20 Sept 2022

Goliński P, Mleczek M, Magdziak Z, Gąsecka M, Borowiak K, Dąbrowski J, Kaczmarek Z, Rutkowski P (2015) Efficiency of Zn phytoextraction, biomass yield, and formation of low-molecular-weight organic acids in *S* × *rubens*—a hydroponic experiment. Chem Ecol 31:345–364. https://doi.org/10.1080/02757540.2014.993976

Gonçalves DA, de Souza ID, Rosa ACG, Melo ESP, Goncalves A-MB, de Lincoln CSO, do Valter AN (2019) Multi-wavelength calibration: determination of trace toxic elements in medicine plants by ICP OES. Microchem J 146:381–386. https://doi.org/10.1016/j.microc.2019.01.021

Gupta N, Yadav KK, Kumar V, Kumar S, Chadd RP, Kumar A (2019) Trace elements in the soil-vegetables interface: Translocation, bioaccumulation, toxicity, and amelioration: a review. Sci Total Environ 651:2927–2942. https://doi.org/10.1016/j.scitotenv.2018.10.047

Han R, Zhou B, Huang Y, Lu X, Li S, Li N (2020) Bibliometric overview of research trends on heavy metal health risks and impacts in 1989–2018. J Clean Product 276:123249. https://doi.org/10.1016/j.jclepro.2020.123249

Hassinen V, Vallinkoski VM, Issakainen S, Tervahauta A, Kärenlampi S, Servomaa K (2009) Correlation of foliar MT2b expression with Cd and Zn concentrations in hybrid aspen (*Populus tremula* × *tremuloides*) grown in contaminated soil. Environ Pollut 157:922–930. https://doi.org/10.1016/j.envpol.2008.10.023

ISO 11260: (1994) Soil quality — determination of effective cation exchange capacity and base saturation level using barium chloride solution. Retrieved from https://www.iso.org/standard/19238.html. Assessed 8 Oct 2022

Jungová M, Asare MO, Jurasová V, Hejcman M (2022) Distribution of micro- (Fe, Zn, Cu, and Mn) and risk (Al, As, Cr, Ni, Pb, and Cd) elements in the organs of *Rumex alpinus* L. in the Alps and Krkonoše Mountains. Plant Soil 477:1–23. https://doi.org/10.1007/s11104-022-05440-2

Kabata-Pendias A (2011) Trace elements in soils and plants. CRC Taylor Fr Group, London New York

Kalra YP, Maynard DG (1991) Methods manual for forest soil and plant analysis. Edmonton: Forestry Canada, Northwest region, Northern Forestry Center. Information Report NOR-X-319. p 125

Kubátová P, Hejcman M, Száková J, Vondráčková S, Tlustoš P (2016) Effects of sewage sludge application on biomass production and concentrations of Cd, Pb and Zn in shoots of *Salix* and *Populus* clones: improvement of phytoremediation efficiency in contaminated soils. Bioenergy Res 9:809–819. https://doi.org/10.1007/s12155-016-9727-1

Kushwaha A, Hans N, Kumar S, Rani R (2018) A critical review of speciation, mobilization, and toxicity of lead in soil-microbe-plant system and bioremediation strategies. Ecotoxicol Environ Saf 147:1035–1045. https://doi.org/10.1016/j.ecoenv.2017.09.049

Kwapong NA (2023) How does Short Rotation Coppice (SRC) willow affect biodiversity https://www.biomassconnect.org/wp-content/uploads/2023/02/TA2-Effect-of-Willow-on-Biodiversity_V2.pdf. Assessed 16 Sept 2023

Licinio A, Laur J, Pitre FE, Labrecque M (2023) Willow and herbaceous species phytoremediation potential in Zn-contaminated farm field soil in Eastern Québec, Canada: a Greenhouse Feasibility Study. Plants 12:167. https://doi.org/10.3390/plants12010167

Liu L, Li W, Song W, Guo M (2018) Remediation techniques for heavy metal contaminated soils: principles and applicability. Sci Total Environ 633:206–219. https://doi.org/10.1016/j.scitotenv.2018.03.161

Liu H, Wang H, Gao W, Liang H, Gao D (2019) Phytoremediation of three herbaceous plants to remove metals from urban runoff. Bull Environ Contam Toxicol 103:336–341. https://doi.org/10.1007/s00128-019-02677-z

Magnusson B, Örnemark U (2014) Eurachem Guide: the fitness for purpose of analytical methods. A laboratory guide to method validation and related topics, 2nd edn. Retrieved from www.eurachem.org. Accessed on 10 Oct 2023

Matanzas N, Afif E, Díaz TE et al (2021) Phytoremediation potential of native herbaceous plant species growing on a paradigmatic brownfield site. Water Air Soil Pollut 232:290. https://doi.org/10.1007/s11270-021-05234-9

Matec Industries (2021) Soil washing – remediation of contaminated sites. Retrieved from https://www.matecindustries.com/en/soil-washing-remediation-of-contaminated-sites/. Assessed on 7 Oct 2022

Matsumoto S, Shimada H, Sasaoka T, Miyajima I, Kusuma GJ, Gautama RS (2017) Effects of acid soils on plant growth and successful revegetation in the case of mine site. In: Oshunsanya (Ed.), *Soil pH for nutrient availability and crop production* Intechopen. https://doi.org/10.5772/intechopen.70928

Mongkhonsin B, Nakbanpote W, Meesungnoen, Prasad MNV (2019) Adaptive and tolerance mechanisms in herbaceous plants exposed to cadmium. (Eds.) Mirza Hasanuzzaman, Majeti Narasimha Vara Prasad, Masayuki Fujita, Cadmium Toxicity and Tolerance in Plants, Academic Press, Pp 73–109. https://doi.org/10.1016/B978-0-12-814864-8.00004-8

Moreno-Peñaranda R, Lloret F, Alcañiz JM (2004) Effects of sewage sludge on plant community composition in restored limestone quarries. Restor Ecol 12:290296. https://doi.org/10.1111/j.1061-2971.2004.00310.x

Murtić S, Zahirović Ć, Čivić H, Sijahović E, Jurković J, Avdić J, Šahinović E, Podrug A (2021) Phytoaccumulation of heavy metals in native plants growing on soils in the Spreča river valley, Bosnia and Herzegovina. Plant Soil Environ 67:533–540

Němeček J, Kozák J (2005) Status of soil surveys, inventory, and soil monitoring in the Czech Republic. In: Jones RJA, Houšková B, Bullock P, Montanarella, L (Eds.), *Soil resources of Europe (2nd ed.) European Soil Bureau Research Report No. 9*, (pp. 103–109), Ispra, Italy: The European Soil Bureau, Joint Research Centre

Nworie OE, Qin J, Lin C (2019) Trace element uptake by herbaceous plants from the soils at a multiple trace element-contaminated site. Toxics 7:3. https://doi.org/10.3390/toxics7010003

Pietrelli L, Menegoni P, Papetti P (2022) Bioaccumulation of heavy metals by herbaceous species grown in urban and rural sites. Water, Air, & Soil Pollut 233. https://doi.org/10.1007/s11270-022-05577-x

R Development Core Team (2010): R: a language and environment for statistical computing. Computer programme

Reeves R (2006) Hyperaccumulation of trace elements by plants. In: Morel J L, Echevarria G, Goncharova N (Eds.) *Phytoremediation of metal-contaminated soils*. NATO Science Series, 68. Springer, Dordrecht. https://doi.org/10.1007/1-4020-4688-X_2

Shahabi-Ghahfarokhi S, Josefsson S, Apler A, Kalbitz K, Åström M, Ketzer M (2021) Baltic Sea sediments record anthropogenic loads of Cd, Pb, and Zn. Environ Sci Pollut Res 28:6162–6175. https://doi.org/10.1007/s11356-020-10735-x

Shen Z, Jin F, O'Connor D, Hou D (2019) Solidification/Stabilization for soil remediation: an old technology with new vitality. Environ Sci Technol 53:11615–11617. https://doi.org/10.1021/acs.est.9b04990

Šlapokas T, Granhall U (1991) Decomposition of litter in fertilized short-rotation forests on a low-humified peat bog. Ecol Manag 41:143–165. https://doi.org/10.1016/0378-1127(91)90125-F

Strawn DG (2021) Sorption mechanisms of chemicals in soils. Soil Systems 5:13. https://doi.org/10.3390/soilsystems5010013

Sun R-L, Zhou Q-X, Jin C-X (2006) Cadmium accumulation in relation to organic acids in leaves of *Solanum nigrum* L. as a newly found cadmium hyperaccumulator. Plant Soil 285:125–134. https://doi.org/10.1007/s11104-006-0064-6

Tonelli FMP, Tonelli FCP, de Melo Nunes NA, Lemos MS (2020) Mechanisms and importance of phytoremediation. In: Bhat, R.A., Hakeem, K.R. (eds) Bioremediation and Biotechnology, Vol 4. Springer, Cham. https://doi.org/10.1007/978-3-030-48690-7_6

U.S. Geological Survey (2020). Mineral comodity summaries. Retrieved from https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf. Assessed 17 Sept 2023

USEPA, METHOD 3051 (1994) Microwave-assisted acid digestion of sediments, sludges, soils, and oils. https://archive.epa.gov/epawaste/hazard/testmethods/web/pdf/method%203051%2C%20revision%200%20-%201994.pdf. Assessed 8 Oct 2022

van der Ent A, Baker AJM, Reeves RD et al (2003) Hyperaccumulators of metal and metalloid trace elements: facts and fiction. Plant Soil 362:319–334. https://doi.org/10.1007/s11104-012-1287-3

Varrica D, Dongarrà G, Alaimo MG, Monna F, Losno R, Sanna E, De Giudici G, Tamburo E (2018) Lead isotopic fingerprint in human scalp hair: the case study of Iglesias mining district (Sardinia, Italy). Sci Total Environ 613–614:456–461. https://doi.org/10.1016/j.scitotenv.2017.09.106

Vetaas OR, Shrestha KB, Sharma LN (2020) Changes in plant species richness after cessation of forest disturbance. Appl Veg Sci 24:e12545. https://doi.org/10.1111/avsc.12545

Vondráčková S, Száková J, Drábek O, Tejnecký V, Hejcman M, Müllerová V, Tlustoš P (2015) Aluminium uptake and translocation in Al Hyperaccumulator Rumex obtusifolius is affected by low-molecular-weight organic acids content and soil pH. PLoS One 10:e0123351. https://doi.org/10.1371/journal.pone.0123351

Wei SH, Zhou QX, Koval PV (2006) Flowering stage characteristics of cadmium hyperaccumulator *Solanum nigrum* L. and their significance to phytoremediation. Sci Total Environ 369:441–446. https://doi.org/10.1016/j.scitotenv.2006.06.014

Weisser WW, Roscher C, Meyer ST et al (2017) Biodiversity effects on ecosystem functioning in a 15-year grassland experiment: patterns, mechanisms, and open questions. Basic Appl Ecol 23:1–73. https://doi.org/10.1016/j.baae.2017.06.002

Wieshammer G, Unterbrunner R, García TB, Zivkovic MF, Puschenreiter M, Wenzel W (2007) Phytoextraction of Cd and Zn from agricultural soils by *Salix ssp.* and intercropping of *Salix caprea* and *Arabidopsis helleri*. Plant Soil 298:255–264. https://doi.org/10.1007/s11104-007-9363-9

World Health Organization [WHO] (1996) Permissible limits of heavy metals in soil and plants. Switzerland, Geneva

Yener İ (2019) Trace element analysis in some plants species by inductively coupled plasma optical emission spectrometry (ICP-OES). J Inst Sci Technol 9:1492–1502. https://doi.org/10.21597/jist.517739

Zárubová P, Hejcman M, Vondráčková S, Mrnka L, Száková J, Tlustoš P (2015) Distribution of P, K, Ca, Mg, Cd, Cu, Fe, Mn, Pb, and Zn in wood and bark age classes of willows and poplars used for phytoextraction on soils contaminated by risk elements. Environ Sci Pollut Res 22:18801–18813. https://doi.org/10.1007/s11356-015-5043-0

Zeng F, Ali S, Zhang H, Ouyang Y, Qiu B, Wu F, Zhang G (2011) The influence of pH and organic matter content in paddy soil on heavy metal availability and their uptake by rice plants. Environ Pollut 159:84–91. https://doi.org/10.1016/j.envpol.2010.09.01