Research Article

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Content of Zn, Cd and Pb in purple moor-grass in soils heavily contaminated with heavy metals around a zinc and lead ore tailing landfill

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Abstract: The paper presents concentrations and correlations between Zn, Cd and Pb in the aboveground parts of purple moor-grass (*Molinia caerulea* L.) in forest soils heavily contaminated with heavy metals around a zinc and lead ore tailing landfill at Mining & Metallurgy Enterprise “Bolesław” SA in Bukowno. Field observations have indicated that purple moor-grass, which occurs as one of the few vascular plants in locations with tailing mud, is probably a species with high adaptability to conditions in contaminated environments. The research was carried out in a network of 20 regular monitoring sites. At these sites, a detailed inventory of purple moor-grass was carried out and samples of the aboveground parts of the plants were collected from the leaves and ears and from the soil at a depth of 0–20 cm. It was found that there was no significant correlation between the concentration of heavy metals in the soils and aboveground parts of the plants in the most heavily contaminated zones. This may indicate the existence of mechanisms limiting uptake of heavy metals by this species, and therefore the need for further research in the context of its suitability for biological regeneration of tailing landfills and phytosanitary protection of adjoining areas.

Keywords: bioaccumulation; translocation factors; tailing wastes; *Molinia caerulea* L.

1 Introduction

Ore mines and zinc and lead ore processing plants are some of the largest heavy metal emitters, mainly of Zn, Cd and Pb. In Poland, zinc-lead ores occur in the regions of Bytom-Tarnowskie Góry, Olkusz-Siewierz and Chrzanów-Trzebinia and they are found in orogenic deposits of Triassic dolomites [1,2,3]. In the process of zinc and lead enrichment, tailing waste is deposited by means of hydrotransport in above ground tailing landfills. As a result of water and eolian erosion, these sediments are dispersed in the form of dust and mud in the surrounding areas which causes soil and water contamination [4,5]. The negative impact of heavy metal contamination primarily affects soils, resulting in their exclusion from agricultural production, reduced biological activity, and lower rate of organic matter decay, which in turn slows down the biogenic cycle [6,7]. Excessive accumulation of heavy elements in soils leads to a decrease in the rate of vascular plant shoot growth or its inhibition, the occurrence of necrotic lesions on the leaves, the reduction of their surface area and of root biomass [8,9]. In environmental pollution studies, bioindicators, which are plant species with narrow tolerance to the limiting factor, have been used for a long time [10,11,12].

Another interesting group of plants connected with the areas where zinc-lead ores occur and the impact of the mining of these metals, are the so-called calamine species (from calamine - zinc ore). These species typically display increased tolerance to heavy elements in the soils and to natural or anthropogenically altered conditions [13]. Investigation of this group of species is, of course, also practical in the context of their potential for biological stabilisation of tailing landfills and phytosanitary protection of surrounding areas where there is a risk of contamination [14].

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The first reports on the occurrence of purple moor-grass (*Molinia caerulea* L.) in the forest adjacent to the Mining & Metallurgy Enterprise “Bolesław” SA in Bukowno tailing landfill in sites along the drainage channels from the landfill which were contaminated by tailing waste were reported by Krzaklewski and Pietrzykowski [1]. The cited authors pointed out that this species probably has the ability to adapt to conditions impacted by tailing landfills with heavy metals soil contamination [4]. Purple moor-grass in natural conditions occurs in lowland Poland in humid coniferous forests and on wet meadows. This species copes very well with difficult conditions associated with barren soils which are poor in minerals. Purple moor-grass also has high tolerance to humidity fluctuations (it tolerates both excess humidity and drought) and soil pH and thus occurs on alkaline and acidic substrates [15].

Due to the occurrence of purple moor-grass in the chemically contaminated sites, pioneering research on the plant's adaptation to soils contaminated with heavy metals and its potential for biological remediation of tailing landfills and phytosanitary protection of adjoining areas has been undertaken. The aim of the study was to determine the concentration and correlations of heavy metals (Zn, Pb, Cd) in soils and aboveground parts of purple moor-grass (*Molinia caerulea* L.) in the forest adjacent to the zinc and lead ore tailings landfill of Mining & Metallurgy Enterprise “Bolesław” SA in Bukowno.

2 Materials and methods

2.1 Study site and sampling scheme

The study was carried out in a forest area directly adjacent in the north-east to a zinc and lead ore tailing landfill of Mining & Metallurgy Enterprise “Bolesław” SA in Bukowno (southern Poland). In the studied area the following types of soils were found: transformed podzols, anthropogenically transformed podzols, anthropogenic soils with undeveloped soil profiles, and fossilized (muddy) deformed podzol with tailing sediments [4]. According to the FAO WRB classification, the soils were considered Albic Podzols and Urbic Anthrosols [16].

The tailing landfill has a height of over 25 m and a shape of a truncated cone, with a clear system of sedimentation section sand embankments on top. Tailing landfills are not covered by vegetation and are thus subjected to strong water and eolian erosion caused by dispersal of dust with high Zn, Pb and Cd content. Moreover, in the study site, there is also a ditch to drain excess technological waters containing

Figure 1: Location of sampling points in the study site adjacent to the tailing waste landfill [4].

considerable quantities of tailing sediments. Within the monitored forest area, a network of regular 20 sampling points was located in 4 zones in 2004 (Figure 1), [4]:

I – up to 30 m from the landfill (points no. 1, 4, 8, 12);

II – from 100 to 200 m from the landfill (points no. 2, 5, 6, 9, 13, 14);

III – from 300 to 400 m from the landfill (points no. 3, 7, 10, 11, 15, 16);

S – at landfill drainage channel (points no. 17, 18, 19, 20)

2.2 Laboratory analysis. Assay method

At each point, soil samples were collected from the upper horizons (0-20 cm), where the pH was determined potentiometrically in 1 mol • dm⁻³ KCl. The Zn, Cd and Pb content in the soils was extracted in a mixture of concentrated HNO₃ (65%) and HClO₄ (70%) acids (3:1, v/v) to determine the total (near total) content of these elements by AAS method [17]. Subsequently, the degree of soil contamination with heavy metals was assessed according to the scale proposed by the Institute of Soil Science and Plant Cultivation (IUNG-PIB) in Puławy [18]. In order to fully define the soils, including grain size and heavy metals content in full soil profiles (in horizons deeper than currently investigated, i.e. below 0-20 cm to 150 cm), the results of 2004 studies were used [4].

At the monitoring sites, the occurrence of the purple moor-grass (*Molinia caerulea* L.) was recorded. At the points where purple moor-grass occurred (i.e. eleven out of twenty) samples of the aboveground plant parts from the ears and leaves were collected to determine heavy metals content. Samples of the aboveground parts of the plants were dried at 105°C, then milled and prepared for

analysis. Zn, Cd and Pb content was determined by ASA after digestion in a mixture of HNO_3 (65%) and HClO_4 (70%) acids (3:1, v/v) [17].

Statistical analysis of the study results was performed using the Statistica 10 PL package. For selected parameters, Pearson's linear correlation coefficient (r) was calculated, with significance level $p=0.05$. In the study a maximum 5% spread between measurements in chemical analysis was adopted.

The following parameters were used based on which Zn, Cd and Pb plant biological content was determined:

1. Heavy metals content in individual parts of plants;
2. Bioaccumulation factor (BCF) - determines the metal uptake from the soil by plants, calculated as the quotient of the Zn, Cd and Pb content in the plant to the soil content [19,20].
3. Translocation factor (TF) - determines the mobility of metals in a plant, calculated as the quotient of the Zn, Cd, and Pb content in the ears to leaf content [21,22].

2.3 Analytical quality control

The AAS method, atomic absorption spectrometer from Thermo Electron Corporation was used to determine heavy metal content in plant and soil materials. Determinations in each of the analysed samples were carried out in three replications. A quantitative analysis mode was used for data acquisition of the samples. Scanning of each single sample was repeated three times to gather reasonably good results. During measurements, care was taken to avoid the memory effect and therefore a wash-out time of 0.5 min was used. The accuracy of the analytical methods was verified based on certified reference materials: CRM IAEA/V – 10 Hay (International Atomic Energy Agency), CRM – CD281 – Rey Grass (Institute for Reference Materials and Measurements), CRM023-050 – Trace Metals – Sandy Loam 7 (RT Corporation).

Ethical approval: The conducted research is not related to either human or animal use.

3 Results

3.1 Physical and chemical soil properties

Soil grain size analysis revealed that the majority of the samples were sand fractions. They were classified as loose sands, clayey sand and light clay sand. At one point (No. 20, Figure 1), the dusty fraction prevailed [23].

The topsoil pH was from acidic ($\text{pH}_{\text{KCl}} = 5.4$ at point 15) to alkaline ($\text{pH}_{\text{KCl}} = 7.8$ at point 1). The highest values of pH_{KCl} (7.2 to 7.8) were recorded in zone S. The alkaline soil pH in this zone was due to tailing sludge from the drainage channel. High values of pH_{KCl} were also found in zone I, closest to the tailing landfill. The pH_{KCl} range was from 6.0 to 7.8. In zone II which was 100 to 200 m from the tailing landfill, pH_{KCl} was lower and ranged from 5.8 to 6.9. In zone III, furthest from the tailing landfill, the biggest pH spread was found, ranging from 5.4 to 7.3. Previous studies of full soil profiles indicate that pH of top horizons was higher than that of the parent rock [4]. This is probably due to the influence of alkaline dust from the tailing landfill from which it is dispersed by water and eolian erosion.

3.2 Heavy metals in the soils

It was found that the topsoil horizons, from 0 to 20 cm, were heavily contaminated with zinc, cadmium and lead (Table 1). The highest Zn concentration was found in the zone contaminated with tailings sediment (zone S), where it ranged from $410.2 \text{ mg} \cdot \text{kg}^{-1}$ (grade III according to IUNG-PIB, i.e. averagely contaminated soils) to $10638.0 \text{ mg} \cdot \text{kg}^{-1}$ (grade V IUNG-PIB, i.e. very heavily contaminated soils). In most cases, zone S was contamination grade V (i.e. very heavily contaminated soils, defined for soils with the following parameters: light soils with low content of floating fraction to 10% with Zn concentration of above $3000 \text{ mg} \cdot \text{kg}^{-1}$). Significant Zn contamination was also observed in zone II, where contamination grade IV was found (i.e., over $700 \text{ mg} \cdot \text{kg}^{-1}$) in four out of the six points. Lead also reached the highest concentration in zone S, ranging from $173.4 \text{ mg} \cdot \text{kg}^{-1}$ (contamination grade III IUNG, i.e. heavily contaminated soils) to $2696.3 \text{ mg} \cdot \text{kg}^{-1}$ (contamination grade V, very heavily contaminated soil). Lead contamination was also found in zone I up to grade IV (given for soils with given parameters at Pb concentrations above $500 \text{ mg} \cdot \text{kg}^{-1}$).

Cadmium also reached its highest concentration in zone S, ranging from $3.5 \text{ mg} \cdot \text{kg}^{-1}$ (grade IV, heavily contaminated soil) to $55.1 \text{ mg} \cdot \text{kg}^{-1}$ (grade V grade, very heavily contaminated soils). High Cd concentrations also occurred in zone I, from $0.9 \text{ mg} \cdot \text{kg}^{-1}$ (grade I, i.e. elevated content) to even $35.2 \text{ mg} \cdot \text{kg}^{-1}$ (grade V, very heavy contamination). However, it should be noted that in each of the distinguished zones there were soils with very high Cd content (grade V, above $10 \text{ mg} \cdot \text{kg}^{-1}$), (Table 1).

A significant positive correlation between pH_{KCl} and Zn content in soil ($r = 0.45$) was found while investigating the correlation (with significance level $p=0.05$) between

Table 1: Content of heavy metals in the soil and plants around the tailing landfill (mg • kg⁻¹ d.m.)

Zone	Point*	Zn			Cd			Pb		
		Soil	Plant		Soil	Plant		Soil	Plant	
			Leaves	Ears		Leaves	Ears		Leaves	Ears
I	1	217.2	31.9	89.1	0.9	0.4	1.5	72.4	3.0	7.2
	4	4731.5	244.3	179.4	35.2	1.0	1.8	1682.7	16.7	20.9
	8	236.9	134.8	103.3	26.1	2.9	6.0	644.6	8.5	7.3
	12	1379.2	286.9	205.6	18.2	1.4	2.8	805.7	11.9	16.4
II	2	156.8	209.3	172.5	1.1	1.2	2.0	69.5	10.2	19.1
	5	1547.7	-**	-	17.1	-	-	347.7	-	-
	6	1032.7	-	-	12.9	-	-	360.7	-	-
	9	49.5	-	-	4.6	-	-	79.5	-	-
	13	1328.2	-	-	17.3	-	-	473.4	-	-
	14	2603.7	-	-	32.7	-	-	981.3	-	-
III	3	150.1	-	-	0.6	-	-	72.1	-	-
	7	282.4	32.8	97.2	2.3	0.51	1.1	55.9	4.9	6.7
	10	1335.6	-	-	11.9	-	-	305.9	-	-
	11	381.3	263.1	193.7	2.9	1.2	2.5	100.9	5.7	13.3
	15	825.2	-	-	9.3	-	-	380.1	-	-
	16	1889.2	-	-	13.9	-	-	712.8	-	-
S	17	2237.7	95.7	123.8	13.4	0.8	1.3	589.8	6.2	12.2
	18	10638.0	86.4	130.2	55.1	0.7	1.3	1825.4	4.8	11.9
	19	410.2	116.2	137.9	3.5	0.6	0.9	173.4	6.1	12.9
	20	7716.2	110.1	105.2	54.8	0.5	0.9	2696.3	6.9	6.1

*number of monitoring sites according to their distribution in Figure 1

**purple moor-grass was not found

the pH_{KCl} and the concentration of heavy metals in the topsoil horizons.

3.3 Heavy metals in purple moor-grass

The highest content of zinc in the leaves and ears of purple moor-grass was found in zone I, closest to the tailing landfill, and more precisely at point 12 (Table 1). High Zn content in the leaves and ears was also reported at point 11 in zone III. Purple moor-grass occurred sporadically in zone II and III, although it also displayed high Zn content in the leaves and ears. In the case of cadmium, the highest content of this metal in the aboveground parts of purple moor-grass was also recorded in zone I at points 8 and 12. High content of this metal in purple moor-grass tissues was also found at point 11, zone III, furthest from the tailing landfill (Table 1). The highest content of lead in the leaves and ears of purple moor-grass was reported in zone I, like in the case of Zn, i.e. at points 4 and 12. Furthermore, high Pb content in the leaves and ears of purple moor-grass was found in zone II (Table 1).

Due to high content of Zn, Cd and Pb in the aboveground parts of purple moor-grass, zone I with sampling sites close to tailing waste landfill was considered most contaminated.

No significant correlation was found between the concentration of particular heavy metals in the soil and the content in the leaves and ears of purple moor-grass, however, there was a correlation between the occurrence of this plant and an elevated concentration of the elements in the soil (Figure 2).

The correlation between Zn, Cd, and Pb content in the soils and plant tissues shown in Figure 2 appears to suggest that the highest concentration of these metals in plant tissues was observed at average content in the soil, while at their highest concentrations, biological retention was limited. This phenomenon may be due to the fact that in samples with higher concentrations of Zn, Cd and Pb, higher values pH_{KCl} were also found which, as mentioned previously, is a factor limiting metal mobility.

Purple moor-grass was found in places with an elevated concentration of trace elements in soils in zone S and zone I. In areas where the concentration of metals in

Table 2: Bioaccumulation (BCF) and translocation factors (TF).

Zone	Point*	Zn			Cd			Pb		
		Factor		TF	Factor		TF	Factor		TF
		BCF			BCF			BCF		
		Leaves	Ears		Leaves	Ears		Leaves	Ears	
I	1	0.15	0.41	2.79	0.44	1.67	3.75	0.04	0.10	2.40
	4	0.05	0.04	0.73	0.03	0.05	1.80	0.01	0.01	1.25
	8	0.57	0.44	0.77	0.11	0.23	2.07	0.01	0.01	0.86
	12	0.21	0.15	0.72	0.08	0.15	2.00	0.01	0.02	1.38
II	2	1.33	1.10	0.82	1.09	1.82	1.67	0.15	0.27	1.87
	5	-**	-	-	-	-	-	-	-	-
	6	-	-	-	-	-	-	-	-	-
	9	-	-	-	-	-	-	-	-	-
	13	-	-	-	-	-	-	-	-	-
	14	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-
III	7	0.12	0.34	2.97	0.22	0.48	2.18	0.09	0.12	1.37
	10	-	-	-	-	-	-	-	-	-
	11	0.69	0.51	0.74	0.41	0.86	2.08	0.06	0.13	2.33
	15	-	-	-	-	-	-	-	-	-
	16	-	-	-	-	-	-	-	-	-
S	17	0.04	0.06	1.29	0.06	0.10	1.63	0.01	0.02	1.97
	18	0.01	0.01	1.51	0.01	0.02	1.86	0.00	0.01	2.48
	19	0.28	0.34	1.19	0.17	0.26	1.50	0.04	0.07	2.11
	20	0.01	0.01	0.96	0.01	0.02	1.80	0.00	0.00	0.88

*number of monitoring sites according to their distribution in Figure 1

**purple moor-grass was not found

the soil was generally lower, there were few occurrences of purple moor-grass (zones II and III).

3.4 Bioaccumulation (BCF) and translocation factors (TF)

The bioaccumulation factor (BCF) was used to show the correlation between trace element content in the aboveground parts of the plant and the content of these metals in the topsoil. From the data presented in Table 2 it may be inferred that the value of the bioaccumulation factor depended on the element as well as the distance from the emitter. The lowest values of the bioaccumulation factor, indicating a reduction in metal uptake rate by purple moor-grass were found in zone S (i.e., in the zone where the soil is covered with the sediment from the drainage channel of the tailing waste landfill). Following an analysis of trace element distribution, it was discovered that the bioaccumulation factor was higher in the ears than in the leaves. This indicates that purple moor-grass,

which grows in heavy metal contamination conditions, accumulated larger amounts of Zn, Cd and Pb in the ears than in the leaves.

Translocation Factor (TF) is the parameter determining the transport (mobility) of metals in a plant. Research has shown that the values of the translocation factor depend on the metal and on its location in the zone (Table 3). It was found that the values of the translocation factor in the analysed zones were in most cases above one suggesting intensive movement of these metals from the leaves to the ears. Of the investigated contaminants, the highest TF was found for cadmium.

4 Discussion

The topsoil pH in the investigated area ranged from acidic to alkaline, and was therefore significantly elevated compared to natural untreated forest podzols on which the coniferous forest habitats occur [24].

Figure 2: Correlation between the content of Zn (a), Cd (b) and Pb (c) in soils and plant tissues: leaves and ears of *Molinia caerulea* L. with polynomial fit (dashed lines represent leaves, solid ones - ears)

As mentioned before, elevated soil pH may be attributed to the alkaline impact of sediments related to the properties of rock ores (dolomites and limestones) that are processed in the tailing process. In the case of waste deposited in landfills in the Olkusz region, the pH ranges between 7.8 and 7.9 [25]. The alkaline impact of tailing waste from the landfill clearly decreased with the distance from the facility. Soil pH is a decisive factor for trace element mobility, with the availability of metals for plants

increasing at lower pH [8,10]. Thus, it may be considered that in the investigated cases, at high concentrations of heavy metals in soils, their alkaline pH was a factor reducing biological sorption [26,27].

The conducted studies have shown that the heavy metals in the topsoil horizons clearly exceeded the permissible values compared to uncontaminated soils with a geochemical background of: Zn: 10-120 mg; Cd: 0.2-1.0 mg; Pb: 5-50 mg • kg⁻¹ dry weight of the soil, respectively [8]. According to the criteria given by IUNG-PIB [18] in the case of the studied soils, critical values for zinc, cadmium and lead were exceeded in zone S located at the drainage channel of the tailing landfill. Such chemical content of soils was caused by mud with tailing waste migrating in water. As it was found in the earlier full-profile soil studies of this facility, the thickness of the muddy sediment in this zone was from about a dozen to several more centimetres [4]. High concentrations of heavy metals were also observed in zone I, up to 30 m from the tailing landfill. The lowest concentration of zinc, cadmium and lead was observed in zone III, most distant from the tailing landfill (over 300 m) which indicated lower impact of dust, eolian and water erosion. The impact of distance from the tailing landfill on contamination of the adjacent soils has also been confirmed by Potra et al. [28].

In the present study, the highest zinc content in soil was recorded in zone S, and it amounted to 10638.0 mg • kg⁻¹ dry weight of the soil. Such high concentrations are not uncommon in areas located around facilities associated with mining of non-ferrous iron ores [2]. Also, the study by Merrington and Alloway [29] from West Chiverton, where copper, zinc and lead ore were mined, confirms such high concentrations in the soils adjacent to tailing waste landfills.

Lead content in the investigated forest area reached the maximum value in zone S, where it amounted to 2696.3 mg • kg⁻¹ dry weight of the soil. Lead content in the soil reported in this study was slightly lower than that reported by Potra et al. [28] for contaminated soils in the Olkusz area, which was 2936 mg • kg⁻¹ dry weight of the soil. According to Pająk et al. [30] in the area of non-ferrous metal works in Olkusz, the maximum lead content in cultivated soils was about 421 mg • kg⁻¹ dry weight of the soil and was much lower compared to the amount in zone S of the analysed area. In West Chiverton, the average Pb content in the soil was 4050 mg • kg⁻¹ dry weight of the soil and was significantly higher in comparison to the analysed area of Olkusz [29]. The highest cadmium concentration was 55.1 mg • kg⁻¹ dry weight of the soil also reported in zone S adjacent to the tailing landfill. In this case, Cd concentration of 50 mg • kg⁻¹ was exceeded. According to

Zwoliński [31] such an amount is critical for coniferous forest soil habitats in southern Poland. In Olkusz region, Cabała et al. [32] reported Zn content in topsoil horizons of up to 55000 mg • kg⁻¹, Pb mg • kg⁻¹ and Cd 220 mg • kg⁻¹ dry weight of the soil

On the basis of long-term studies on the toxicity of heavy metals in the forest environment, Zwoliński [31] proposed the threshold content of these elements in soils of forest habitats for the southern region of Poland. The cited author identified as critical zinc concentration of 500 mg • kg⁻¹, lead 1500 mg • kg⁻¹, and cadmium 50 mg • kg⁻¹ dry weight of the soil. Taking into account the obtained results, it may be stated that the values given by Zwoliński [31] for Zn were exceeded at 12 points, while for Pb at 3 points, and Cd at 2 points out of 20 points distributed in the studied zones.

Critical total concentration of Zn + Pb + Cd adopted by Zwoliński [31] for coniferous soil habitats amounts to 2050 mg • kg⁻¹ dry weight of the soil. It was found that this value was exceeded in 6 out of 20 points of the investigated zones. Elevated heavy metal concentrations clearly demonstrate their anthropogenic origin, i.e. the impact of the tailing landfill (dust fall) and coating with tailing sediment. Contamination of soils with several metals at the same time is very typical of areas affected by industrial immission, therefore even the lowest content of one metal exceeding the allowable content qualifies such soil as contaminated [4,18,28]. In the investigated area, cadmium was the most frequent contaminant. At most points (i.e. 13 out of 20), the highest contamination, grade V was found in the topsoil, which indicated very heavy contamination [18].

Looking at the permissible levels of heavy metals in topsoil horizons of forest soil (Group III) which amount to: 1000 mg Zn; 10 mg Cd; 500 mg Pb • kg⁻¹ dry weight of the soils [33], zinc content was exceeded in 11 points, Cd in 12 points, and Pb in 8 points of the investigated zones.

In the case of plants, toxic trace element content is often several times higher than the natural content which satisfies their physiological needs [8,34]. Excess toxic heavy metal content in plants amounts to: Zn 100-400 mg; for Cd 5-30 mg; for Pb 30-300 mg • kg⁻¹ dry weight of the soil [8]. Despite significant accumulation of contaminants in the studied environment, the concentrations of heavy metals found in the aboveground parts of purple moor-grass did not exceed the critical values for plants given by Kabata-Pendias and Pendias [8]. Studies show that the highest concentrations of Zn, Cd, and Pb in purple moor-grass tissues were found in zone I, which is closest to the tailing landfill. Similar correlations confirming the impact of the distance from the tailing landfill on trace element

content in plants were reported by Potra et al. [28]. Further studies by Karna and Hettiarachchi [35] and Karbowska et al. [5], indicate that the concentration of heavy metals in the soil and their uptake by plants largely depends on the distance from the emitter.

Detailed studies on the uptake of metals from the soil by plants and their translocation into the aboveground part allow to determine the ability of particular plant species to accumulate metals, and thus to identify them as potential contaminant indicators or phytoremediation agents [34,36,37]. According to Ogunkunle et al. [38], Ghosh and Singh [39], Korzeniowska and Stanisławska-Głubiak [40], the translocation (TF) and bioaccumulation (BCF) factors are key parameters for assessing the ability of plants to hyperaccumulate elements and determine their availability in the environment. The adaptive and phytoremediation potentials of plants very widely and depend among other things on plant species and the type of contaminants [8,34]. Plants may exhibit the ability to accumulate only selected metals or to uptake them with their synergistic impact on the environment [41,42].

The calculated bioaccumulation factor (BCF) confirmed that purple moor-grass found in the most chemically contaminated environment (zone S), bioaccumulates the smallest amounts of heavy metals compared to other zones. It may therefore be inferred that the investigated species probably adapts to excessive concentrations of phytotoxic elements in the environment [34]. This may be due to mechanisms for limiting the uptake of these metals from the soil environment, but this phenomenon should be further investigated [32].

In post-industrial areas metallophytes often occur. They are ecotypes of plant species showing increased tolerance to high soil contamination with trace metals [43,44]. Such plants may block the mechanism of element uptake from the soil or they may uptake the elements and neutralise them in their cells [34,44]. Perhaps in the course of further research purple moor-grass will be included in this group of plants.

The calculated translocation factor (TF) for the examined plants was above one. Based on the results obtained, it may also be stated that the plant's ears accumulate more Cd and Pb than its leaves. In the case of Zn, the leaves accumulate more than ears, apart from zone S, where the accumulation was higher in the ears than in the leaves. It should be emphasised that the lowest accumulation of trace metals in purple moor-grass tissues was recorded in zone S, where the highest concentrations of contaminants in the soil occurred. The calculated translocation factor for the investigated metals

is confirmed in the scientific literature, which reports high intensity of Cd mobility in plant tissue [34,45,46,47].

5 Conclusions

1. The heaviest contamination of forest soils adjacent to the tailing landfill of Mining & Metallurgy Enterprise “Bolesław” SA in Bukowno was found in zone S, located along the drainage channel of industrial leachate, where the surface was contaminated with tailing sediments.
2. Tailing sediments as a waste product of processing dolomitic ore are alkaline and, therefore, in addition to heavy soil contamination with zinc, cadmium and lead they result in alkalinity which is unfavourable to coniferous forest habitat soil. On the other hand, alkaline pH lowers trace metal mobility in the soil environment, which in turn is likely to affect the reduction of biological absorption by the plants.
3. Purple moor-grass was found in sites where the soils were heavily contaminated with heavy metals, often being the only vascular plant species in the undergrowth. This indicated its increased resistance to the investigated degrading agent.
4. An analysis of the bioaccumulation factor indicated that metal uptake by purple moor-grass was less intensive in zone S with the highest chemical contamination. The calculated translocation factor indicates that purple moor-grass accumulated more Cd and Pb in the ears than in the leaves.
5. No significant correlations were found between the content of heavy metals in the most heavily contaminated soils and their content in the aboveground parts of purple moor-grass which may indicate the existence of a mechanism for limiting biological absorption, but this phenomenon should be further investigated.

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