Assessment of the effect of drainage on the accumulation of Zn, Cu, Pb, and Cd in bog plants: a case study of two raised bogs in Western Siberia

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SUMMARY

The lowering of water level caused by bog drainage increases the exposure of the upper layers of peat deposits to oxygen, which leads to an increase in the degree of peat decomposition. Elements become more readily available to plants and their biological absorption increases. The aim of this study is to estimate the differences in element accumulation by plants in pristine and drained areas of bogs. We conducted a study of otherwise similar drained and pristine bog sites. We took samples of four plant species (*Chamaedaphne calyculata*, *Andromeda polifolia*, *Eriophorum vaginatum* and *Rhododendron tomentosum*) and of the peat in which these plants were growing. We analysed the plants and peat for Zn, Cd, Pb and Cu content. We found an increase in the elemental content of plants in drained areas, but the increase was not always significant. We developed, and tested on our data, a coefficient that takes into account both the ability of a species to absorb elements from peat and differences in element content between the pristine and drained areas, to indicate the effect of drainage.

KEY WORDS: biomonitoring, coefficient of biological absorption, dwarf shrubs, *Eriophorum*, heavy metals

INTRODUCTION

The mires of Western Siberia are unique natural phenomena, with preserved pristine areas which could be polluted only via atmospheric transport. Drainage causes not only a sharp decrease in the water level of the bog, the transformation of plant communities (Abolina *et al*. 2001, Landry & Rochefort 2012, Benavides 2014) and changes in the abundance of certain species of testate amoebae (Warner & Chmielewski 1992) and microrelief, but also becomes one of the main causes of peat fires (Evseeva *et al*. 2012, Gashkova & Sinyutkina 2015, Maloletko *et al*. 2018, Schulte *et al*. 2019). Significant surface subsidence and peat compaction also occurs (Sloan *et al*. 2019); microbial activity in the peat changes (Urbanová & Bárta 2016, Könönen *et al*. 2018); the water content of the peat decreases but the production of carbon dioxide increases (Wang *et al*. 2018, Hermans *et al*. 2019); the redox balance of the soil changes and the decomposition of organic matter accelerates, which leads to an increase in the mobile forms of elements and changes in geochemical conditions (Perelman & Kasimov 1999, Ikkonen 2010, Bragazza *et al*. 2013, Glina *et al*. 2018, Vroom *et al*. 2020). Changes in geochemical conditions in the drained bogs of Western Siberia also cause a transformation of plant communities and microtopography (Gashkova & Sinyutkina 2015, Maloletko *et al*. 2018).

Plants are the most responsive indicators of change in geochemical conditions of the landscape. Bryophytes have been studied in particular detail (Berg *et al*. 1995, Berg & Steinnes 1997, Zechmeister *et al*. 2003, Kempter & Frenzel 2008, Ceschin *et al*. 2012, Barandovski *et al*. 2013, Koz & Cevik 2014, Barrett & Watmough 2015, Kolon *et al*. 2015, Antreich *et al*. 2016, Shotyk & Cuss 2019). However, vascular plants such as *Phragmites australis*, *Andromeda polifolia* and *Oxycoccus microcarpus* can be used in biomonitoring and as bioindicators of the state of the environment (Wang & Jia 2009, Yang *et al*. 2010, Zhang *et al*. 2011, Wojtuń *et al*. 2013, Eid & Shaltout 2014, Borgulat *et al*. 2018).

The effect of bog drainage is quite often studied in terms of the metal content of peat (Shikhova *et al*. 2016, Borodkina *et al*. 2018, Novosyolova *et al*. 2019). However, to identify the changes in geochemical conditions when there is human interference in a mire, a comprehensive study which considers the absorption of elements by plants is necessary. The development of biogeochemical coefficients is highly relevant because a comparison of the absolute values of the elemental content of plants from disturbed and unaltered areas does not always indicate the influence of a human pressure

(Desaules 2012). However, the elemental content of plants in the bogs of Western Siberia has been insufficiently studied; little information is available regarding the elemental content of plants in areas polluted by oil and gas production and from urban sources, or in unpolluted bogs (Lyapina *et al*. 2009, Moskovchenko *et al*. 2012, Veretennikova 2015, Ryzhakova *et al*. 2017). No data are available on the accumulation of heavy metals in plants growing in drained bogs in Western Siberia. Bryophytes mostly indicate the atmospheric deposition of microelements, while vascular plants characterise changes in environmental conditions (Shotyk 2020) which can be associated both with a decrease in water level during the establishment of a drainage network and with climate change (Bragazza *et al*. 2013, Benavides 2014).

The use of vascular plants as bioindicators is especially important in the studied territory of Western Siberia, where vast areas of bogs are located outside the zones of influence of large industrial enterprises and the long-range atmospheric transport of pollutants represents the main external source of microelements. Bogs in the vast swampy areas of Western Siberia that have been drained without additional alterations to vegetation and soil can also become promising models for studying the transformation of geochemical conditions that can be expected to arise from a decrease in moisture due to climate change. Therefore, in this article we address the following questions:

1) To what extent does the drainage of bogs affect the Zn, Cu, Pb, and Cd content of plants in bogs in the south-east of the West Siberian Plain?
2) Which coefficients and indicators most accurately reflect the process of accumulation of trace elements in drained bogs?
3) How do estimated levels of trace elements in the dry mass of plants and peat in our study sites compare with data for similar bogs in Europe and Western Siberia?

METHODS

Study area

The studied areas are located in the south-east of the West Siberian Plain, in the southern taiga subzone, over 2 km from major roads and more than 200 km from any industrial centres (Figure 1).

Figure 1. Location of the study area. Sites 7–12 and 16: terrace of the Ket River; Sites 1–6 and 13–15: Vasyugan mire. Green symbols indicate pristine areas and red symbols denote drained areas.

South-easterly winds prevail in the study area, average annual air temperatures in the Vasyugan Bog range from -1.1 °C to +0.46 °C, and in the Ket River basin from -1.5 °C to -0.4 °C. Annual precipitation is 630 to 650 mm and possible total evaporation ranges from 400 to 520 mm. Sandy-argillaceous deposits dominate the interfluves and sandy deposits dominate on the river terrace (Evseeva *et al*. 2012).

We conducted research on four bogs, in two areas that had been drained and in two untouched areas that were otherwise similar to the drained areas (Table 1, Figure 1). The vegetation represented *Pinus*-*Carex*-shrub-*Sphagnum* (high ryam), *Pinus*-shrub-*Sphagnum* (low ryam), and *Scheuchzeria*-*Carex*-*Sphagnum* plant communities in the studied sites (Table 1, Figure 1).

The studied bogs were drained during the 1970s and 1980s for the purpose of growing forests. After draining, no agrotechnical measures were implemented in the bogs, so the vegetation remained intact and changes occurred only due to lowering of the water level. A more detailed description can be found in our previous articles on drained bogs (Gashkova & Sinyutkina 2015) and pristine bogs (Kharanzhevskaya *et al*. 2020).

Field study

Geobotanical description of the sites, and the sampling of plants and peat to determine their heavy metal content, was carried out from 2013 to 2017. Samples were taken during the second half of July, during dry weather. The timing was chosen because the maximum accumulation of elements in plants occurs during the first half of summer, and there is no further significant change in their concentrations by autumn (Brekken & Steinnes 2004). Four plant species were selected for analysis, namely: *Chamaedaphne calyculata*, *Andromeda polifolia*, *Eriophorum vaginatum* and *Rhododendron tomentosum*. Samples were collected in bogs with an area of at least 10 m^2. At each site, samples were taken from ten individuals of each of the studied species, if the species was present at the site. For each sample, approximately 100 g of shoots from the current year were cut with stainless steel scissors and placed in a disposable plastic bag. Peat samples were collected at the same locations as plant sampling, from a depth of 0–25 cm where the highest concentration of suction roots was to be found. Thus, *R. tomentosum* was analysed from four drained and eight pristine sites (120 samples), *E. vaginatum* from four drained and four pristine

Table 1. Locations and characteristics of the studied bogs. WTL = depth of water table below surface in cm.

Site location	№	Latitude	Longitude	Plant community	WTL	Condition
Interfluve of Bakchar and Iksa Rivers	1	56°58'15.3"N	82°36'09.7"E	*Pinus*-*Carex*-shrubs-*Sphagnum*	-40	pristine
	2	56°58'32.9"N	82°36'17.0"E	*Pinus*-*Carex*-shrubs-*Sphagnum*	-40	
	3	56°58'24.3"N	82°36'41.2"E	*Pinus*-shrubs-*Sphagnum*	-30	
	4	56°58'17.3"N	82°37'04.5"E	*Scheuchzeria*-*Carex*-*Sphagnum*	-10	
	5	56º58'50.4"N	82º36'56.2"E	*Pinus*-shrubs-*Sphagnum*	-30	
	6	56°51'25.3"N	82°41'40.9"E	*Scheuchzeria*-*Carex*-*Sphagnum*	-5	
Terrace of Ket River	7	58°23'26.3"N	83°11'33.9"E	*Pinus*-shrubs-*Sphagnum*	-35	pristine
	8	58°23'20.6"N	83°11'32.4"E	*Pinus*-shrubs-*Sphagnum*	-35	
	9	58°23'16.7"N	83°11'30.0"E	*Pinus*-shrubs-*Sphagnum*	-30	
	10	58°23'12.8"N	83°11'31.2"E	*Pinus*-shrubs-*Sphagnum*	-30	
	11	58°23'13.6"N	83°11'26.9"E	*Pinus*-shrubs-*Sphagnum*	-20	
	12	58°26'03.2"N	83°26'12.9"E	*Pinus*-shrubs-*Sphagnum*	-35	
Interfluve of Iksa and Shegarka Rivers	13	56°49'59.7"N	83°14'40.4"E	*Pinus*-shrubs-*Sphagnum*	-40	drained
	14	56°49'54.9"N	83°14'30.1"E	*Carex*-shrubs-*Sphagnum*	-20	
	15	56°50'29.5"N	83°15'49.2"E	*Carex*-shrubs-*Sphagnum*	-15	
Terrace of Ket River	16	58°19'06.8"N	83°06'37.3"E	*Pinus*-shrubs-*Sphagnum*	-80	drained

sites (80 samples), *C. calyculata* from four drained and ten pristine sites (140 samples), and *A. polifolia* from four drained and five pristine sites (100 samples).

Analytical methods

Determination of the mass concentrations of Zn, Cd, Pb and Cu in plants and peat was carried out by inverse voltammetry (STA, Russia) after preliminary sample preparation. Sample preparation comprised: drying to absolute dry weight; grinding to powder in a laboratory mill; ashing in a muffle furnace with preliminary addition of nitric acid and hydrogen peroxide; and dissolving the resulting ash in concentrated hydrochloric acid. The analysis was carried out according to the MU 31-04/04 (FR.1.31.2004.00986) methodology (TPU 2004). Measurement range of mass concentration of ions (g/m^3): Zn, Pb, Cu from 0.001 to 0.1; Cd from 0.001 to 1.0. The limits of permissible relative error of measurements of mass concentration of ions of zinc, cadmium, lead and copper did not exceed ± 30 %. Verification was performed by microwave plasma atomic emission spectroscopy (Agilent 4100, № AU 12510346).

Statistical analysis

To assess the degree of difference in the biogeochemical attributes of drained bogs in comparison with pristine bogs, in terms of the geochemical characteristics of the accumulation of heavy metals, we used a comparative analysis based on a number of different geochemical coefficients proposed by different researchers.

1. The biological absorption coefficient (BAC) is the quotient of the content of an element in the ash of plant material (CV) to its content in peat (CP) (Perelman & Kasimov 1999):

   BAC = CV/CP.

   The biogeochemical activity of a species (BAS) is the sum of the BACs of the elements under consideration (Ayvazyan 1974):

   BAS = ΣBAC,

   in our case calculated as follows:

   BAS = BAC Zn + BAC Cu + BAC Pb + BAC Cd.

2. The enrichment factor (EF) is the quotient of the concentration of an element in plants from a dry area (CVD) to the concentration of the element in plants from an intact area (CVP):

   EF = CVD/ CVP.

3. Our proposed enrichment factor of the biological absorption coefficient (EF BAC) is the quotient of BAC in the drained area (BACD) to BAC in the control area (BACP):

   EF BAC = BACD/BACP.

4. The proposed EF for the biogeochemical activity of species (EF BAS) is the quotient of BAS in the drained area (BASD) to BAS in the control area (BASP):

   EF BAS = BASD/BASP.

Statistical analysis was performed on the original data using Microsoft Excel 2007 (Microsoft, Redmond, WA, USA) and STATISTICA (Statsoft 2007). Spearman's rank correlation coefficient was used to assess the relationship between the variables. Comparison and significance of differences between the samples was established using the nonparametric Mann-Whitney and Kruskal-Wallis tests. The identification and illustration of the degree of influence of various factors on the accumulation of heavy metals in plants was carried out using the method of principal components (PCA) and Linear Discriminant Analysis (LDA).

RESULTS

Cu, Pb, Zn and Cd content of dry peat from drained and pristine sites

Comparison of the elemental content of dry peat showed that the Zn content of pristine and drained areas is almost the same ($p = 0.84$). The Pb content of peat is 1.7 times higher in drained areas than in pristine ones ($p = 0.0004$). Conversely, the concentrations of Cu and Cd are lower in the drained areas, compared to the pristine areas. The Cu content is 1.4 times lower ($p = 0.012$) and the Cd content is 13 times lower ($p = 0.018$) in drained bogs, as compared to pristine ones (Figure 2).

Cu, Pb, Zn and Cd content of plant dry weight from drained and pristine sites

Comparison of the elemental concentration in the dry mass of each of the studied plant species showed that each of the species has its own characteristics and they shared common features.

The median values for the concentrations of all elements in the tissues of *R. tomentosum*, except for Cd, were higher in the drained areas than in the pristine sites. Statistically significant differences between the pristine and drained areas (U test,

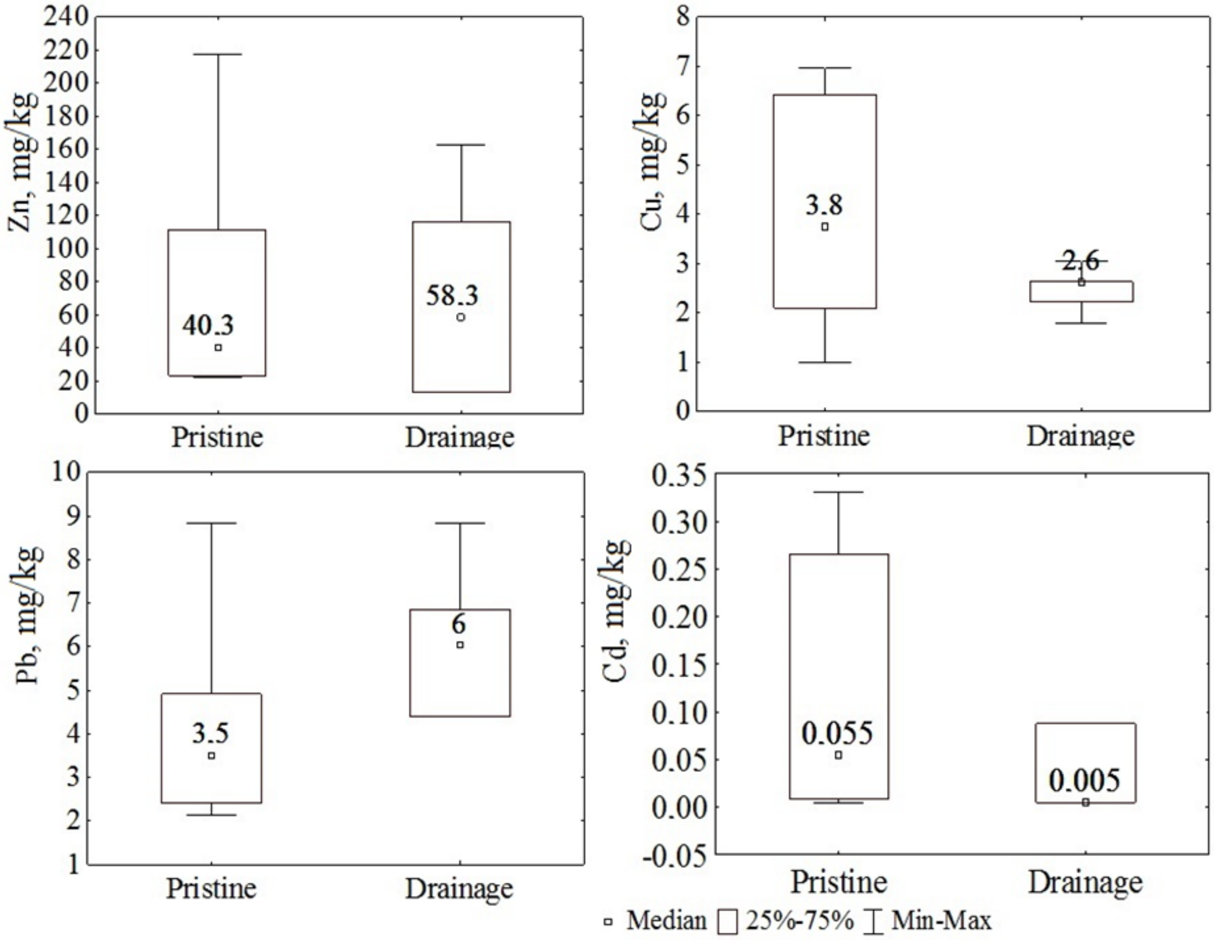

Figure 2. Element content of the peat (dry weight, mg/kg) compared between pristine and drained areas of the bogs.

$P < 0.05$) are observed only in respect of Zn and Cu content (Figure 3A). The Zn content is two times higher, and Cu is four times higher, in drained areas than in the pristine bog.

In the tissues of *C. calyculata*, the concentrations of Zn (U test, $P < 0.005$) and Cu (U test, $P < 0.05$) are higher in plants from the drained sites than in plants from pristine sites. The Pb and Cd values in drained bogs do not differ from those in pristine bogs (Figure 3B).

In the tissues of *A. polifolia*, significant differences between pristine and drained bogs are observed only in the content of Zn (U test, $P < 0.05$). The content of Cu and Cd in the drained areas is slightly higher. Of all the species considered, *A. polifolia* is the only one in which the Pb concentration in the drained sites does not increase but, indeed, slightly decreases (Figure 3C).

In *E. vaginatum*, only the Zn content was significantly higher in the drained bogs (U test, $P < 0.05$), although the median values in the drained areas increase eight-fold for Cu and four-fold for Pb. The Cd content does not really differ between the control and drained bogs (Figure 3D).

Comparing the elemental content of the plants, we found that only Zn content increases in the drained sites for all the species considered. The concentration of the other elements does not change significantly. Thus, a comparison of the level of absolute element content is not sufficient to detect any interspecies differences in element absorption.

Geochemical coefficients

EFs were calculated in order to visualise the results of comparing the element concentrations in the pristine (CVP) and drained (CVD) sites in different plant species. When comparing EF, approximately the same increase in concentration was found for Zn and Cd among the different species in the drained areas. However, the EF ratio for Pb and Cu vary greatly, ranging from 0.7 to 4 for Pb and from 2 to 8 for Cu among different species (Figure 4A).

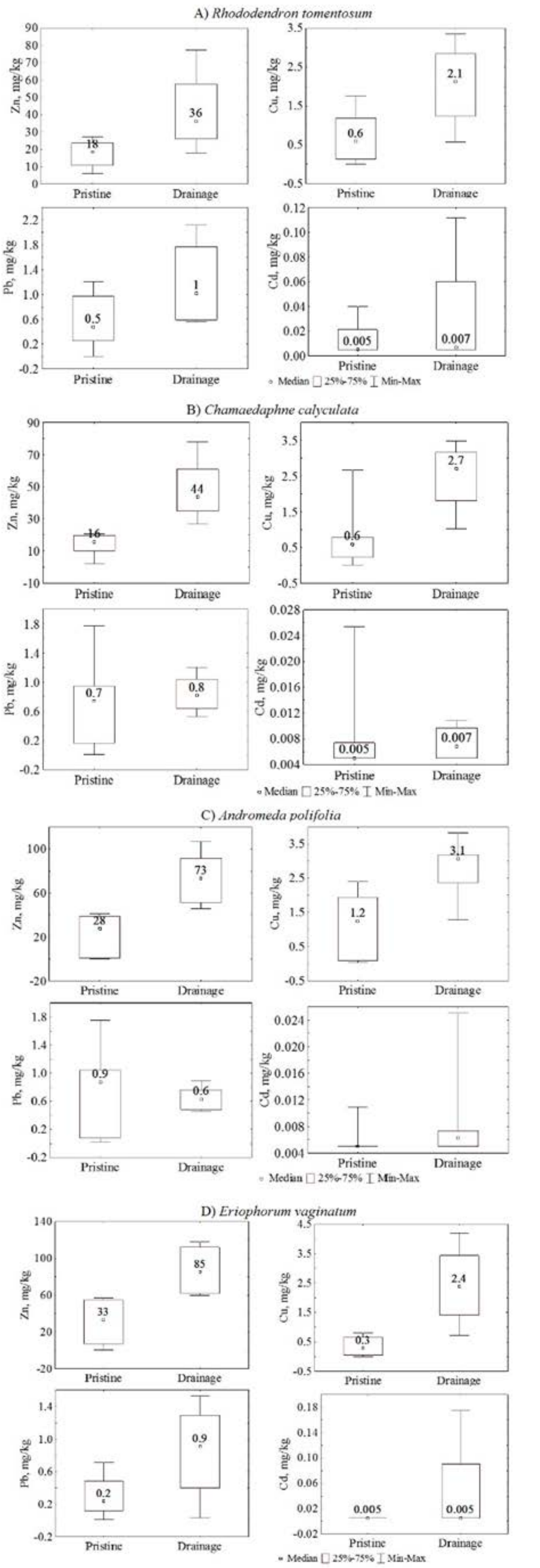

Figure 3. Element content of plants (dry weight, mg/kg) in pristine and drained areas of the bogs.

Thus, the comparison of EF values clearly shows a change in the concentration of elements in plant tissues among different plant species, but does not take into account the level of concentration of elements in the substrate on which the plants grow. To calculate the EF adequately, it is necessary also to consider the concentration of elements in the peat on which the plants grow and the ability of the species to absorb elements from the peat. It is especially important to take into account the concentration of elements in the nutrient substrate in the case of upland bog plants, which usually exist in conditions of micronutrient deficiency. Therefore, we have developed an EF for BACs that reflects the ability of each species to absorb elements from peat (EF BAC).

From examining the EF BAC it is easy to detect the difference in the accumulation of elements by each species under the influence of drainage and the degree of accumulation of various elements by the plants. Comparison of the coefficients shows that the accumulation of Cd and Cu by plants increases most in the drained areas, and Zn and Pb accumulate least actively. This pattern is observed for all of the species studied. *Eriophorum vaginatum* accumulates Cd and Cu most strongly in the drained bogs. The least active species is *R. tomentosum*, while *C. calyculata* and *A. polifolia* show intermediate results. *A. polifolia* accumulates Zn most strongly, as compared to the pristine plots, and *E. vaginatum* accumulates Zn the least efficiently. Pb accumulates poorly in all the studied species, but the highest EF values for the BACs are associated with *E. vaginatum* (Figure 4B).

By analogy with the EF BAC for each species, the EF BAS was calculated. This coefficient most accurately shows the differences in the change in the intensity of element accumulation in the pristine and drained plots among different plant species (Figure 4C). Comparison of the obtained EF BAS shows that *R. tomentosum* exhibits the smallest increase in BAS, and *E. vaginatum experiences* the largest increase. These differences must be taken into account when selecting species as bioindicators, and when assessing the degree of change in the geochemical conditions of the bog under anthropogenic impact.

The results of discriminant analysis, based on data on the concentrations of Zn, Cu, Pb and Cd in plant ash and the BAC and BAS coefficients, illustrate the interspecies differences in the absorption of elements (Figure 5).

Thus, an increase in EF BAS resulting from drainage of the bog indicates an increase in the uptake of elements in the drained sites and differences between plant species in the accumulation of elements.

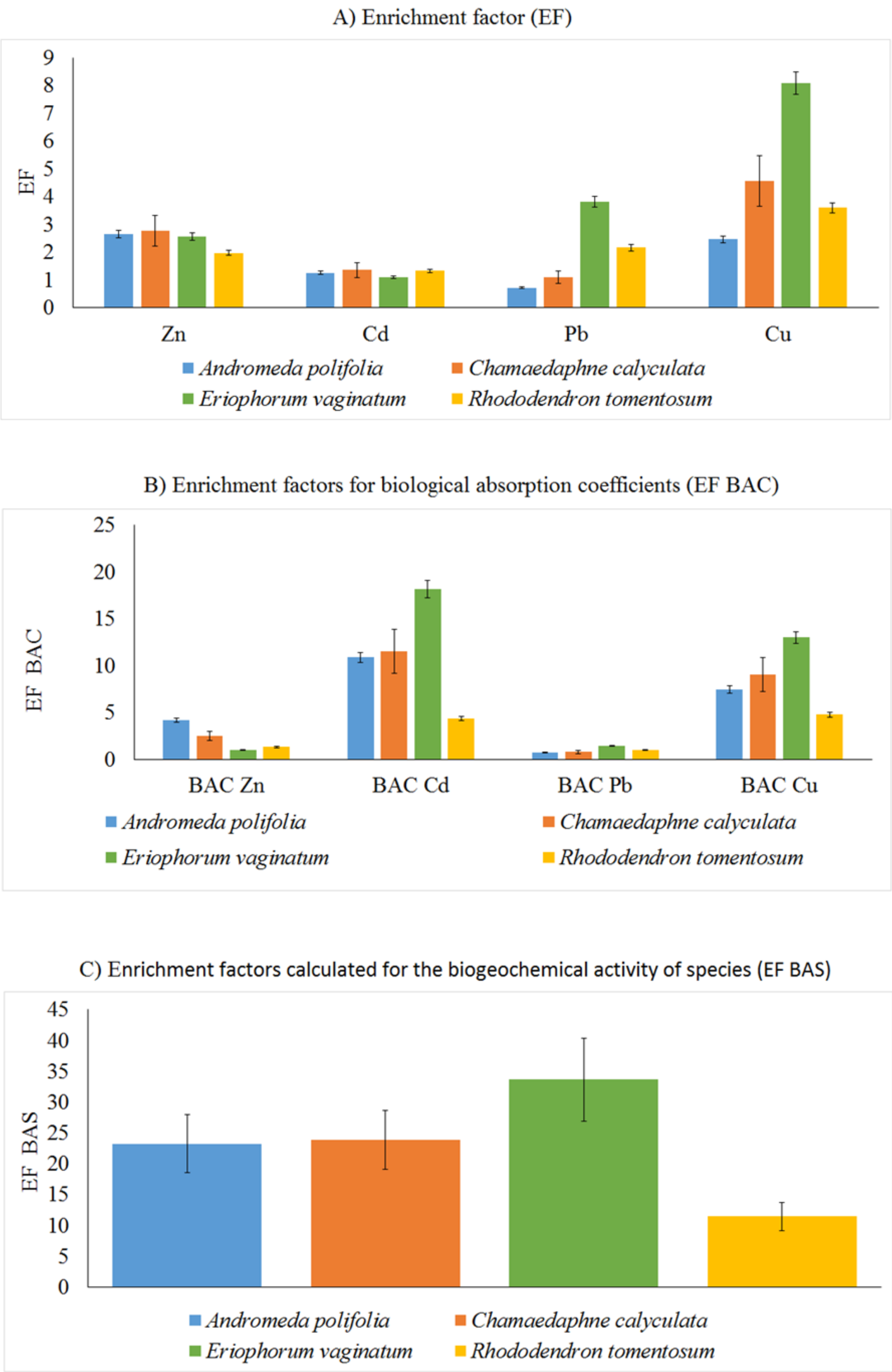

Figure 4. Comparison of the geochemical coefficients calculated for bog plant species.

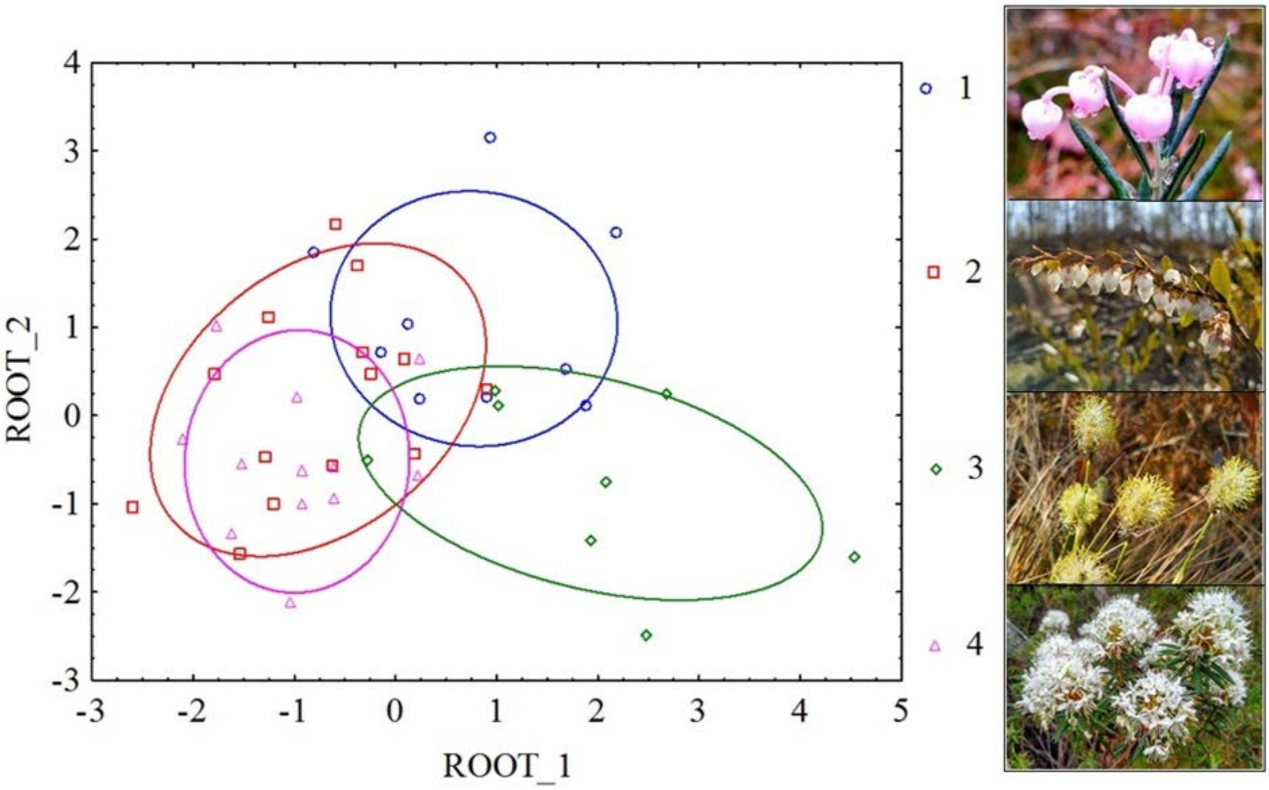

Figure 5. Differences between plant species (1: *Andromeda polifolia*; 2: *Chamaedaphne calyculata*; 3: *Eriophorum vaginatum*; 4: *Rhododendron tomentosum*) in the accumulation of Zn, Cu, Pb and Cd.

DISCUSSION

Heavy metal content of plant dry mass

Changes in the accumulation of elements in plant tissues are assessed using geochemical coefficients in many studies (Laureysens *et al*. 2004, Wojtuń *et al*. 2013, Borgulat *et al*. 2018). In these studies, coefficients are calculated for plant dry weights; whereas we have calculated geochemical coefficients for plant ash, which enables a more detailed assessment of changes in the intensity of biological absorption (according to Perelman & Kasimov 1999).

Comparison of our data for the concentration of elements in plant dry matter with the data of other authors showed that Zn content at our pristine sites is lower than reported from Europe (Stoltz & Greger 2002, Wojtuń *et al*. 2013, Borgulat *et al*. 2018) by a factor of 1.5–2. Data from Siberia (Moskovchenko *et al*. 2012, Ryzhakova *et al*. 2017) coincide with our data from pristine bogs. An exception is *Eriophorum* from the Urengoy tundra (Moskovchenko *et al*. 2012), whose Zn content is higher and corresponds to that of the plants sampled in our drained bogs. The Zn content of the plant dry mass from different species growing in the drained areas studied here is equal to, or 1.5–2 times higher than, almost all of the data we found for comparison (Borgulat *et al*. 2018, Moskovchenko *et al*. 2012, Ryzhakova *et al*. 2017, Wojtuń *et al*. 2013). Only plants from northern Sweden accumulate more Zn (Stoltz & Greger 2002).

Our values for the Cd content of plant dry mass in both pristine and drained bogs are very low compared to the data of other authors (Borgulat *et al*. 2018, Stoltz & Greger 2002, Wojtuń *et al*. 2013). The Pb content of plant dry matter from all of our sites is 1.3 to 77 times less than found by other authors (Stoltz & Greger 2002, Moskovchenko *et al*. 2012, Wojtuń *et al*. 2013, Ryzhakova *et al*. 2017). An exception is *R. tomentosum* from Szeroki (Borgulat *et al*. 2018), which is consistent with our data. The Cu content of plant dry matter in our pristine plots is 1.5–12 times lower than that in the drained plots, and from 3 to 34 times lower than reported by other authors (Moskovchenko *et al*. 2012, Wojtuń *et al*. 2013). Compared to contaminated sites in northern Sweden (Stoltz & Greger 2002), the Cu concentration in the tissues of *Eriophorum* from the Ket river terrace is 251 times lower (Table 2).

Thus, the Cd, Pb, and Cu content of plant dry mass in our bogs is mainly lower than in other regions, based on similar data (Stoltz & Greger 2002, Wojtuń *et al*. 2013, Borgulat *et al*. 2018), and Zn content is

Table 2. Element content of plant dry matter, according to different authors.

Authors	Region	Species	Plant dry mass content (mg/kg)			
			Zn	Cd	Pb	Cu
Borgulat *et al*. 2018	NE Poland	*R. tomentosum*	40	0.7	0.5	-
	SE Poland	*R. tomentosum*	25	0.05	1.9	-
Wojtuń *et al*. 2013	SW Poland	*A. polifolia*	52	0.13	4.1	7.1
Stoltz & Greger 2002	N Sweden	*E. angustifolium*	187	0.7	38.3	22.6
Moskovchenko *et al*. 2012	NW Siberia, Russia	*R. tomentosum*	21	0.11	1.3	4.8
		E. polystachion	81	-	4.7	10
Ryzhakova *et al*. 2017	NW Siberia, Russia	*R. tomentosum*	22.6	-	1.7	-
		C. calyculata	31	-	1.8	-
Our data: pristine bogs	South-east W Siberia, Russia: Vasyugan Mire	*A. polifolia*	0.68	0.005	0.05	0.06
		R. tomentosum	14.4	0.02	0.2	0.02
		C. calyculata	10.2	0.006	0.2	0.2
		E. vaginatum	14.2	0.005	0.2	0.09
	South-east W Siberia, Russia: terrace of the Ket River	*A. polifolia*	33.2	0.008	1.4	1.6
		R. tomentosum	20.8	0.005	0.9	1.03
		C. calyculata	19.5	0.005	0.9	0.6
		E. vaginatum	52.5	0.005	0.7	0.5
Our data: drained bogs	South-east W Siberia, Russia: Vasyugan Mire	*A. polifolia*	51.7	0.006	0.5	2.4
		R. tomentosum	34.3	0.005	0.6	1.9
		C. calyculata	42.9	0.009	0.8	2.6
		E. vaginatum	64.2	0.005	0.8	2.1
	South-east W Siberia, Russia: terrace of the Ket River	*A. polifolia*	99.2	0.02	0.7	3.4
		R. tomentosum	77.5	0.1	2.1	3.4
		C. calyculata	77.7	0.005	1.2	2.8
		E. vaginatum	106.6	0.2	1.5	4.2

lower only in our pristine sites. An increase in the concentration of elements in plant dry matter from drained areas is associated with an increase in the degree of peat decomposition and with the effect of fires. Fires are quite frequent in drained bogs (Gashkova & Sinyutkina 2015, Maloletko *et al*. 2018), leading to an increase in the bioavailability of elements and an acceleration of biogeochemical cycles.

In addition to the data presented (Moskovchenko *et al*. 2012) (Table 2), the ability of the genus *Eriophorum* to accumulate high concentrations of heavy metals has been noted by others (Stoltz & Greger 2002, Närhi *et al*. 2012), which fully confirms our conclusions on the capacity of *Eriophorum* to perform as a bioindicator.

Heavy metal content of peat

The dry peat Zn content of our bogs is quite high, close to values reported from Poland (Wojtuń *et al*. 2013), and higher than other data with which we compared our results (Stepanova *et al*. 2015, Borgulat *et al*. 2018, Borodkina *et al*. 2018, Novosyolova *et al*. 2019) (Table 3). The high Zn concentrations are explained by the specific geochemical characteristics of the region (Siromlya 2017), which are associated with the underlying rock that contains high concentrations of this element. Drained bogs on our territory are subject to frequent fires, as a result of which Zn is released from burnt peat (Leonova *et al*. 2020). The Cd content of the dry peat of our pristine and drained bogs is very low

Table 3. Element content of dry peat, according to different authors.

Authors	Region	Peat dry mass content (mg/kg)			
		Zn	Cd	Pb	Cu
Wojtuń *et al*. 2013	SW Poland	60	2.1	99	10
		60	2	124	11
Borgulat *et al*. 2018	NE Poland	20	0.5	40	-
	SE Poland	18	0.8	55	-
Orru & Orru 2006	Estonia	-	0.19	9.6	1.36
Novosyolova *et al*. 2019: drained bogs	European part of Russia	2.4	0.59	5.6	0.9
Borodkina *et al*. 2018	European part of Russia	6.06	0.045	2.28	0.91
Stepanova *et al*. 2015	W Siberia, Russia	9.07	0.34	0.65	1.04
		7.02	0.32	1.23	1.24
		10.05	0.14	2.75	2.64
		7.79	0.32	1.75	1.82
		6.22	0.22	0.98	2.3
Our data: pristine bogs	South-east W Siberia, Russia: Vasyugan Mire	33.6	0.27	2.67	3.13
	South-east W Siberia, Russia: terrace of the Ket River	77.14	0.05	4.91	3.76
Our data: drained bogs	South-east W Siberia, Russia: Vasyugan mire	116.2	0.005	6.85	2.22
	South-east W Siberia, Russia: terrace of the Ket River	12.93	0.09	4.39	2.63

compared to values reported by Wojtuń *et al*. (2013) and Borgulat *et al*. (2018). The low content of this element is associated with its origin being predominantly atmospheric, and it indicates low levels of air pollution at our site. In addition, the Cd content is significantly lower in the drained bogs. A decrease in peat Cd content may be associated with the high bioavailability of this element (Kumar *et al*. 2020) causing a change in hydrological conditions, which strongly affect the absorption of Cd by plants and the leaching of the element from the soil (Liu *et al*. 2021). The Pb content of dry peat in our pristine and drained bogs is similar to values reported from Siberia and from the European part of Russia (Stepanova *et al*. 2015, Novosyolova *et al*. 2019), but much lower than European data (Wojtuń *et al*. 2013, Borgulat *et al*. 2018). The difference between the values found for Eastern Europe (Orru & Orru 2006, Wojtuń *et al*. 2013, Borgulat *et al*. 2018) and Western Siberia (Stepanova *et al*. 2015) ranges from 6 to 190 times. The differences are most probably associated with different levels of industrial load on these regions.

The Cu content of dry peat from pristine bogs is 1.4 times higher than that of peat from drained bogs, and is higher than all the data presented in the literature (Orru & Orru 2006, Stepanova *et al*. 2015), except for Wojtuń *et al*. (2013), who recorded values exceeding our pristine values by 2.7–2.9 times (Table 3). This increase is associated with the hydrological removal of Cu from drained bogs and the absorption of Cu by plants. When the bog is drained, as a result of a decrease in the level of the bog water table, the degree of decomposition of peat increases, which results in the transition of Cu into a bioavailable form. Thus, drainage contributes to the hydrological removal of the element and an increase in the absorption by plants of Cu, which is usually deficient in the raised bogs of Siberia (Vodyanitskii *et al*. 2012).

Application of geochemical coefficients

In order to identify changes in the geochemical conditions of bogs, coefficients are used that take into account the elemental content levels in plant tissues. Such coefficients are used in studies investigating atmospheric pollution (Laureysens *et al*. 2004, Wojtuń *et al*. 2013, Borgulat *et al*. 2018). Other researchers have used the relative elemental compositions of mosses and vascular plants, although there is a barrier to the absorption of some elements in vascular plants, unlike mosses (Shotyk *et al*. 2019). In addition, an enrichment factor (EF) may be applied, which is determined by dividing the trace element content of samples from sites with human interference by control values (Nieminen *et al*. 2002).

The biological absorption coefficient (BAC) is used widely in Russia to determine the ability of plants to absorb elements from the soil. However, most of the published BACs are for plants growing on mineral soils rather than on peat. V.V. Dobrovolsky calculated average BAC values for plants growing on mineral soils (Dobrovolsky 2003). The level of BAC calculated by Dobrovolsky is lower than our median values for plants from pristine sites, with the exception of the BAC for Zn, which coincides with our data (Table 4). In addition, there have been many studies in which BACs were calculated for cultivated and wild plants growing on mineral soils (Sosorova *et al*. 2012, Samylina & Biryukov 2013, Vorobyeva *et al*. 2016, Ilinskiy 2020, etc.) in which the BAC for Zn was also higher than our data, while the BAC for other elements was slightly lower. This pattern is explained by an excess of Zn in our peat and a deficiency of other microelements. Only a few BACs have been calculated for bog plants, and these are presented in Table 4. The Moskovchenko data calculated for *E. polystachion* and *R. tomentosum* coincide with our data, apart from the data for Cd whose absorption rate is likely to be strongly influenced by local conditions for the transport of pollutants with air masses.

The biogeochemical activity of species (BAS) is used by the authors for various purposes. For example, it can be used to compare several species in terms of the intensity of accumulation of several elements at once (Korotchenko 2018, Ivanisova & Kurinskaya 2019, Sibgatullina & Valiev 2019). In addition, differences in BAS have been detected in plants of various lines induced through the process of cell selection, which makes it possible to use the lines with the lowest BAS for toxic elements for food purposes (Tovstik *et al*. 2020). The works of Avessalomova show the effectiveness of BAS in identifying differences between elementary landscapes. For example, the most noticeable change in BAS occurs when a forest transitions into a mire (Avessalomova 2016, 2020). A similar problem is addressed in our work but, instead of natural microlandscapes, we compare pristine and drained areas. In the process of comparing changes in the BAS level in several plant species simultaneously during the drainage of bogs, we noted that it is much easier to show interspecific differences in changes in the intensity of absorption of elements using the enrichment factor for the biogeochemical activity of species (EFBAS). This coefficient allows one to compare as many species as necessary, and to estimate the absorption of several elements at once. In addition, EFBAS makes it possible to present results of the comparison as clearly as possible for many indicators at once, in order to identify the plant species that are most sensitive to changes in environmental conditions. Thus, EFBAS is the most effective factor for identifying the plant species which are most suitable for bioindication and phytoremediation.

Comprehensive analysis of geochemical indicators

The elemental contents of peat and plants and their quotients reflect differences in the accumulation and activity of element absorption between bog areas.

Discriminant analysis based on the data for heavy metal contents of plants and peat shows differences between sites, revealing that undisturbed areas - even if they are geographically distant from one another -

Table 4. BAC, according to different authors.

Authors	Species	BAC			
		Zn	Cd	Pb	Cu
Dobrovolsky 2003	Average BAC values for plants on mineral soils	11.8	4.4	1.5	2.3
Our data: pristine bogs	Median for plants from pristine areas	11.9	12.2	4.2	5.1
Moskovchenko *et al*. 2012	*E. polystachion*	12.1	15.4	4.9	2.7
	R. tomentosum	12.0	8.8	5.2	5.1

are very similar in terms of the elemental concentrations in plants and peat. However, drained areas differ significantly, not only from undisturbed areas, but also amongst themselves (Figure 6).

The results of discriminant analysis confirm the need for a comprehensive analysis of the data regarding the elemental content of plants and peat, especially since the elemental content of peat in a site typically does not correlate with the elemental content of plants (Table 5), and depends on the forms of the elements in the peat. Therefore, it is necessary to use biogeochemical coefficients to assess changes in the intensity of biological absorption of elements by plants following drainage of the bog.

Similar data were obtained by Pająk *et al*. (2017) who found a relationship between plants and soil for only some of the elements considered.

Comparison of the heavy metal content of plants and peat from different bogs in Siberia and Europe clearly shows how these indicators vary, depending on the geochemical characteristics of the region.

Table 5. Spearman Rank Order Correlations of the elemental content of plant and peat dry matter. Bold type indicates significant correlations at $P < 0.05$.

	Zn (peat)	Cd (peat)	Pb (peat)	Cu (peat)
Zn (plant)	-0.1	-0.2	**0.4**	-0.1
Cd (plant)	**-0.3**	0.2	-0.01	-0.03
Pb (plant)	-0.06	-0.1	0.3	0.1
Cu (plant)	-0.09	-0.1	**0.4**	-0.1

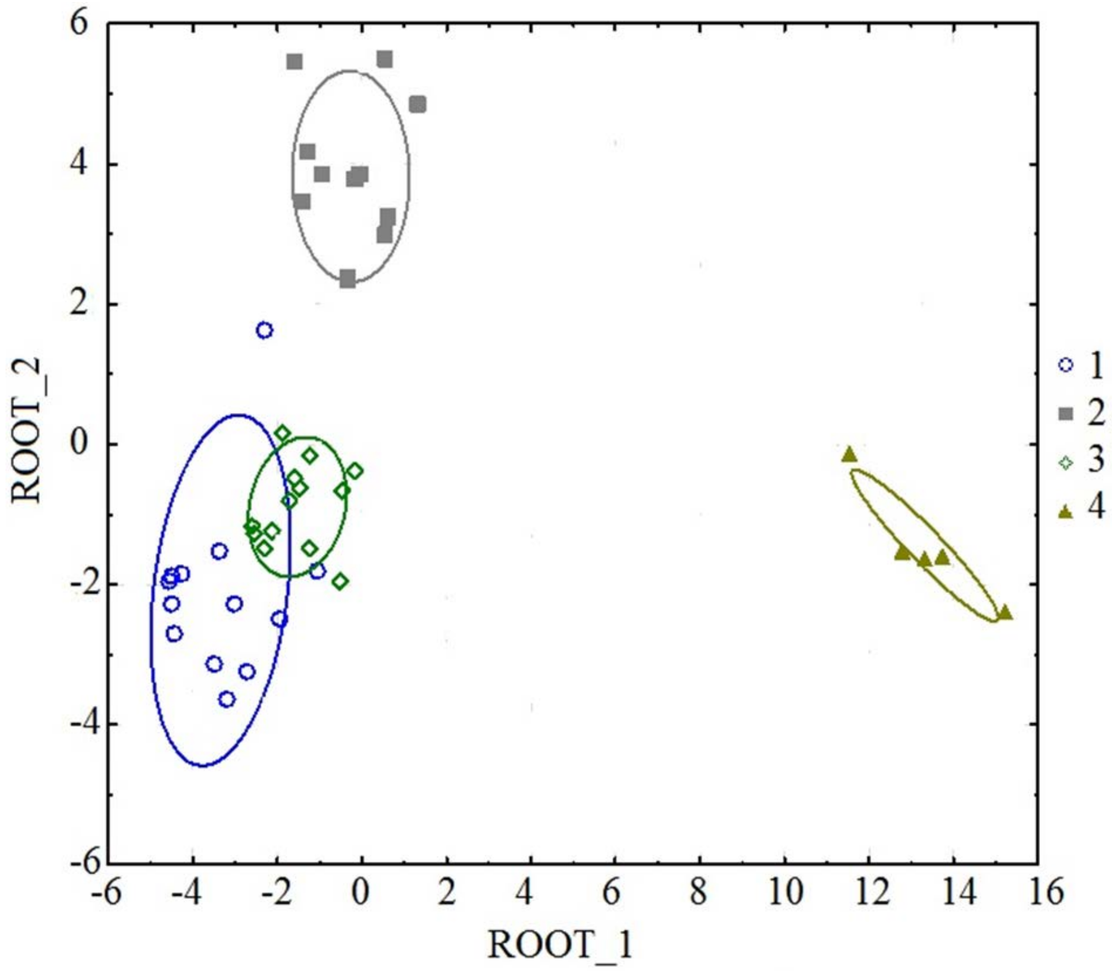

Figure 6. The results of discriminant analysis for the Zn, Cu, Pb and Cd content of plants and peat. 1: Vasyugan Mire, pristine sites; 2: Vasyugan Mire, drained sites; 3: terrace of the Ket River, pristine sites; 4: terrace of the Ket River, drained sites.

CONCLUSIONS

The research presented in this article enables us to answer the three research questions set out in the Introduction as follows:

1. The Zn, Pb, Cd and Cu contents of plants from drained areas are higher than those from pristine bogs; but the increase is insignificant, and these indicators cannot serve as indicators of drainage.

2. The most effective indicator of drainage may be EFBAC if the accumulation of one element is being estimated, and EFBAS if the accumulation of several elements is being estimated simultaneously.

3. The Cd, Pb and Cu contents of the dry mass of plants in our bogs is lower than for bogs in Europe and Western Siberia, and the Zn content is lower only in our pristine areas. In the peat of our bogs, the Zn content is also higher than in most literature sources, while the Cd content is lower. The Pb concentration coincides with data for the European part of Russia and for Western Siberia. The Cu content of the peat in our territories is 2–3 times higher than for most of the data we used for comparisons.

In addition, we have shown that the EFBAS allows one to compare several plant species at once, according to the degree of change in the intensity of absorption of a complex of elements.

On the basis of these coefficients, *E. vaginatum* is the most effective of the species considered as an indicator of changes in the biogeochemical conditions of a drained bog. In the course of further research, a deeper study of the influence of microclimatic and other abiotic factors on the patterns of distribution and accumulation of heavy metals by bog plants is necessary.

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AUTHOR CONTRIBUTIONS

LPG: conceptualisation, data curation, formal analysis, investigation, methodology, visualisation, writing the original draft of the manuscript. YAK: data curation, formal analysis. AAS: data curation. All authors: review and editing of later versions of the manuscript.

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