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ORIGINAL PAPER

BIOACCUMULATION OF MACRO- AND MICRONUTRIENTS IN HERBACEOUS PLANTS OF HEADWATER AREAS – A CASE STUDY FROM NORTHERN POLAND*

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Abstract

The aim of the study was to compare ten species of herbaceous plants of mid-forest spring niches in terms of the accumulation of N, P, K, Mg, Ca, Zn, Cu, Ni, Mn, Fe, Sr and Al. The content of nutrients in aerial shoots of plants was analyzed by considering each component separately and in an integrated way, comparing the demand of the examined species for nutritional components. The research was done in a headwater riparian forest situated in the upper course of the Kamienna Creek valley, located on the territory of the Leśny Dwór Forest Inspectorate (Northern Poland). The examined species of plants demonstrated statistically significant differences in concentrations of macro- and microelements in shoots, except for zinc. The plants accumulated from 1754.3 to 2934.8 $mmol_c$ kg^{-1} of the examined components in total, and a percentage of each component in their sum was determined by the nutritional requirements of particular species of plants in respect to macro- and microelements. Macroelements in total constituted from 99.39% to 99.71% of the sum of the components. The highest content of nutrients was noted in the shoots of *Urtica dioica*, and the lowest one in *Carex echinata*. Nitrogen in the examined species constituted 42.6% - 52.9% of the sum of nutrients, phosphorus 2.9% - 14.2%, potassium 19.1% - 34.9%, magnesium 7.0% - 24.8% and calcium 4.8% - 8.5%, and total microelements constituted from 0.29% in the shoots of *Caltha palustris* to 0.67% in the shoots of *Valeriana officinalis*. Fe represented the highest share in the sum of microelements: 20.9% - 51.6 %, Al 17.3% - 40.6% and Mn 8.4% - 28.9%, which represents substantial migration of these elements from roots to aerial shoots. It was also found that the species of plants which belonged to the same families of plants showed similar accumulation capacity.

Keywords: riparian forest, soil, plants, accumulation nutrients.

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INTRODUCTION

Nutrient uptake by plants largely depends on plant traits, such as a plant species, age or development phase, as well as on synergic and antagonistic ionic interactions (Veselkin et al. 2014). Quantities of elements taken up by plants depend on their physiological demand (Kabata-Pendias, Szteke 2005), although some absorption may occur passively, due to extensive accumulation of pollutants in the soil and water (Parzych et al. 2015). Seasonal variability of the environment and different needs of plants during their life span underlie the dynamic character of the plant – environment relationship, especially in marshy ecosystems, where underground waters flowing out on the surface create specific conditions for development of marshy land plants (Parzych et al. 2016*a*). The characteristic nature of underground waters, introducing a specific ion load to an ecosystem (Tabacchi et al. 2000), and their high level stimulate the swamping of a given area and development of rich plant species (Osadowski 2006). Plants of headwater riparian forests, by retention, uptake and accumulation of several nutritional components, play a very important role in the formation of water chemistry (Maine et al. 2006, Hazlett et al. 2008). Research completed up to date indicates that headwater plants are characterized by a relatively high capacity to accumulate macro- and microelements (Horska-Schwarz, Spałek 2008, Yu et al. 2014). Jansson et al. (2007) and Kuglerová et al. (2014) reported that plants in riparian forests have an easy access to nutrients, since water transports the mineral material and organic substances in a form of suspended matter. In recent years, special attention has been paid to the composition of species of forest fauna, which substantially modifies physical and chemical properties of waters (Parzych et al. 2017), while simultaneously contributing to their purification. Interactions between water, plants and soil in mid-forest spring niches are very close and anisotropic (Devito et al. 2000). Comparison of the accumulation capacity of various plant species in reference to macro- and micronutrients in an area free from any major anthropogenic impact will broaden the current knowledge on a possible use of some such plants for environmental protection (Lone et al. 2008, Viers et al. 2012).

The aim of the study was to compare ten species of herbaceous plants of mid-forest spring niches regarding the accumulation of N, P, K, Mg, Ca, Zn, Cu, Ni, Mn, Fe, Sr and Al. The content of macro- and microelements was analyzed, considering each component separately and in an integrated way, and comparing the results with the demand of the examined species for nutrients.

MATERIAL AND METHODS

Research site

The studies were conducted in the upper course of Kamienna Creek, which is a left tributary of the Słupia River, flowing through the Leśny Dwór Forest Inspectorate area in the northern part of Poland (54°19′N; 17°10′E). It is the area with an average annual precipitation of about 770 mm and average annual air temperature of 7.6°C (Kirschenstein, Baranowski 2008). The area of the catchments of the Kamienna Creek is almost completely overgrown with forests with a spatially diverse species composition, where dominant tree species are beech, pine and spruce trees in its plateau part and common alder (*Alnus glutinosa*) at the bottom of the valley. The 40-86-year-old old black alder (*Alnus glutinosa* Gaertn) constitutes the layer of trees within the headwater system, growing on domed bogs consisting of the wood and sedge peat (Jonczak et al. 2014). In the examined spring niche, the presence of 106 species of vascular plants, 17 species of moss and 8 species of liverworts was discovered. Over the area covered by headwater marshy meadow, there were for example: *Galium palustre* L., *Lycopus europaeus* L., *Solanum dulcamara* L., *Cardamine amara* L., *Chrysosplenium alternifolium* L. and *Scirpus sylvaticus* L.

Sampling and analysis

The study included 10 representative species of herbaceous plants characterized by the highest frequency, growing on three domed bogs (location 1, 2 and 3) – Table 1. The samples of aerial shoots were taken three times during the growing period (May, July and September) in the years 2012-2014. During the study, 90 samples of plants were collected. A single sample comprised the shoots originating from several specimens of a given

Table 1

Characteristics of herbaceous plants in the riparian forest

Species	Code	Location
Ajuga reptans L.	*Aju_rep*	1
Caltha palustris L.	*Cal_pal*	2
Carex echinata Murray	*Car_ech*	3
Geranium robertianum L.	*Ger_rob*	2
Gymnocarpium dryopteris (L.) Newman	*Gym_dry*	1
Mentha aquatica L.	*Men_aqu*	3
Scirpus sylvaticus L.	*Sci_syl*	1
Solanum dulcamara L.	*Sol_dul*	2, 3
Urtica dioica L.	*Urt_dio*	1, 2
Valeriana officinalis L.	*Val_off*	3

species, of which a mixed sample was subsequently created separately for each species. In the laboratory, the shoots were washed in distilled water in order to remove the soil. Then, they were dried at 65°C and homogenized in a laboratory mill.

The content of total nitrogen in plants was analyzed by the Kjeldahl method (Büchi 350K) and phosphorus by the molybdenum blue method after samples had been digested in a mixture of 98% H_2SO_4 and 30% H_2O_2. To determine metallic elements, the plant samples were digested in a mixture of 65% HNO_3 and 30% H_2O_2. Then, the solutions were filled up to the volume of 50 ml with deionized water. In these solutions, the content of K, Mg, Ca, Zn, Cu, Ni, Mn and Fe was analyzed by atomic absorption spectrometry (Aanalyst 300, Perkin Elmer) and that of Al and Sr by microwave plasma atomic emission spectrometry (Agilent 4100 MP-AES). Original Merck KGaA (1g/1000mL) standards were used for the preparation of standard solutions. The wavelengths at which the metals were detected are as follows: 769.9 nm for K, 202.6 for Mg, 422.7 for Ca, 213.9 for Zn, 324.8 for Cu, 232.0 for Ni, 279.5 for Mn, 248.3 for Fe, 283.3 for Sr and 396.1 for Al. Quality control of the analytical procedures was carried out by analyzing the standard certified reference material (aquatic plants CRM 060).

Soil samples were taken every 10 cm from the rhizosphere of the examined plants (0-30 cm) at the beginning of experiment. After removing fresh plant particles, the samples were dried at 40°C, milled into powder and analyzed. The content of organic matter was analyzed by loss on ignition at 550°C, soil reaction was determined with the potentiometer method in a suspension with water (pH_{H_2O}) and 1mol dm^{-3} KCl solution (pH_{KCl}), the content of N was identified by the Kjeldahl method, while the content of P was tested by the molybdenum-blue method after digestion of the samples in a mixture of 65% HNO_3, 30% H_2O_2, and the content of K, Mg, Ca, Zn, Cu, Ni, Mn, Fe, Sr and Al was assayed in the same solution by microwave plasma atomic emission spectrometry (Agilent 4100 MP-AES). All analytical measurements were made in triplicate.

Statistical analysis

Distribution of the content of elements in the shoots of plants and in soil samples was examined by the Shapiro-Wilk test. In order to compare the physicochemical properties and the content of macro- and microelements in the soil between 3 locations, the mean values for the layers of 0-30 cm were calculated. In these layers there is the largest number roots of herbaceous plants. The significance of statistical variance regarding concentrations of macro- and microelements in the shoots of plants and in the soil was compared by the Kruskal-Wallis test. All calculations were performed using Statistica 7.1 software. The demand of the examined species for nutrients was described with the ANE method – *Accumulation Nutrient Elements* (Ostrowska 1999). The sum of macro- and microelements calculated by the

ANE method reflects the so-called nutritional factor. The value of the sum of components and their ionic composition identifies the circulation of components between soils and plants. Percentages of particular components in their sum depend on the alimentary requirements of plants in relation to particular components. The sum of components (Y) in $mmol_c$ kg^{-1} was calculated from the formula:

$$\overset{i}{\underset{i=1}{Y}} = \Sigma(Z : z),$$

where: Z – content of the element (mg kg^{-1}),
z – atomic weight/ion valency.

After the calculation of Y, the percentage (X) of each element in the sum of:

$$X = \frac{(Z : z) \cdot 100}{Y}$$

was calculated.

Hierarchical cluster analysis (the Ward's method) was used to classify plant species based on the macro- and microelement content in shoots.

RESULTS AND DISCUSSION

Physicochemical properties of soils

Histosols underlying the investigated headwater riparian forest showed spatially diversified thickness of no more than 1 m. They were characterized by an average content of organic matter at the level of 74.0-81.0%, changing with the depth. These are slightly acid to acid soils, abundant in nitrogen, relatively poor in phosphorus, potassium and magnesium and with an average abundance of calcium (Table 2). The content of microelements remained at the levels characteristic for Histosols, indicating a limited impact of anthropogenic factors (Jonczak et al. 2014) – Table 3. The soils presented many specific features resulting from their functioning in the headwater environment and in a transient zone between the underground and surface part of a water circulation system in the river catchment. In those soils, there is a continuous water flow of groundwater towards the river, concentrated above the mineral substratum, which leads to characteristic vertical gradients of concentrations of different components (Jonczak et al. 2015*a*, Jonczak, Parzych 2016). Litterfall plays a specific role in the determination of characteristics of the topsoil. The examined soils were regularly supplied with nutrients released during the rapid decomposition of plant debris (Jonczak et al. 2016). The damp microclimate and a large abundance of nutrients in the soil of the examined headwater riparian forest had a positive effect on the release of potassium and magnesium, which enriched the topsoil (Jonczak et al.

Table 2

Physicochemical properties and macroelement content in the topsoil (0-10 cm, 10-20 cm, 20-30 cm) of the studied headwater riparian forest, assessed with the Kruskal-Wallis (K-W) test

Parameter	Depth (cm)	Location 1	Location 2	Location 3	K-W *p*
OM (%)	0-10	72.5	81.1	80.5	-
	10-20	74.1	80.4	82.9	
	20-30	75.3	81.4	79.5	
	mean	74.0 ± 1.41	80.9 ± 0.50	81.0 ± 1.76	
pH (H_2O)	0-10	6.1	6.5	5.8	<0.05
	10-20	5.9	6.4	5.6	
	20-30	5.8	6.5	5.7	
	median	5.9 ± 0.12	6.4 ± 0.10	5.7 ± 0.12	
pH (KCl)	0-10	5.5	5.9	5.2	<0.05
	10-20	5.4	5.8	5.0	
	20-30	5.3	6.0	5.1	
	median	5.4 ± 0.09	5.9 ± 0.14	5.1 ± 0.10	
N (mg kg^{-1})	0-10	32 980	32 931	29 735	-
	10-20	33 586	31 951	29 308	
	20-30	32 405	30 512	33 187	
	mean	32 990 ± 588	31 798 ± 2553	30 744 ± 1326	
P (mg kg^{-1})	0-10	1208.1	1020.6	1562.2	-
	10-20	1161.1	783.3	853.4	
	20-30	704.6	712.6	769.8	
	mean	1 024.6 ± 276	838.8 ± 161	1 061.8 ± 435	
K (mg kg^{-1})	0-10	868.7	548.3	513.5	-
	10-20	516.0	343.2	324.1	
	20-30	316.9	164.5	295.3	
	mean	581.9 ± 260	352.0 ± 192	377.6 ± 118	
Mg (mg kg^{-1})	0-10	1097.0	1128.3	1010.6	-
	10-20	935.0	1114.9	787.8	
	20-30	933.4	1057.3	839.2	
	mean	988.5 ± 94	1 100.2 ± 38	879.2 ± 117	
Ca (mg kg^{-1})	0-10	22 282.5	23 552.2	20 174.1	<0.05
	10-20	21 441.1	24 185.2	17 371.7	
	20-30	23 968.1	25 225.2	18 829.2	
	mean	22 564.0 ± 1287	24 321 ± 845	18 792 ± 1401	

p – significance level, – no significant differences

Table 3

Microelement content in the topsoil (0-10 cm, 10-20 cm, 20-30 cm) of the studied headwater riparian forest, assessed with the Kruskal-Wallis (K-W) test

Parameter (mg kg^{-1})	Depth (cm)	Location 1	Location 2	Location 3	K-W *p*
Sr	0-10	85.4	100.8	82.9	-
	10-20	76.8	107.0	70.5	
	20-30	176.2	92.3	83.4	
	mean	112.8 ± 55	100.0 ± 7	78.9 ± 7	
Zn	0-10	34.5	65.0	66.8	-
	10-20	32.7	56.1	59.7	
	20-30	15.1	21.7	48.9	
	mean	27.4 ± 11	47.6 ± 23	58.4 ± 9	
Cu	0-10	10.3	10.0	10.4	-
	10-20	10.3	9.7	9.7	
	20-30	10.2	7.3	10.1	
	mean	10.3 ± 0.1	8.9 ± 1.5	10.1 ± 0.4	
Ni	0-10	7.6	8.0	7.5	-
	10-20	6.6	7.0	6.5	
	20-30	7.0	6.3	6.7	
	mean	7.1 ± 0.5	7.1 ± 0.8	6.9 ± 0.5	
Fe	0-10	10 262.5	2 946.5	19 755.5	<0.05
	10-20	9 024.4	2 492.3	14 536.1	
	20-30	6 561.1	2 894.1	13 702.1	
	mean	8 616 ± 1884	2 778 ± 248	15 998 ± 3280	
Mn	0-10	1 053.8	474.8	850.7	-
	10-20	628.2	265.5	532.3	
	20-30	340.5	166.3	488.9	
	mean	674.1 ± 359	302.2 ± 158	623.9 ± 197	
Al	0-10	2 432.1	1 305.3	2 203.3	<0.05
	10-20	2 382.9	1 210.3	1 850.7	
	20-30	2 115.7	804.2	2 010.1	
	mean	2 310.2 ± 170	1 106.6 ± 266	2 021.4 ± 176	

p – significance level, – no significant differences

2015*b*) and accumulated in herbaceous plants, often in quantities exceeding their physiological demand (Parzych et al. 2017).

Macro- and microelement concentrations in plant shoots

The examined species of plants were characterized by a good supply of N, P and Ca, except *Val_off* which accumulated substantially larger quantities of phosphorus than requird physiologically by most species. The largest quantities of N, Mg and Ca were found in the shoots of *Urt_dio*, P in the shoots of *Val_off*, and K in the shoots of *Ger_rob* (Table 4). The lowest concentration of macronutrients was found in the shoots of *Car_ech* (N, K), *Men_aqu* (P) and *Sci_syl* (Mg, Ca). All of the examined species accumulated excessive quantities of potassium, and increased values of magnesium were found in the shoots of *Cal_pal*, *Car_ech*, *Ger_rob*, *Gym_dry*, *Men_aqu*, *Sol_dul* and *Urt_dio*. Most plant species accumulate most commonly from 13000 to 31 000 mg kg^{-1} N, from 1000 to 4000 mg kg^{-1} P, from 2000 to 18 000 mg kg^{-1} K, from 1000 to 3000 mg kg^{-1} Mg and from 1000 to 33 000 mg kg^{-1} Ca in shoots (Ostrowska 1999). High accumulation of macroelements in the headwater plants was also described by Horska-Schwarz and Spałek (2008). High accumulation of potassium in the plants found in ecosystems with a high level of dampness was confirmed experimentally by Parzych et al. (2017). The research by Jonczak et al. (2015*b*) indicated that these elements were very quickly released during the processes of litterfall decomposition, through which they enriched the surface soil horizon with bioavailable forms. To a large extent, it had an impact on accumulation processes of herbaceous plants growing both on peat swamps and along streams. The accumulation of K and Mg in shoots of plants in the quantities often exceeding the plants' physiological demand was confirmed by the results reported by Horska-Schwarz and Spałek (2008) and Parzych et al. (2016*a*, 2017).

The shoots of the analyzed species of plants showed a good supply of trace elements such as Zn, Cu, Sr, Mn, Fe and Al. The highest quantities of metals were found in the shoots of *Val_off* (Cu, Fe), *Urt_dio* (Sr), *Men_aqu* (Zn), *Sci-syl* (Mn) and in *Aju_rep* (Al). The lowest concentrations of microelements were noted in the shoots of *Urt_dio* (Zn), *Sol_dul* (Cu), *Car_ech* (Sr), *Sci_syl* (Fe), *Ger_rob* (Mn) and *Cal_pal* (Al). It was also demonstrated that the shoots of *Aju_rep*, *Gym_dym*, *Sci_syl*, *Sol_dul* and *Urt_dio* accumulated increased concentrations of Ni (>10 mg kg^{-1}, Parzych 2014) in their shoots (Table 4). The soil and litterfall were major sources of nickel in the examined headwater riparian forest. The research results reported by Jonczak et al. (2014) indicated that the soils in a headwater system contained substantially less of this metal than alder leaf litter. Among the analyzed metallic elements, nickel was most easily released. Following numerous research studies dealing with the life of plants in an area free from the impact of anthropogenic factors, it can be concluded that microelements are accumulated mostly in roots and rhizomes of plants (Zang et al. 2010).

Table 4

Mean concentrations ($mg \cdot kg^{-1}$) ± standard deviation of elements in the shoots of plants assessed with the Kruskal-Walis (K-W) test

Elements	*Aju_rep*	*Cal_pal*	*Car_ech*	*Ger_rob*	*Gym_dry*	*Men_aqu*	*Sci_syl*	*Sol_dul*	*Urt_dio*	*Val_off*	K-W p
N	14 786 ± 2758	15 293 ± 2895	12 473 ±2195	15 755 ± 2250	14 432 ± 2551	14 938 ± 2901	14 024 ± 2022	17 897 ± 4331	18 243 ± 3053	12 810 ± 437	<0.001
P	2 334 ± 570	2 282 ± 561	21 57 ± 326	2 339 ± 353	2 721 ± 837	1 908 ± 280	2 915 ± 799	2 582 ± 425	3 803 ± 837	9 461 ± 2943	<0.001
K	22 393 ± 3099	27 880 ± 7701	18 289 ± 4315	29 699 ± 7518	22 994 ± 380	20 694 ± 7708	28 070 ± 5589	25 242 ± 5077	21 805 ± 3146	22 870 ± 951	<0.001
Mg	2 722 ± 474	4 965 ± 602	3 546 ± 850	3243 ± 439	3 305 ± 477	3 413 ± 655	2 495 ± 868	3 272 ± 730	5 127 ± 581	2 499 ± 1069	<0.001
Ca	17 874 ± 5472	18 863 ± 5157	6 688 ± 3308	17 770 ± 5412	8 300 ± 4897	13 174 ± 1869	5 818 ± 4390	10 809 ± 2733	29 018 ± 8144	9 461 ± 2943	<0.001
Sr	64.4 ± 21.8	97.7 ± 28.8	34.4 ± 8.5	76.5 ± 13.1	53.0 ± 29.1	64.3 ± 16.2	28.8 ± 11.3	36.7 ± 8.4	115.7 ± 37.7	52.0 ± 4.4	<0.001
Zn	19.2 ± 9.5	25.9 ± 17.2	27.4 ± 12.3	23.7 ± 4.3	17.6 ± 3.6	26.4 ± 9.0	40.3 ± 35.8	18.5 ± 6.6	16.1 ± 4.5	18.7 ± 11.9	0.138
Cu	12.4 ± 2.9	10.4 ± 1.3	10.2 ± 1.3	10.9 ± 0.7	13.5 ± 3.3	12.9 ± 1.2	11.2 ± 3.1	8.9 ± 0.9	11.7 ± 2.5	13.8 ± 1.1	<0.01
Ni	16.9 ± 6.4	9.6 ± 2.8	9.3 ± 5.1	8.4 ± 4.0	11.5 ± 4.1	8.9 ± 4.2	21.3 ± 6.9	14.0 ± 3.4	18.3 ± 10.4	9.1 ± 2.2	<0.001
Fe	241.3 ± 66.9	171.4 ± 40.3	236.1 ± 114.3	157.4 ± 21.0	159.1 ± 51.8	260.5 ± 85.2	133.4 ± 24.9	152.5 ± 49.5	188.8 ± 41.5	380.2 ± 19.2	<0.001
Mn	63.2 ± 18.2	55.1 ± 24.9	157.7 ± 40.0	35.8 ± 10.7	99.6 ± 83.4	66.8 ± 20.3	297.8 ± 149.2	97.0 ± 31.3	144.5 ± 55.8	81.9 ± 66.7	<0.001
Al	128.9 ± 77.7	40.1 ± 10.4	46.3 ± 12.2	74.4 ± 41.8	58.6 ± 23.1	88.9 ± 41.3	57.6 ± 30.3	54.0 ± 21.0	76.0 ± 40.9	97.7 ± 94.9	<0.001

p – significance level

Bioaccumulation of macro- and microelements

The uptake of nutrients from the soil solution by plants to a large extent is affected by factors dependent on the plant and soil characteristics (Parzych et al. 2017).

The shoots of the examined plants accumulated from 1754.3 to 2934.8 $mmol_c$ kg^{-1} of the analyzed components in total, while the macroelements constituted from 99.39 to 99.71% of the determined content (Table 5).

Table 5

The average accumulation of macro- and microelements in shoots of plants in the headwater riparian forest

Species	Σ macro, ($mmol_c$ kg^{-1})	Σ micro ($mmol_c$ kg^{-1}) (participation %)	Σ macro + Σ micro, ($mmol_c$ kg)
Aju_rep	2265.9	11.7 (0.51)	2277.6
Cal_pal	2559.3	7.4 (0.29)	2566.7
Car_ech	1744.4	9.9 (0.56)	1754.3
Ger_rob	2541.7	7.8 (0.31)	2549.5
Gym_dry	2053.4	8.1 (0.39)	2061.5
Men_aqu	2130.7	10.7 (0.49)	2141.4
Sci_syl	2064.9	11.4 (0.55)	2076.3
Sol_dul	2415.4	7.6 (0.31)	2423.0
Urt_dio	2923.9	10.9 (0.37)	2934.8
Val_off	2147.3	13.2 (0.61)	2160.4
Range	1744.4 - 2923.9	7.6 - 13.2 (0.29 - 0.61)	1754.3 - 2934.8

The total content of macro- and microelements in the examined species of herbaceous plants decreased in the order: *Urt_dio>Cal_pal>Ger_rob >Sol_dul >Aju_rep>Val_off >Men_aqu >Sci_syl >Gym_dry >Car_ech*. Nitrogen constituted from 42.6% (*Val_off*) to 52.9% (*Sol_dul*) of that sum, phosphorus from 2.9% (*Cal_pal*, *Men_aqu*) to 14.2% (*Val_off*), potassium from 19.1% (*Urt_dio*) to 34.9% (*Sci_syl*), magnesium from 7.0% (*Sci_syl*) to 24.8% (*Urt_dio*), calcium from 4.8% (*Val_off*) to 8.5% (*Car_ech*), and the total participation of microelements constituted from 0.29% in the shoots of *Caltha palustris* to 0.67% in the case of *Valeriana officinalis* (Figures 1, 2). The research results indicated that *Urt_dio* had the highest nutritional requirements. According to Ostrowska (1999), average values of the sum of components accumulated in plants in most cases vary from 1200 to 2500 $mmol_c$ kg^{-1}, and the contribution of microelements is less than 1%.

Iron showed the highest share in the sum of microelements, from 20.9% (*Sci_syl*) to 51.6% (*Val_off*), aluminum from 17.3% (*Ger_rob*) to 40.6% (*Aju_rep*) and manganese from 8.4% (*Ger_rob*) to 28.9% (*Car_ech*). The high participation of Fe, Mn and Al in the sum of the measured components (Figure 2) indicated their excessive uptake by plants, and it was due to the

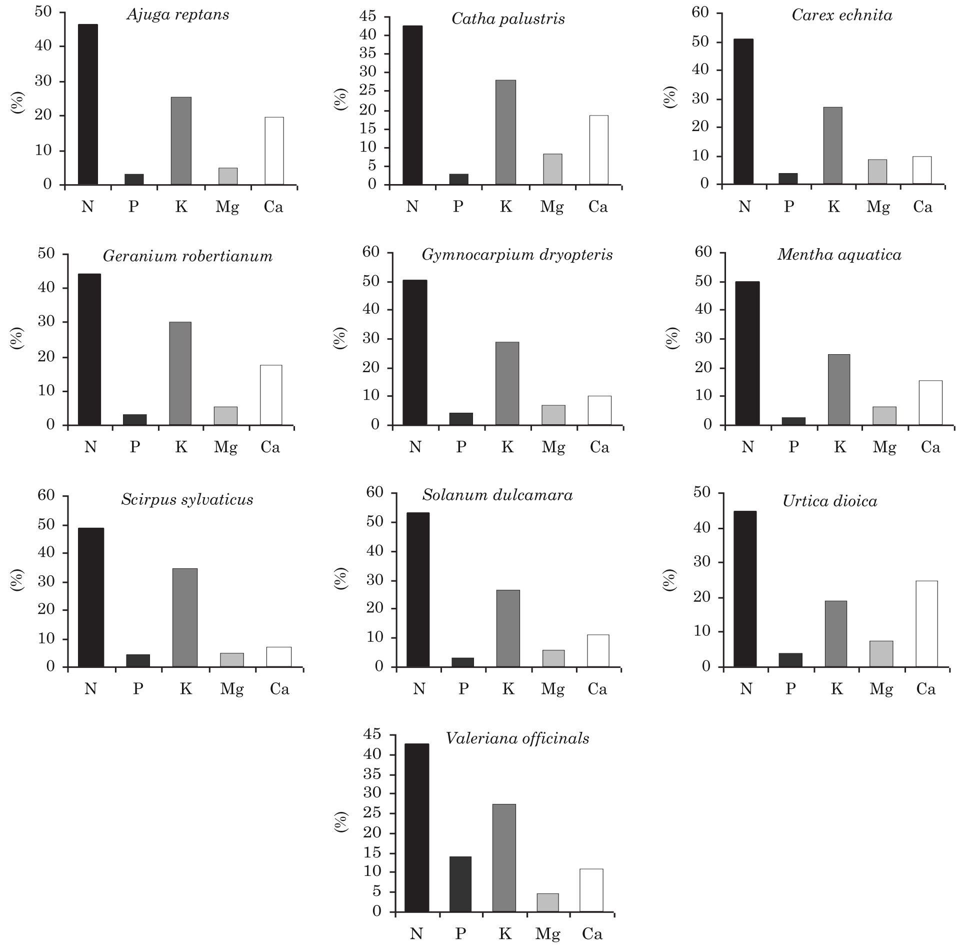

Fig. 1. Average percentages of N, P, K, Mg and Ca in Σ of macroelements in plant shoots

slightly acidic reaction of the soils (Table 2). According to Parzych et al. (2016*b*), Fe belongs to elements characterized by low mobility in plants, and it is most often accumulated in underground shoots. Under conditions stimulating its availability, substantial quantities of iron can be also accumulated in aerial shoots (Demirezen, Aksoy 2006). Essential percentages of Fe, Mn and Al in the composition of aerial shoots of the examined plants indicate mobility of those elements to aerial plant parts (Figure 2). The results of the research demonstrate that the analyzed species of plants are characterized a composition with substantially higher percentages of N, Ca, Zn, Ni and Mn and lower percentages of P, Mg, Cu and Fe than *Typha latifolia, Glyceria maxima, Phragmites australis* or *Phalaris arundinacea* (Parzych et al. 2015). Similar shares of N and Ca and slightly lower shares of P, K and Mg in shoots of plants growing on peat swamps were reported by Ostrowska (1999).

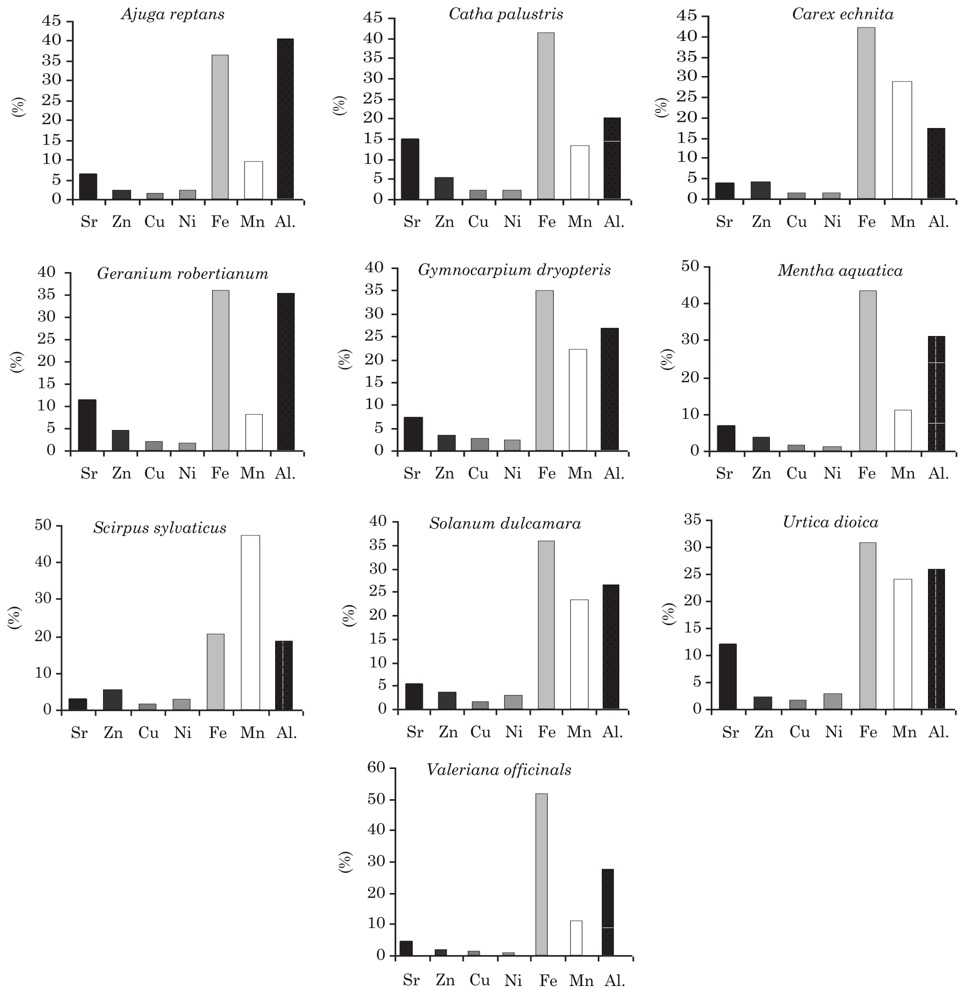

Fig. 2. Average percentages of Sr, Zn, Cu, Ni, Fe, Mn and Al in Σ of microelements in plant shoots

High bio-diversity of plant species in headwater swamp meadows and their varied abilities to accumulate elements create a situation where a wide spectrum of the compounds disposed from waters, mostly biogenic ones or heavy metals, can be absorbed (Gottschwall et al. 2007, Wu et al. 2011).

To compare the examined species of plants with respect to their accumulation capacity relative to macro- and microelements, the Ward method was applied, which distinguished 3 main groups of species (Figure 3). Group A comprised *Sci_syl*, *Gym_dry*, *Val_off*, *Sol_dul* and *Car_ech*, characterized by high total participation of N, P and K > 81.9% and a relatively low total contribution of Al, Fe and Mn <75.1% (Figures 1, 2). Group B encompassed *Aju_rep*, *Men_aqu*, *Cal_pal* and *Ger_rob*, representing medium total partici-

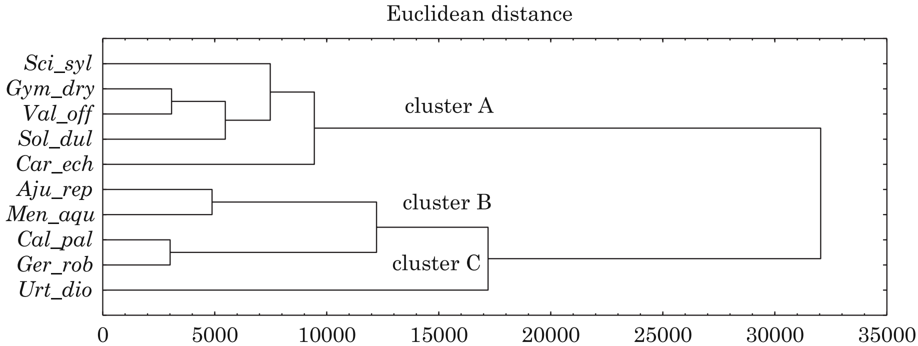

Fig. 3. Dendrogram of hierarchical cluster analysis of the accumulation of macro- and microelements in shoots of plants in the riparian forest

pation of N, P and K, within the range of 73.5 to 77.9% and high total contribution of Al, Fe and Mn >84.2% (Figures 1, 2). Group C consisted of just *Urt_dio*, which distinguished itself from the other examined species of plants by the highest accumulation of components: 2934.8 $mmol_c$ kg^{-1} (Table 4). However, the total share of N, P and K remained at 67.9%, and that of Al, Fe and Mn was at 81.0% in relation to the other species (Figures 1, 2).

The applied Ward method indicates similar accumulation properties of the species of plants belonging to the same families (Cluster A: *Sci_syl*, *Car_ech – Cyperaceae*, Cluster B: *Aju_rep*, *Men_aqu – Lamiaceae*).

CONCLUSIONS

High dampness and slight acidification of Histosols in the studied headwater riparian forest were conducive to the accumulation of macro- and microelements in shoots of plants. The examined plant species accumulated substantial quantities of components, which suggested that they were an effective protective barrier for waters flowing across the peat swamp. The plants accumulated from 1754.3 to 2934.8 $mmol_c$ kg^{-1} of all components, in which 99.39% to 99.71% were macroelements. The highest sum of nutrients was found in the shoots of *Urtica dioica*, and the lowest one appeared in *Carex echinata*. The share of nitrogen in the examined species was 42.6% -52.9% of the total accumulation, phosphorus – 2.9% - 14.2%, potassium – 19.1%-34.9%, magnesium – 7.0%-24.8% and calcium – 4.8%-8.5%. The total microelements accounted for 0.29% of the total of accumulated elements in the shoots of *Caltha palustris* to 0.67% in the shoots of *Valeriana officinalis*. Fe showed a high share in the sum of the microelements (20.9%--51.6%), Al (17.3%-40.6%) and Mn (8.4%-28.9%), which indicates excessive uptake of these components by plants.

The investigated plants can accumulated especially high amounts of nitrogen, phosphorus, potassium, iron, manganese and aluminum, which make them an excellent choice for phytoremediation.

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