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Accumulation and bioconcentration factors of mineral macronutrients in representative species of macrofungi prevailing in beech-dominated forests affected by air pollution

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The contents of mineral macronutrients (phosphorus, potassium, calcium, magnesium) in forest soil samples, but also in samples of fruit bodies of dominant fungal taxa were analysed. The monitoring took place in three research plots in beech-dominated forests located near the aluminium plant at Žiar nad Hronom (Central Slovakia, Europe). The observed macrofungal taxa have different abilities of accumulating macronutrients. In forest soils, the terrestrial saprotrophic species *Clitocybe nebularis* accumulated phosphorus, attaining a maximum bioconcentration factor of 160 in the mineral A-horizon and 10.6 in the organic matter soil horizons (O-horizons). The ectomycorrhizal species *Xerocomellus chrysenteron* was rich in potassium in the A-horizon (181), but also in the O-horizons (18.8). The lignicolous saprotrophic species *Polyporus varius* accumulated calcium to a small extent in the A-horizon (9.36) and O-horizons (0.64), and magnesium in the A-horizon (14.2) and O-horizons (1.09).

Key words: macrofungi, macronutrients, phosphorus, potassium, calcium, magnesium, beech forest ecosystems.

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Vybrané druhy húb sa vyznačujú diferencovanou schopnosťou akumulovať makroelementy. Vo vzorkách dominujúcich druhov húb a vo vzorkách lesnej pôdy odobratých z troch výskumných plôch z okolia hliníkárne v Žiari nad Hronom bol stanovený obsah makroživín (fosfor, draslík, vápnik, horčík) a ich biokoncentračné faktory. V prevažujúcich kambizemiach bučín terestrický saprotrofný druh *Clitocybe nebularis* hromadil fosfor v minerálnych A-horizontoch, kde biokoncentračný faktor dosiahol hodnotu 160, a tiež v horizontoch nadložného humusu – O-horizontoch (10.6). Ektomykorízny druh *Xerocomellus chrysenteron* bol bohatý na draslík v A-horizontoch (181) a aj v O-horizontoch (18.8). Lignikolný saprotrofný druh *Polyporus varius* akumuloval vápnik len v malom rozsahu v A-horizonte (9.36) a minimálne v O-horizontoch (0.64) a podobne aj horčík v A-horizonte (14.2) a v O-horizontoch (1.09).

INTRODUCTION

One of the most serious current ecological problems is removal of some macronutrients from soils at localities stressed by airborne pollutants. Excessive losses of macronutrients occur in soils of forest ecosystems long influenced by acid airborne pollutants produced by the aluminium plant at Žiar nad Hronom, Slovakia. These included flying ash, hydrogen fluoride (HF), aluminium oxide (Al_2O_3), sulphur dioxide (SO_2), carbon dioxide (CO_2), carbon monoxide (CO) and polycyclic aromatic hydrocarbons (PAH) and were produced in high amounts especially in the period 1953–1996, contributing substantially to pollution stress on the forest ecosystems. In the past, the impact of airborne pollutants on forest communities and environmental pollution in the surroundings was assessed by Kuklová & Kukla (2008), Kozlov et al. (2009), and García-Gil et al. (2013).

Fungi play an important role in aggregation and stabilisation of the soil structure. Fungal organisms can mechanically and chemically decompose soil minerals and disintegrate various materials. For example they are able to disintegrate bedrock into gravel and minerals, decompose dead plant remnants and wood, and contribute to the formation of soil. However, in terrestrial ecosystems stressed by airborne pollutants, the cardinal importance of macrofungi is due to their power to concentrate nutrients in their biomass and to return these nutrients into the soil and the covering humus in the course of bio-geochemical cycles (Leake et al. 2002, De Vries & Posch 2011). The networks of fungal mycelia also play a key role in accumulation, mobilisation and transport of macronutrients (Watkinson et al. 2005).

The primary research question of this study was based on the hypothesis that contents of macronutrients are accumulated in the examined macromycetes, which are then higher than in soil horizons.

To confirm or reject this primary research question it was necessary to compare the vertical differentiation of macronutrients in O-horizons (organic matter subhorizons), organo-mineral A-horizons and macrofungi by:

(1) analysis and assessment of macronutrient composition in the organo-mineral A-horizons, O-horizons and in fruit bodies of predominant macrofungal species in the monitoring plots;

(2) assessing the bioconcentration capability of the predominant macrofungi;

(3) testing the differences of P, K, Ca, and Mg contents in predominant macrofungi and between the vertical components of the ecosystems.

Material and methods

M o n i t o r i n g p l o t s. Research on accumulation of selected macronutrients (phosphorus – P, potassium – K, calcium – Ca, magnesium – Mg) in dominant macrofungal species was conducted in 2007 in three monitoring plots: Žiar, Močiar, and Kremnické vrchy Ecological Experimental Site (EES) near Žiar nad Hronom.

All monitoring plots (MP) are located in a temperate deciduous forest, with mean daily temperatures of 17–18 °C in July, a mean annual temperature of 6–7 °C, and mean annual precipitation of 700–800 mm (Lapin et al. 2002). The airborne pollution load produced by the aluminium plant in Žiar nad Hronom in the past was the highest in the Žiar MP in the Štiavnické vrchy Mts. (48°32'38" N, 18°51'44" E), located at only 1.5 km from this source of pollution (Fig. 1). Less affected plots were the Močiar MP in the Štiavnické vrchy Mts. (48°33'98" N, 18°56'93" E), situated 7.0 km from the discussed aluminium plant, and the EES MP in the Kremnické vrchy Mts. (48°38'10" N, 19°04'08" E), 18.0 km from this plant (Maňkovská 2004, Jamnická et al. 2007). Cambisols are often the prevailing soil type in all MPs. The dominating forest types in all MPs belong to *Fagetum pauper* (species-poor beech forest community). The average stand age is 85–120 years (Kuklová et al. 2005).

F u n g a l t a x a s e l e c t e d f o r a n a l y s e s. For the analyses, the most abundant fungal species in the studied forest stands were selected (according to Bučinová & Mihál 2008). On fine woody debris, the highest relative abundance was found for representatives of the lignicolous saprotrophic species *Polyporus varius* (Pers.) Fr. and *Hymenopellis radicata* (Relhan) R.H. Petersen, whereas *Gymnopus aquosus* (Bull.) Antonín & Noordel. and *Clitocybe nebularis* (Batsch) P. Kumm. were the most abundant of the group of terrestrial saprotrophic fungi. *Xerocomellus chrysenteron* (Bull.) Šutara and species of *Russula* subsect. *Foetentinae* (Melzer & Zvára) Singer were the most abundant in the ectomycorrhizal species group. Fruit bodies of all these species were collected in the studied monitoring plots to provide material for macronutrient analysis.

S a m p l i n g, m e a s u r i n g a n d a n a l y s e s. Soil samples from the organo-mineral A-horizons (0.05 m), from O-horizons (organic matter subhorizons – Ool, Oof, Ooh) and samples of fungal fruit bodies were taken in the growing season April–July 2007, in three replications. The soil samples and samples of the O-horizons were passed through a 2-mm mesh sieve, dried at 80 °C and ground in a Planetary Micro Mill Pulverisette 7 (Fritsch, Germany).

Soil pH and O-horizons pH were measured potentiometrically using a WTW INOLAB 720 pH meter (Weilheim, Germany). Humus forms were classified according to Šály & Ciesarik (1991), soil classification followed Bedrna et al. (2000) and IUSS Working Group WRB (2007).

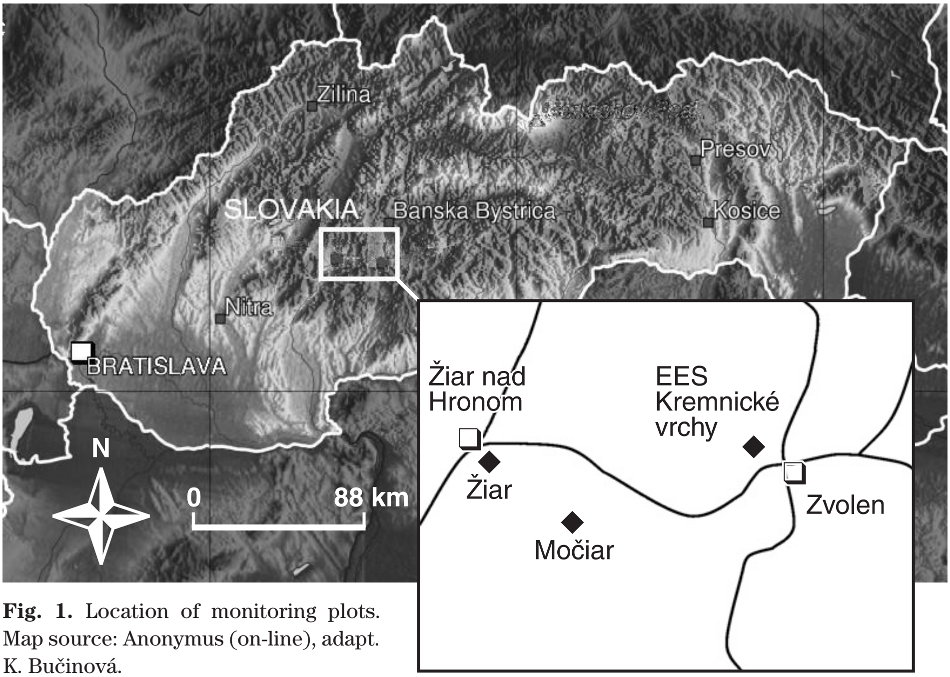

Fig. 1. Location of monitoring plots. Map source: Anonymus (on-line), adapt. K. Bučinová.

The contents of macronutrients (Ca, Mg, K and P) in the soil samples and O-horizon samples were determined in a mineralising agent (mixture of HCl and HNO_3) by means of Inductively coupled plasma atomic emission spectroscopy (ICP-AES method), using the LECO ICP-3000 equipment (LECO Corp., Michigan, USA). Samples of fruit bodies of the predominant macrofungal species (lignicolous saprotrophs – *Polyporus varius*, *Hymenopellis radicata*, terrestrial saprotrophs – *Gymnopus aquosus*, *Clitocybe nebularis*, and ectomycorrhizal species – *Xerocomellus chrysenteron*, *Russula* subsect. *Foetentinae*) were dried at 80 °C in an ABC GM 601.107 hot air drier (ABC Electro, France), homogenised in an agate ball mill (Fritsch, Germany) and mineralised in a Uniclever micro-wave oven (Plasmatronica, Poland). The contents of macronutrients (Ca, Mg, K and P) were determined with the ICP-AES method, also using the LECO ICP-3000 equipment. The bioconcentration factors (BCF) for the studied macrofungi were calculated as the ratio of mean concentration values of macronutrients in samples of macrofungi and substrates (separately for the forest floor O-horizons and the organo-mineral A-horizon). All data were analysed for statistical significance with the Spearman R-test using the Mann-Whitney U-test and the non-parametric Kruskal-Wallis test performed in Statistica v. 9 (StatSoft, USA).

Results

Macronutrient contents in the studied macrofungi

The average content of phosphorus in dry mass (dm) of the studied macrofungi varied from 4,336 mg·kg^{-1} (dm) in the samples from Žiar to 4,646 mg·kg^{-1} (dm) in the samples taken from Močiar, for Kremnické vrchy it was 4,402 mg·kg^{-1} (dm). The minimum average values of P were found in samples of the lignicolous saprotrophic *Polyporus varius* (1,087 mg·kg^{-1}), the maximum ones (10,320 mg·kg^{-1}) in samples of the terrestrial saprotrophic species *Clitocybe nebularis* (Fig. 2).

The lowest average value of potassium content (25,594 mg·kg^{-1}) was found in macrofungal fruit bodies sampled in Močiar MP; the highest value (30,696 mg·kg^{-1}) was found in fruit bodies sampled in the Kremnické vrchy EES. The lowest K values (4,806 mg·kg^{-1}) were found in fruit bodies of the species *Polyporus varius*; the highest (40,557 mg·kg^{-1}) in fruit bodies of the species *Xerocomellus chrysenteron* (Fig. 3).

The highest average calcium contents in dry fungal fruit bodies were recorded at Žiar (2,817 mg·kg^{-1}). Slightly lower average values were found in fungal samples from the Kremnické vrchy EES (2,652 mg·kg^{-1}) and Močiar MP (2,453 mg·kg^{-1}). The lowest Ca content (296 mg·kg^{-1}) was obtained from samples of *Clitocybe nebularis*, the highest (8,716 mg·kg^{-1}) from samples of *Polyporus varius* (Fig. 4).

The average magnesium contents in dry matter of macrofungal fruit bodies were found to be lower in samples from Žiar (1,085 mg·kg^{-1}) than in samples from the Kremnické vrchy EES (1,263 mg·kg^{-1}) and Močiar (1,268 mg·kg^{-1}). The lowest values were obtained in the case of *Russula* subsect. *Foetentinae* (848 mg·kg^{-1}). The highest Mg content in macrofungal fruit bodies was detected in the species *Polyporus varius* (1,781 mg·kg^{-1}) (Fig. 5).

Bioaccumulative capability of selected species of macrofungi

The amount of macronutrients in O-horizons exceeded the concentration of these elements in the organo-mineral A-horizon in all monitored plots. This was also reflected in the values of the bioconcentration factors (BCF, see Tab. 1).

Of the selected macrofungi species, the terrestrial saprotrophic species *Clitocybe nebularis* can accumulate phosphorus most effectively. The highest phosphorus bioconcentration factors (BCF P) were found in the samples of this species for the A-horizon in Žiar MP (240) and for the O-horizons in EES Kremnické vrchy MP (12). The bioconcentration factors for this species in the fruit body – O-horizon system were in the range of 9 to 12 (average 10.6) and were significantly lower than those determined in the fruit body – soil system (111–240, average 160).

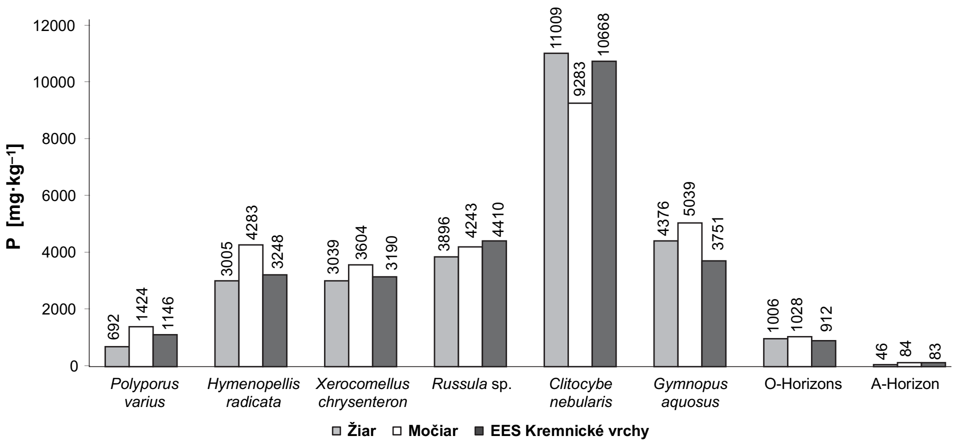

Fig. 2. Average contents of phosphorus (mg·kg^{-1}) in macrofungal fruit bodies and in soil horizons. (*Russula* sp. indicates closely related species of subsect. *Foetentinae.*)

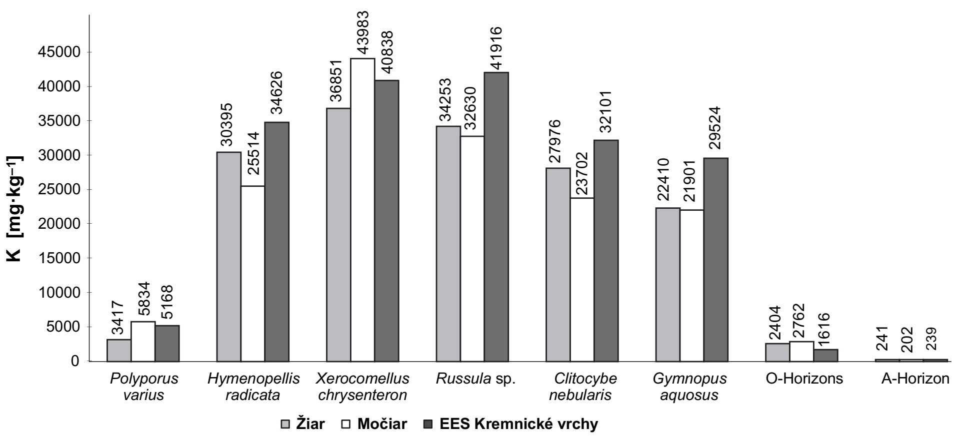

Fig. 3. Average contents of potassium (mg·kg^{-1}) in macrofungal fruit bodies and in soil horizons. (*Russula* sp. indicates closely related species of subsect. *Foetentinae.*)

The highest value (218) of the potassium bioconcentration factor (BCF K) was recorded in Močiar MP for the ectomycorrhizal species *Xerocomellus chrysenteron*. BCF K ranges from 15 to 25 (average 18.8) in the fruit body – O-horizon system and from 153 to 218 (average 181) in the fruit body – soil system.

The calcium bioconcentration factors (BCF Ca) are substantially lower in all the monitoring plots. The lignicolous species *Polyporus varius* accumulated calcium in Žiar MP in the fruit body – O-horizon system at a factor of 0.4 to 0.9 (average 0.64), as well as in the fruit body – soil system where BCF Ca reached values of 4 to 13 (average 9.36).

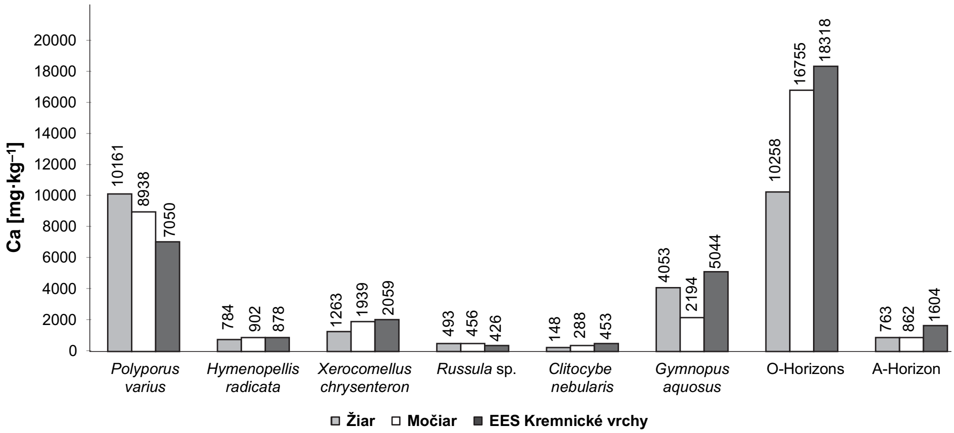

Fig. 4. Average contents of calcium (mg·kg^{-1}) in macrofungal fruit bodies and in soil horizons. (*Russula* sp. indicates closely related species of subsect. *Foetentinae.*)

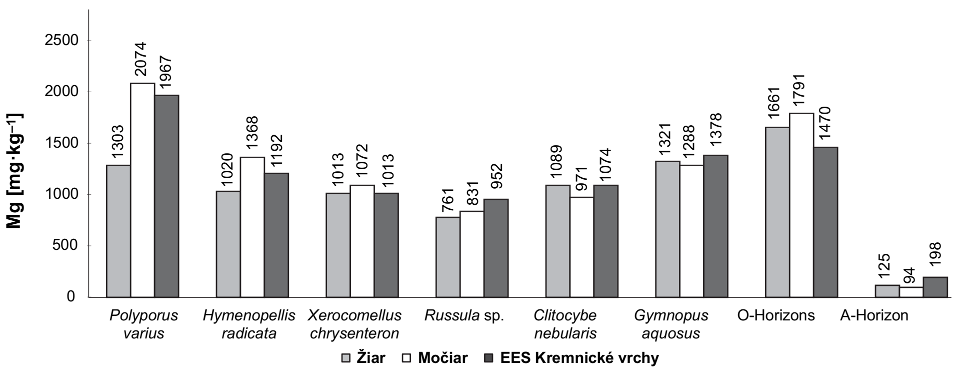

Fig. 5. Average contents of magnesium (mg·kg^{-1}) in macrofungal fruit bodies and in soil horizons. (*Russula* sp. indicates closely related species of subsect. *Foetentinae.*)

The magnesium bioconcentration factors (BCF Mg) in Žiar and Močiar MP were higher in comparison with the EES Kremnické vrchy MP and similarly to calcium, magnesium was also accumulated well by the lignicolous saprotrophic species *Polyporus varius*. The bioconcentration factors of magnesium for *P. varius* in the fruit body – A-horizon system range from 10 to 22 (average 14.2), where those in the fruit body – O-horizon system are lower (0.8 to 1.3; average 1.09).

Tab. 1. Average values of bioconcentration factors (BCF) of the observed elements in predominant macrofungal species. BCF values are rounded to integers or (in cases of small values) to two or three significant figures (unified in each column). Numbers in parentheses indicate the standard deviation.

Bioconcentration factors (BCF)	Phosphorus		Potassium		Calcium		Magnesium	
Taxon	O-Horizons	A-Horizon	O-Horizons	A-Horizon	O-Horizons	A-Horizon	O-Horizons	A-Horizon
Gymnopus aquosus	4.5 (0.4)	67 (26)	11.8 (5.6)	108 (15)	0.27 (0.13)	3.67 (1.46)	0.82 (0.11)	10.4 (3.4)
Clitocybe nebularis	10.6 (1.4)	160 (70)	13.4 (5.8)	123 (10)	0.02 (0.01)	0.27 (0.07)	0.64 (0.10)	8.2 (2.5)
Xerocomellus chrysenteron	3.3 (0.3)	49 (15)	18.8 (5.6)	181 (33)	0.12 (0.01)	1.73 (0.49)	0.63 (0.05)	8.2 (3.2)
Russula subsect. *Foetentinae*	4.1 (0.3)	63 (19)	17.3 (7.6)	160 (17)	0.03 (0.01)	0.48 (0.20)	0.52 (0.11)	6.6 (2.1)
Hymenopellis radicata	3.6 (0.6)	42 (8)	14.4 (6.3)	133 (11)	0.06 (0.02)	0.87 (0.28)	0.73 (0.10)	9.6 (4.4)
Polyporus varius	1.1 (0.4)	15 (2)	2.2 (0.9)	22 (7)	0.64 (0.32)	9.36 (4.54)	1.09 (0.28)	14.2 (6.9)

Relationships between relevant ecological characteristics and selected variables

Statistically significant differences were proven for the content of macronutrients. The differences between the macronutrient contents in the O-horizons in the monitoring plots were statistically proven for all elements, in A-horizons only the differences in K content between the monitoring plots were not confirmed (Tab. 2).

Tab. 2. Relationships between ecological conditions and selected variables. Asterisks indicate statistical significance $p<0.05$ (*); $p<0.01$ (**); $p<0.001$ (***); ns = not significant.
Abbreviations: Z = Žiar MP, M = Močiar MP, E = EES Kremnické vrchy MP; LS = lignicolous saprotrophs, TS = terrestrial saprotrophs, EM = ectomycorrhizal species.

	P	Ca	Mg	K	pH
Macronutrient contents in A-horizon – differences between sites	***Z–M ***Z–E *M–E	**Z–M **Z–E **M–E	**Z–M **Z–E **M–E	ns	**Z–M **Z–E **M–E
Macronutrient contents in O-horizons – differences between sites	**Z–E **M–E	**Z–M **Z–E *M–E	*Z–M **Z–E **M–E	**Z–M **Z–E **M–E	ns
Macronutrient contents in sporocarps – differences between sites	ns	ns	ns	ns	ns
Macronutrient contents in A-horizon – differences between trophic groups	ns	ns	ns	**LS–TS *LS–EM	ns
Macronutrient contents in O-horizons – differences between trophic groups	*LS–TS	ns	ns	ns	*LS–EM
Macronutrient contents in sporocarps – differences between trophic groups	**LS–TS **TS–EM	ns	**LS–EM **TS–EM	**EM–TS **LS–EM	ns

DISCUSSION

Accessibility of particular elements

P h o s p h o r u s . In the more acidic soils of the studied localities, phosphorus is less accessible for plants, but in the overall phosphorus cycle of the forest ecosystem it is present also in the accessible form of dihydrophosphate ($H_2PO_4^-$), or possibly ortophosphate anions (HPO_4^{2-}). Thanks to the activity of microorganisms and mycorrhizal fungi it can be absorbed directly from soil minerals, e.g. apatite, by plants (Plassard et al. 2011, Richardson & Simpson 2011). Kobza (2010) states that natural resources of phosphorus are low (0.02–0.04%) in the Slovak soils. Accessibility of phosphorus from the soil is influenced not only by a sufficient level of organic matter and soil moisture but also by pH, for which the optimum levels are considered to be 5.5–7 (Brady & Weil 2002). For temperate deciduous forests, Cole & Rapp (1981) mention the accumulation of phosphorus in the forest floor and above-ground organic matter to be on average 25 $kg \cdot ha^{-1}$ and 35 $kg \cdot ha^{-1}$ respectively, whereas in the Slovak beech woods the total supply of phosphorus in woody species and in cover humus reaches values of 122 $kg \cdot ha^{-1}$ (Bublinec 1994).

Of the studied macrofungal species the highest level of phosphorus was present in samples of the saprotrophic terrestrial species *Clitocybe nebularis* and *Gymnopus aquosus* [10,320 $mg \cdot kg^{-1}$ (dm), respectively 4,707 $mg \cdot kg^{-1}$]. In accordance with the data presented by Vetter et al. (2005), Kalač (2009), and Falandysz & Borovička (2013) these values fall into the interval of standard values for saprotrophic terrestrial species and are on average higher than the values for ectomycorrhizal and lignicolous species. For the ectomycorrhizal species *Xerocomellus chrysenteron* Koukol et al. (2008) indicate an average content of 8,300 $mg \cdot kg^{-1}$, whereas in our studied samples the average phosphorus contents were lower [*Russula* sp. 4,183 $mg \cdot kg^{-1}$ (dm), *Xerocomellus chrysenteron* 3,278 $mg \cdot kg^{-1}$]. Ayaz et al. (2011) mention values of 3,980 $\mu g \cdot g^{-1}$ for the related species *Russula rosea* and Falandysz & Borovička (2013) mention the same values for ectomycorrhizal species *Leccinum duriusculum*, *L. scabrum*, *Suillus grevillei*, *Xerocomus badius* and *Cantharellus cibarius*. In our study, fruit bodies of the lignicolous saprotrophic species *Polyporus varius* and *Hymenopellis radicata* contained the lowest amount of phosphorus.

P o t a s s i u m . Plants as well as macrofungi are capable of receiving potassium in amounts that substantially exceed its concentration in the surrounding environment (Kalač 2009). A large proportion of potassium in the soil (90–95%) is inexchangeable (an inaccessible for plants). The accessible potassium is only present in the soil solution or in a form bound to the cover of coloidal elements of the adsorption complex. Cole & Rapp (1981) mention an average accumulation of potassium in the forest floor and above-ground organic matter of temperate deciduous forests of 53 kg·ha^{-1} and 224 kg·ha^{-1} respectively, whereas Bublinec (1994) found that the total supply potassium in woody species and in the cover humus in beech woods reaches values of 544 kg·ha^{-1}.

The ability of macrufungi to accumulate potassium is species specific. This macronutrient is, besides phosphorus, the most represented in fruit bodies of terrestrial species (ectomycorrhizal and saprotrophic), for which Kalač (2009) indicates an interval of 20,000–40,000 mg·kg^{-1}. In the fruit bodies of the studied species *Xerocomellus chrysenteron* a content corresponding to the upper limit of this interval (40,557 ± 3,574 mg·kg^{-1}) was found, just as the average determined for the same species by Rudawska & Leski (2005). However, for the related species *Boletus edulis* slightly lower values for potassium are indicated in the review by Falandysz & Borovička (2013) and Ayaz et al. (2011). The lowest average potassium contents (4,806 mg·kg^{-1}) were found in fruit bodies of the lignicolous species *Polyporus varius*.

Calcium. An important place in the balance of nutrients in the forest ecosystem is taken in by calcium, the concentration of which is variable and depends on soil moisture and seasonal climatic conditions as well as on saturation of the adsorption complex by bases (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}). According to Cole & Rapp (1981), the accumulation of calcium in temperate deciduous forests averages 205 kg·ha^{-1} for the forest floor. Bublinec (1994) indicates that the total supply of calcium in beech woods (dendromass + forest floor) is 1,335 kg·ha^{-1}.

In macrofungi, calcium is a component of the cell wall system and in case of a calcium surplus the calcite crystals or calcium-oxalate compounds form aggregates on the surface of hyphae (Tuason & Arocena 2009, Guggiari et al. 2011). Although base cations easily wither away especially by erosion, but also by washing out in case of an inhibitory aluminium (Al^{3+}) load in the soil, their losses are replenished by weathering of soil minerals also thanks to the secretion of ectomycorrhizal macrofungi which contribute to acidification of the substrate and therewith provide access to nutrient-containing soil minerals (Van Schöll et al. 2008, Urban 2011). In the fruit bodies of ectomycorrhizal and saprotrophic macrofungal species, calcium reaches relatively low concentrations, e.g. Kalač (2009) indicates in his review prevalent values of calcium in fruit bodies of fungi of 100 to 500 mg·kg^{-1}. Falandysz et al. (2008) indicate for the ectomycorrhizal species *Boletus edulis* an interval of 38–190 mg·kg^{-1} (dm), which is lower than the values determined for the related species *Xerocomellus chrysenteron* (1,754 mg·kg^{-1}) and also for the saprotrophic terrestrial species *Clitocybe nebularis* (296 mg·kg^{-1}). Győrfi et al. (2010) determined an average Ca content in fruit bodies of *Agaricus* spp. (saprotrophic terrestrial species) of 1,400 mg·kg^{-1}, whereas Vetter et al. (2005) indicate for another lignicolous saprotrophic species, *Lentinula edodes* (caps), a value of 1,100 mg·kg^{-1}, which is in accordance with the findings by

Clinton et al. (1999), i.e. that most fungi show a low level of Ca accumulation with the exception of some species of the *Polyporaceae* family. This was confirmed for the studied saprotrophic lignicolous species *Polyporus varius*, in which much higher average levels of calcium (8,716 mg·kg^{-1}) were found.

Magnesium. As stated by Brady & Weil (2002), magnesium in the soil is a component of various primary (olivene, serpentine, biotite) and secondary minerals (smectites, chlorites, vermikulites). In carbonate soils it occurs as magnesite ($MgCO_3$) and dolomite [$CaMg(CO_3)_2$]. Kobza (2010) states that the Mg content of Slovak soils is satisfactory and varies from 31.98 mg·kg^{-1} to 282.37 mg·kg^{-1}. Cole & Rapp (1981) indicate an average magnesium accumulation of 28–57 kg·ha^{-1} for organic matter in the forest floor of temperate deciduous forests. Bublinec (1994) found that the total supply of magnesium in woody species and in the cover humus in beech woods reaches values of 264 kg·ha^{-1}. Kalač (2009) indicates that the standard Mg concentration in macromycetes varies from 800 to 1,800 mg·kg^{-1} (dm). These data are in accordance with our findings. The average magnesium content in fungal fruit bodies from less pollution-stressed monitoring plots was slightly higher than in fruit bodies from the monitoring plot close to the aluminium plant (Kremnické vrchy EES: 1,263 mg·kg^{-1}; Močiar: 1,268 mg·kg^{-1}; Žiar: 1,084 mg·kg^{-1}). We found the highest Mg content in fruiting bodies of the lignicolous saprotrophic species *Polyporus varius* (1,781 mg·kg^{-1}). Vetter et al. (2005) indicate that magnesium contents are the highest in lignicolous saprotrophs such as *Pleurotus* spp. (1,300–2,000 mg·kg^{-1}).

Bioaccumulative capability of the predominant macrofungal species

Urban (2011) states that the bioconcentration factors of fungi growing on substrates with an excessive concentration of a certain metal are usually drastically reduced due to the physiological control of metal intake. Kalač (2009) states that fungi are capable to accumulate phosphorus in concentrations which are 10–50 times higher than in the substrate, the best accumulators being saprotrophic terrestrial species. This was also confirmed for *Clitocybe nebularis* and it is this species that Vetter (1993) indicates as having a high capability of accumulating phosphorus.

The ectomycorrhizal *Russula* sp. and *Xerocomellus chrysenteron* accumulated significantly high amounts of potassium. For *X. chrysenteron* the highest potassium bioconcentration factors (BCF K) were calculated in the fruit body – A-horizon system (181) and fruit body – O-horizon system (18.8), which corresponds to the capability of fruit bodies accumulating the amount of potassium contained in the soil with a factor of 20–40 (Kalač 2009). Seeger & Hüttner (1981) indicate that fungi are not good in accumulating calcium and magnesium from the substrate. According to Karaman & Matavulj (2005) species bound to wood (lignicolous) are an exception. For example, in *Polyporus varius*, a species of the *Polyporaceae* family we found the highest BCF Ca in the fruit body – O-horizon system (0.64) and fruit body – A-horizon system (9.36). Similarly, we also found the highest BCF Mg in *P. varius* (14.2 in the fruit body – A-horizon system; 1.09 in the fruit body – O-horizon system).

This high Ca content was probably the consequence of the fact that lignicolous species were dominant in the total number of analysed species and also of the fact that they use wood as a substrate on which draw Ca, whose concentration increases with age (Vetter 1993). Mycorrhizal macromycetes can take macroelements for their functioning from trees, which acquired them from deeper soil horizons (Lilleskov et al. 2002).

CONCLUSIONS

The main ecological hypothesis that higher contents of macronutrients (except calcium) are accumulated in the examined macromycetes compared to soil horizons was confirmed. The highest amount of potassium in samples of macrofungal fruit bodies was found at Kremnické vrchy EES, reaching a value of 30,696 $mg \cdot kg^{-1}$ (dm). The highest amount was accumulated by the ectomycorrhizal species *Xerocomellus chrysenteron*. For this species the highest BCF K were recorded in the fruit body – A-horizon system (181) and in the fruit body – O-horizon system (18.8).

The highest average amounts of magnesium in the dry matter of macrofungal fruit bodies were found in the samples from Močiar MP (1,268 $mg \cdot kg^{-1}$). The maximum average content of the studied element in macrofungal fruit bodies was detected in the species *Polyporus varius* (1,781 $mg \cdot kg^{-1}$). This species also reached the highest values of BCF Mg (14.2 in the fruit body – A-horizon system; 1.09 in the fruit body – O-horizon system).

The highest amounts of calcium in the dry matter of macrofungal fruit bodies were recorded in the Žiar MP (2,817 $mg \cdot kg^{-1}$). The lignicolous saprotrophic species *Polyporus varius* reached the highest values of BCF Ca of the studied macrofungal species (9.36 in the fruit body – A-horizon system; 0.64 in the fruit body – O-horizon system).

The highest amounts of phosphorus in macrofungi were recorded in the Močiar MP, reaching values 4,646 $mg \cdot kg^{-1}$ (DM). The terrestrial species *Clitocybe nebularis* had the highest capability of accumulating phosphorus. For this species the highest value of BCF P (160) was found in the fruit body – A-horizon system and also in the fruit body – O-horizon system (10.6).

Higher amounts of nutrients were recorded in the vicinity of the source of emissions (Žiar) only in the case of the lignicolous saprotrophic species *Polyporus varius* for calcium and in the terrestrial saprotrophic species *Clitocybe* *nebularis* for phosphorus. The highest amounts of potassium and magnesium were recorded for species collected in the monitoring plots which were not directly exposed to emissions (for potassium in the fruit bodies of *Xerocomellus chrysenteron* taken from the Kremnické vrchy EES and for magnesium in the fruit bodies of *Polyporus varius* taken from Močiar).

Nevertheless, no significant influence of the emissions on the increase of macronutrient contents in macrofungi was confirmed. A balanced proportion of macronutrients in the organo-mineral soil of the studied localities and its saturation by bases, as well as the synergistic effect of terrestrial and ectomycorrhizal macrofungi and their bioconcentration capability contributed to the preservation of the vegetation at Žiar, a locality that was the most affected by emissions from the nearby aluminium plant.

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