Original Paper

Bioaccumulation of macronutrients in herbaceous plants of the Sławno glaciolacustrine plain, northern Poland

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The studies aimed to compare bioaccumulation and translocation of macronutrients from roots to above-ground organs for six species of herbaceous plants (*Taraxacum officinale*, *Rumex acetosa* L., *Plantago major* L., *Plantago lanceolata*, *Potentilla anserina* L. and *Hypericum perforatum* L.) growing in the area of the Sławno Plain, northern Poland. Soil and plant samples were collected in June 2015 from 30 locations (five replications per species) and analysed using standard procedures, including content of nitrogen, phosphorus, potassium, calcium and magnesium. Mean contents of elements in the soil, roots and above-ground organs were calculated based on the results obtained. The content of organic carbon and pH were additionally determined in soil samples. The studied soils have been developed from silty-clayey glaciolacustrine deposits. They were characterised by acid and strongly acid reaction and contained from 9.5 to 28.7 g kg^{-1} of organic carbon. They were relatively abundant in nitrogen (1.44–1.87 g kg^{-1}) and potassium (4.30–5.34 g kg^{-1}), whereas poor in phosphorus (0.41–0.57 g kg^{-1}), calcium (1.63–2.84 g kg^{-1}) and magnesium (3.21–4.08 g kg^{-1}). The content of these elements in roots and above-ground parts of the studied plants was usually higher as compared to the soil. It was typical for herbs, reflecting their physiological demands. Only K occurred in higher amounts. The observed contents of nutrients suggest sufficient supply. The lowest bioaccumulation factors in roots were noticed for *Hypericum perforatum* L. (for N, P, Ca and Mg) or *Rumex acetosa* L. (for K) and the highest for *Plantago major* L. (for N, P, K and Ca) or *Rumex acetosa* L. (for Ca). In above-ground organs weakest bioaccumulation occurred in *Hypericum perforatum* L. (for K, Ca and Mg), *Rumex acetosa* L. (for P) or *Potentilla anserina* L. (for N) and the strongest in *Plantago major* L. (for N and Ca), *Taraxacum officinale* (for K and Mg) or *Plantago lanceolata* (for P). The values of translocation factors from roots to above-ground organs ranged from 1.3 to 3.1 for nitrogen, from 0.8 to 2.0 for phosphorus, from 1.3 to 3.3 for potassium, from 1.1 to 3.7 for calcium and from 1.1 to 3.1 for magnesium. Potassium and calcium were strongly translocated in *Taraxacum officinale*, whereas nitrogen, phosphorus and magnesium in *Hypericum perforatum* L.

Keywords: herbs, macronutrients, bioaccumulation, translocation, nutrient cycling

1 Introduction

Biogeochemical cycling of elements cover various interrelated links associated with marine and terrestrial ecosystems and countless physical and chemical processes leading to qualitative and quantitative transformation of these substances. It can be considered at different spatial and temporal scales and living organisms play an important role at any scale. Most of elements are nutrients and soils and rocks are major sources of these substances in terrestrial ecosystems. Abundance of elements in soils is strongly conditioned by origin and mineral composition of parent material. Its weathering constitutes primary source of bioavailable forms of these substances (Augusto et al., 2000). Litterfall, throughfall and stemflow are major secondary sources in forest ecosystems (Jonczak, 2013; Kozłowski, 2013), whereas mineral and organic fertilizers in agroecosystems (Rutkowska et al., 2014). Bioavailability of elements is controlled by soil ecochemical state, particularly pH (Kowalkowski, 2002; Devau et al., 2009), redox conditions (Tokarz and Urban, 2015), water regime (Mistra and Tyler, 2000), as well as a number of other environmental factors. The same factors determine toxicity of some elements (Cronan and Grigal, 1995). Demand for nutritional elements in natural and some modified ecosystems usually exceeds stocks of their bioavailable forms in rhizosphere, therefore some organisms have developed active (enzymatic) mechanisms of uptake

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(Antibus et al., 1992). Retranslocation is another adaptive mechanism to nutrients deficit in site (Dziadowiec et al., 2007). Abundance of elements and soil ecochemical state are reflected in chemistry of plant organs (Jonczak and Parzych, 2015; Šimanský et al., 2018). Close plant-soil interrelationships in this regard have been noted not only for nutritional elements, but also for heavy metals, as hazardous substances in environment (Tangahu et al., 2011). This relationship becomes the basis of bio-indicative methods in the assessment of environmental pollution with these substances (Čeburnis and Steinnes, 2000). Although the studies on elements uptake from soil, translocation and bioaccumulation in plants are conducted from many years under natural and controlled conditions, there are many gaps in knowledge in this area. Getting knowledge about some of them can be of great practical importance.

Our studies aimed to compare bioaccumulation and translocation of macronutrients from roots to above-ground organs of selected herbaceous plants growing in the area of the Sławno Plain, northern Poland. The studies included nitrogen, phosphorus, potassium, calcium and magnesium in six plant species – *Taraxacum officinale*, *Rumex acetosa* L., *Plantago major* L., *Plantago lanceolata*, *Potentilla anserina* L. and *Hypericum perforatum* L and associated soils.

2 Material and methods

Study area

The studies have been conducted in the area of the Sławno Plain near the villages of Mazów and Stary Kraków, northern Poland. This is a part of glaciolacustrine plain developed at the close of Pleistocene. Silty and clayey deposits constitute parent material of the soils, which according to the WRB classification system (IUSS 2014) should be classified as Stagnosols, Alisols or Luvisols. Mild climatic conditions are strongly influenced by the Baltic Sea. Average annual temperatures are about 7.5 °C, showing variability from 4.9 °C to 9.7 °C during the years 1871–2000. Mean annual sum of precipitation for this period ranged from 483 mm to 1,013 mm (Kirschenstein and Baranowski, 2009). The studied area is used in a variety of ways, including forests, arable fields, meadows and pastures. The history of agriculture dates back to the 14th century.

Soil and plant sampling and analysis

Soil and plant samples were collected in June 2015 from 30 locations within meadows, pastures and arable fields. The locations included five replications for each of six species of herbaceous plants – *Taraxacum officinale* (TO), *Rumex acetosa* L. (RA), *Plantago major* L. (PM), *Plantago lanceolata* (PL), *Potentilla anserina* L. (PA) and *Hypericum perforatum* L. (HP). Soil samples were collected from root zone. After removal of plant remains they were dried at 40 °C and sieved through a 2.0 mm mesh sieve to remove skeleton fraction. A part of sample was milled into powder for the purposes of elemental analysis. Soil analysis included determination of pH with potentiometric method (Elmetron CPC-401), total organic carbon (TOC) by Tyurin method (Dziadowiec and Gonet, 1999), total nitrogen (TN) by Kjeldahl method and the content of P, K, Ca and Mg after digestion of ashed samples in 20% HCl using microwave digestion system (Milestone ETHOS PLUS). The content of P in a solution was determined with molybdenum-blue method, whereas the remaining elements by flame atomic absorption spectrometry (Perkin Elmer 2100) at wavelengths 766.5 nm for K, 422.7 nm for Ca and 285.2 nm for Mg.

Plant samples have been washed with distilled water, dried at 65°C, milled into powder and analysed, including content of total nitrogen by Kjeldahl method and total content of P, K, Ca and Mg after samples digestion in a mixture of 65% HNO_3 and 30% H_2O_2. Concentrations of elements in the solutions were determined using the same methods and equipment like for soils.

Data processing

Average concentrations of elements in soils and plants and standard deviations were calculated for the individual plant species using Excel software. Bioaccumulation factors (BF) were calculated for the studied elements as a quotient of element concentration in plant (above-ground organs or roots) and in the soils (Zang et al., 2009). Translocation factors (TF) were calculated as a quotient of element concentration in plant roots and above-ground parts (Bose et al., 2008).

Results

3.1 Basic characteristics of the soils

The studied soils were characterised by acid and strongly acid reaction, with average pH at 4.9–6.0. The lowest value was noticed under HP, whereas the highest under TO and PA (Figure 1). Differences in pH measured at five stands of the individual herb species ranged from 0.6 to 1.6 of unit. The soils were relatively abundant in organic carbon, which content was from 9.5 to 28.7 g kg^{-1}. The lowest mean content of this element was observed at RA (15.6 g·kg^{-1}) and the highest at PA (20.0 g kg^{-1}) stands (Figure 1).

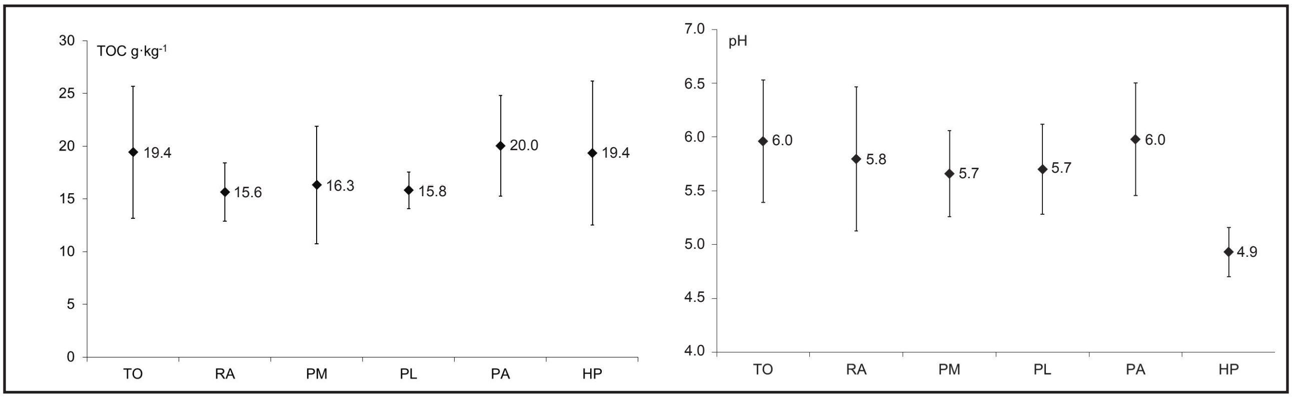

Figure 1 Mean contents of total organic carbon and pH in the soils under plant species (mean ±SD)

3.2 Retention and translocation of nitrogen

Although nitrogen is one of the most widespread elements in the environment, it is usually present in deficient amounts in soils. Therefore, it constitutes an important limiting factor for plant growth and succession (Oren et al., 2001), as well as biomass primary production (Elser et al., 2007). Nitrogen strongly influences also microorganisms and soil fauna (Aira et al., 2006). The content and forms of nitrogen in soils are regarded as useful indices of their quality and tools in the assessment of fertility and productivity (Schloter et al., 2003). Average contents of nitrogen in the studied soils ranged from 1.44 g kg^{-1} under PL to 1.87 g kg^{-1} under TO, showing relatively low variability between herb species (Figure 2). Much greater variability showed nitrogen in plants, both roots and above-ground organs. In roots its content ranged from 4.70 to 13.09 g kg^{-1}, whereas in above-ground biomass from 15.16 to 19.47 (Figure 2). In TO, RA, PA and HP the differences between roots and above-ground organs were statistically significant at $p < 0.05$. The observed contents were among natural for most of plants (Ostrowska and Porębska, 2002). They also indicate sufficient supplying with this element. All studied plants accumulated nitrogen. Higher intensity of this process was observed in above-ground parts than in roots, which is typical for herbaceous plants (Yu

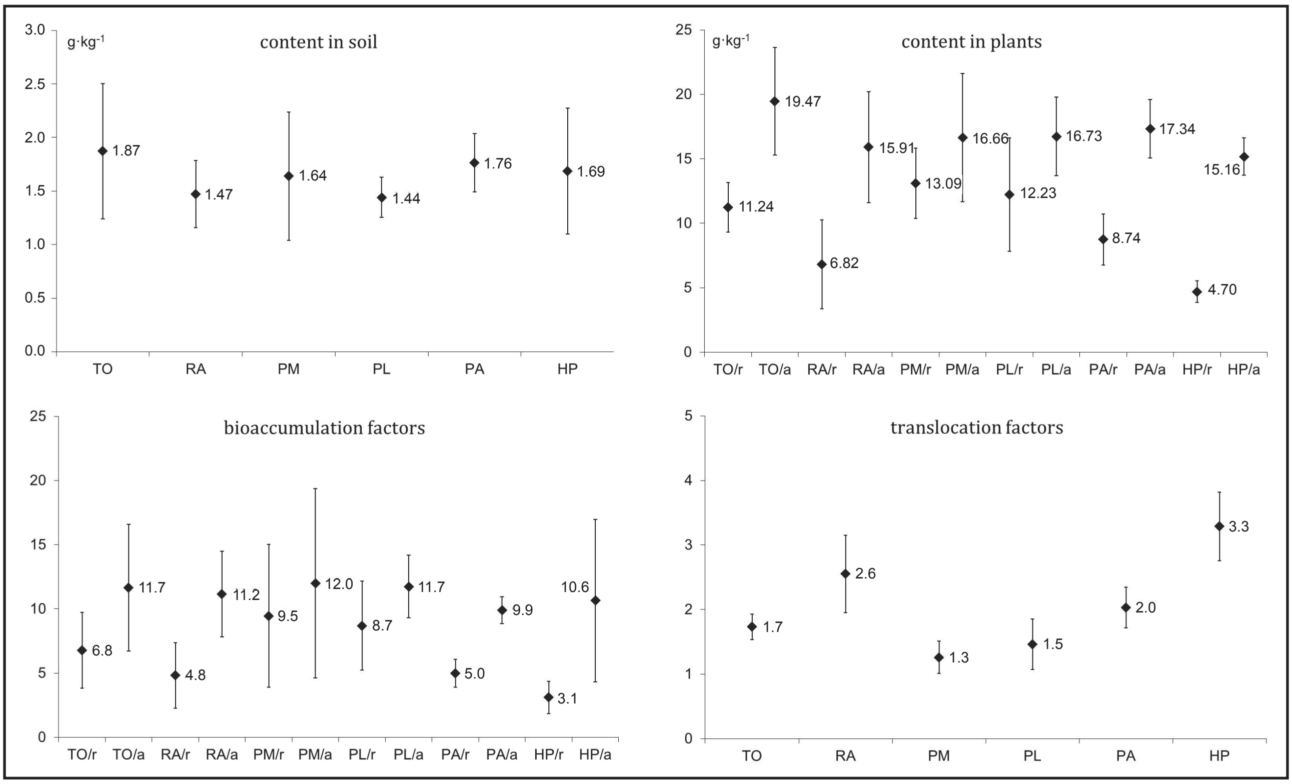

Figure 2 The content of total nitrogen in soils and plants, bioaccumulation factors in roots (/r) and above-ground parts (/a) and translocation factors from roots to above-ground organs (mean ±SD)

et al., 2014). High values of BF confirm high demand of the studied plants for nitrogen, which plays a key role in many physiological processes (Ostrowska and Porębska, 2002). The observed differences between plant species in BF were not significant statistically in most cases. Nitrogen was characterised by varied mobility from roots to above-ground organs in the studied plants, which is confirmed by significant differences (p <0.05) in translocation factors (Figure 2). It was the highest for HP, whereas the lowest for PM and PL. The observed differences can be due to varied acidification of the soils.

3.3 Retention and translocation of phosphorus

Apatites constitute major primary source of soil phosphorus. These are relatively susceptible to weathering minerals, therefore abundance in this element is decreasing during pedogenesis. This process is accompanied by qualitative changes of the element and its complexation with various soil components (Walker and Syers, 1976; Lair et al., 2009). The studied soils contained phosphorus in amounts from 0.41 g kg^{-1} under PL to 0.57 g kg^{-1} under RA (Figure 3). These are low contents, in particular considering the silty-clay character of the soils. Strongly acidic and acidic pH of the soils (Figure 1) can be an important factor limiting bioavailability of phosphorus. At pH <6.5 it is bounded by Fe and Al oxides, especially their amorphous fraction (Richardson, 1985; Achat et al., 2013). However, formation of phosphates can be inhibited by humic substances (Kodama and Schnitzer, 1980; Borggaard et al., 1990). Phosphorus is present in soils usually in deficient amounts, therefore it is strongly accumulated by plants. Its concentration in the studied herb species was several times greater as compared to the soils. In the roots it ranged from 1.50 g kg^{-1} in HP to 3.41 g kg^{-1} in MP, whereas in above-ground biomass from 2.41 g kg^{-1} in RA to 3.72 g kg^{-1} in PL on average (Figure 3). Mean phosphorus contents were higher in above-ground parts than in roots in most cases, however only under HP the differences were statistically significant. The noticed values suggests sufficient accumulation of this element (Ostrowska and Porębska, 2002). It is important, because phosphorus plays many physiological functions, i.a. accelerates development of generative organs (Gaj and Grzebisz, 2003). Bioaccumulation factors of phosphorus in the studied plants ranged from 3.2 to 7.4 in roots and from 4.6 to 9.2 in above-ground organs. Translocation factors ranged from 0.8 to 2.0 and were the highest for HP, whereas lowest for PM.

3.4 Retention and translocation of potassium

Soils are in general abundant in potassium, however its content gradually decreases during pedogenesis as an effect of weathering of primary and secondary minerals and leaching of the products of this process (Graham and

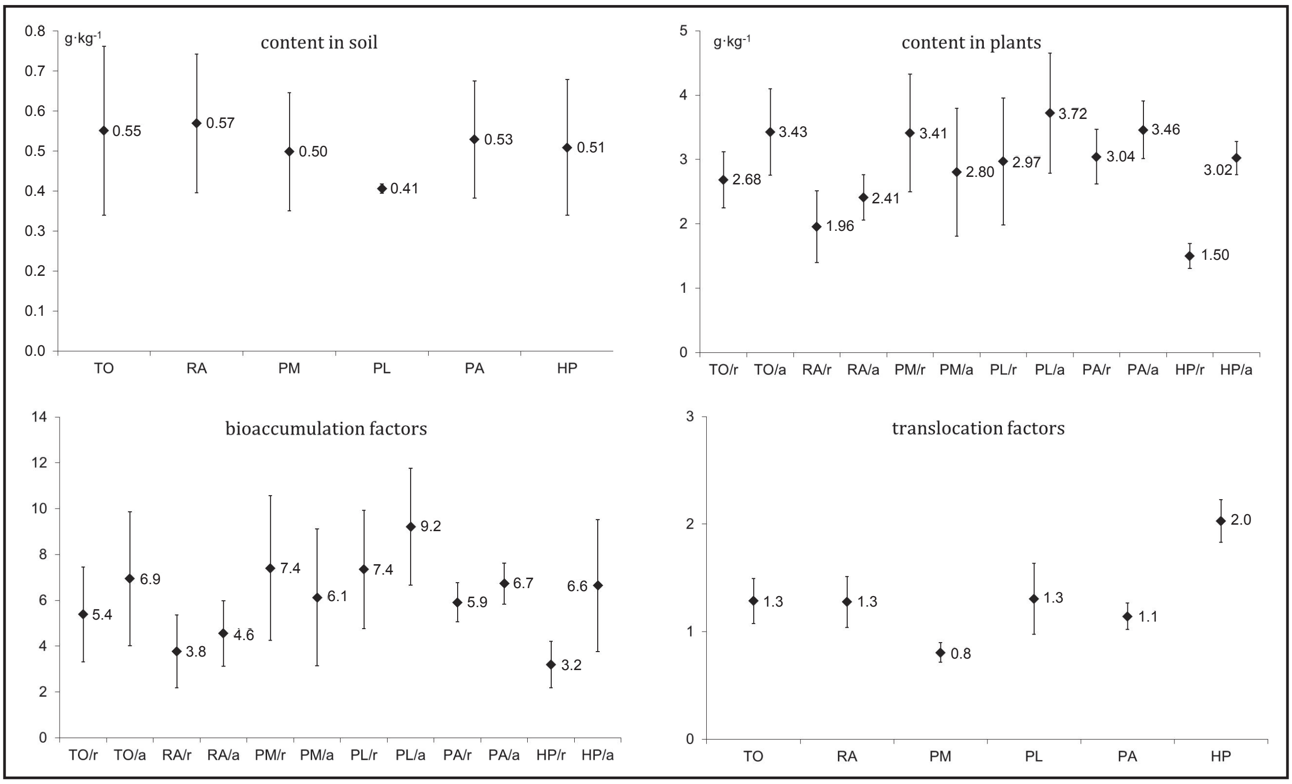

Figure 3 The content of phosphorus in soils and plants, bioaccumulation factors in roots (/r) and above-ground parts (/a) and translocation factors from roots to above-ground organs (mean ±SD)

Fox, 1971). K^+ ions are highly mobile in the environment, which was confirmed by lysimetric studies (Katutis et al., 2007), as well as in the studies on litter decomposition in forest ecosystems using litterbag method (Rutigliano et al., 1998; Jonczak et al., 2015). The studied area is located in young-glacial landscape developed just over 10,000 years ago. Young age of parent materials and their abundance in silt and clay textural fractions are main factors conditioning relatively high content of potassium in the studied soils. Its average contents were comparable at every stands and ranged from 4.30 g kg^{-1} under PL to 5.34 g kg^{-1} under PA (Figure 4). Potassium was strongly accumulated by the studied herb species, which is confirmed by much higher concentrations both in roots (from 5.97 g kg^{-1} in RA to 18.24 g kg^{-1} in MP) and above-ground biomass (from 9.83 g kg^{-1} in HP to 43.31 g kg^{-1} in TO) as compared to the soil, as well as by BF, which ranged from 1.4 to 4.6 in roots and from 2.6 to 10.6 in above-ground parts. The observed contents sometimes exceed values considered natural for plants (Ostrowska and Porębska, 2002). This phenomenon was observed also in our previous studies (Parzych and Jonczak, 2018) and by other authors (Czerwiński and Pracz, 1995; Krzywy, 2007). It is due to large mobility and bioavailability of the element. Strong accumulation of potassium can have some negative effects, including limiting uptake of other nutrients, especially Mg.

3.5 Retention and translocation of calcium

The content and profile distribution patterns of calcium in soils are conditioned by primary abundance of parent materials, water regime, leaching intensity, inflow of Ca^{2+} and carbonates from external sources (including groundwater and fertilizers) and many other natural and anthropogenic factors. The content of Ca is strongly varied among deposits/sediments and soils developed from them, as well as groundwater, where Ca^{2+} constitutes main cation. Vegetation, as a source of acidifying substances promotes decalcification of the soils in general. However, there are large differences between the individual species, in particular between deciduous vs coniferous trees (Quideau et al., 1996; Augusto et al., 2000). In the studied soils the content of calcium was low, which is typical for the soils developed from glaciolacustrine deposits of the Sławno Plain (Jonczak, 2015). It was on average from 1.63 g kg^{-1} under HP to 2.84 g kg^{-1} under PA (Figure 4). The content of Ca in plants was much higher, however strongly varied among the species. It was lower in roots (on average from 2.57 g kg^{-1} in HP to 13.44 g kg^{-1} in RA) than in above-ground parts (on average from 5.65 g kg^{-1} in HP to 33.79 g kg^{-1} in PM). BF ranged from 1.6 to 6.7 in roots and from 3.7 to 16.9 in above-ground organs. The observed contents of Ca in plants were at optimal level (Ostrowska and Porębska, 2002).

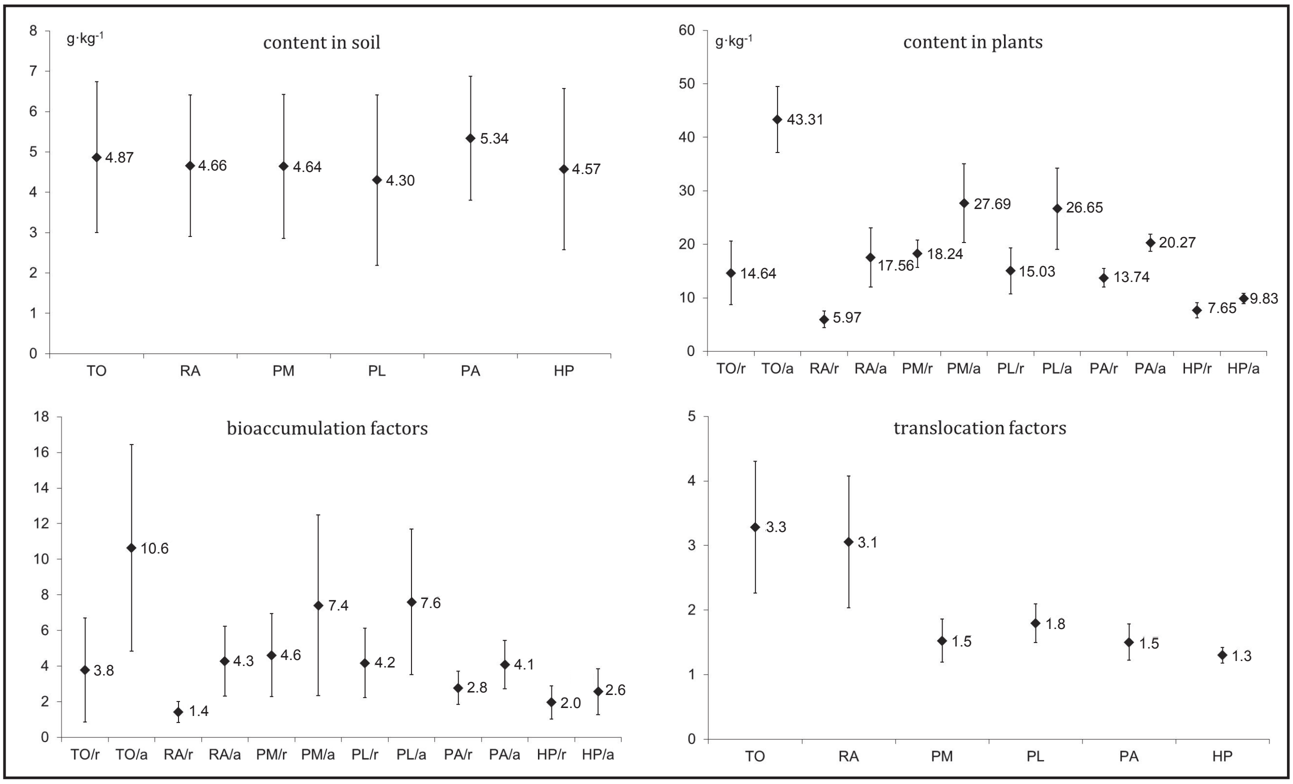

Figure 4 The content of potassium in soils and plants, bioaccumulation factors in roots (/r) and above-ground parts (/a) and translocation factors from roots to above-ground organs (mean ±SD)

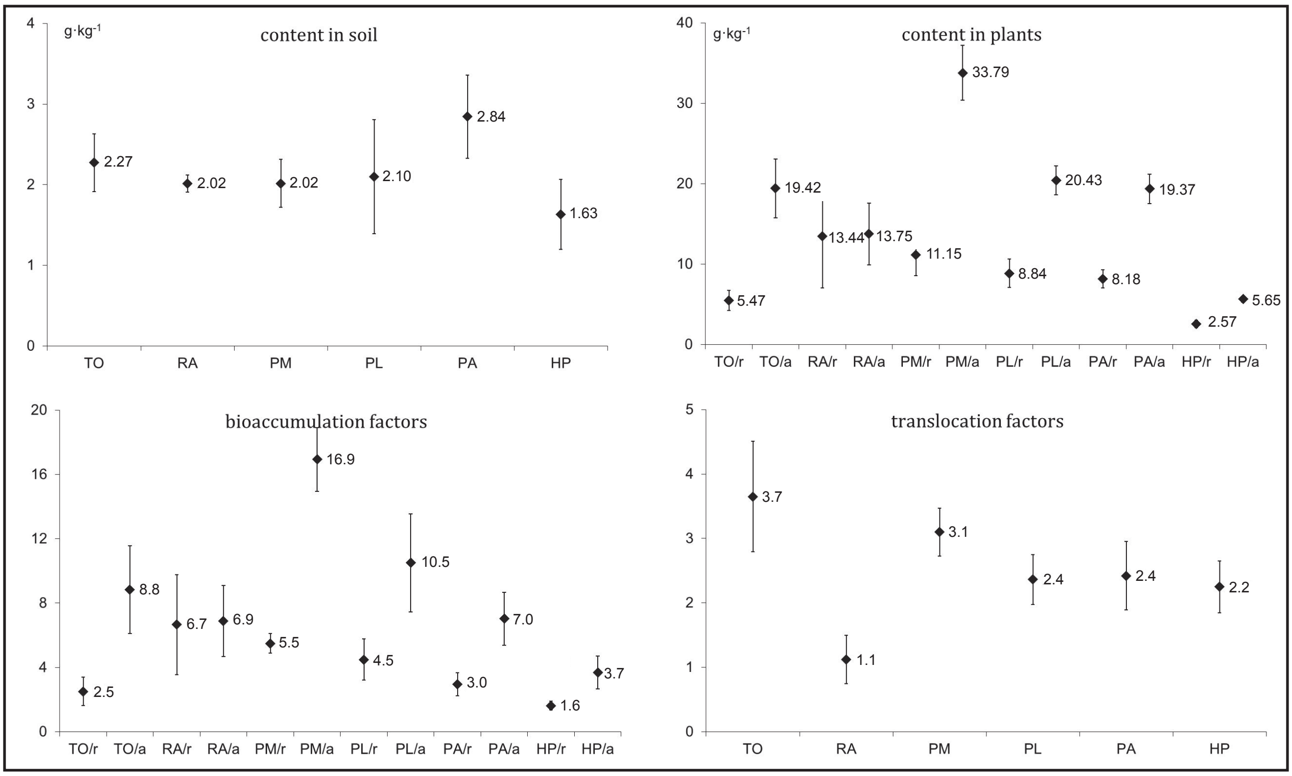

Figure 5 The content of calcium in soils and plants, bioaccumulation factors in roots (/r) and above-ground parts (/a) and translocation factors from roots to above-ground organs (mean ±SD)

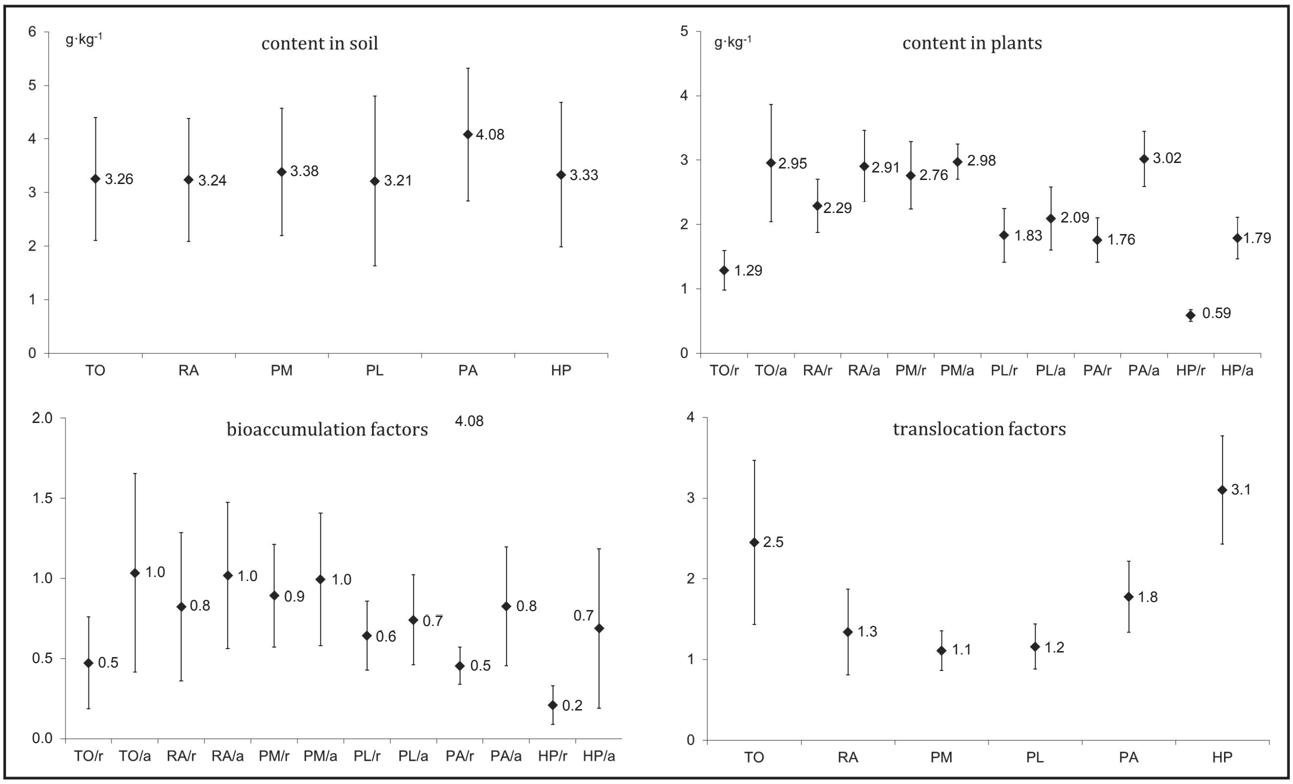

Figure 6 The content of magnesium in soils and plants, bioaccumulation factors in roots (/r) and above-ground parts (/a) and translocation factors from roots to above-ground organs (mean ±SD)

3.6 Retention and translocation of magnesium

Chlorite and mica are major sources of magnesium in soils developed from sedimentary rocks. Its content and profile distribution is conditioned by a complex of the same factors like for calcium, however contents are usually several times lower. It is reflected also in chemical composition of biomass of associated plants (Dziadowiec et al., 2007; Jonczak, 2013). In the studied soils content of Mg ranged on average from 3.21 g kg^{-1} under PL to 4.08 g kg^{-1} under PA, showing large variability within the stands of the individual herb species (Figure 6). In plants were noted comparable or lower amounts, slightly higher in above-ground organs as compared to the roots. Plants require at least 1–1.3 g kg^{-1} of Mg in their biomass for normal growth (Falkowski et al., 2000). The observed concentrations were much higher, despite potential negative effect of elevated contents of K. Magnesium showed different mobility depending on the species. It was the highest in HP and TO, whereas the lowest in PM (Figure 6).

4 Conclusions

The contents of N, P, Ca and Mg in roots and above-ground organs of the studied plants were among typical for herbs, reflecting their physiological demands. The content of K was higher. In general, the observed concentrations suggest sufficient bioavailability of elements in the studied soils and relatively high abilities to uptake by the studied plants. Based on mean bioaccumulation factors in roots and above-ground organs, the studied species form the following series:

N: roots – HP < RA < PA < TO < PL < PM
above-ground organs – PA < HP < RA < TO < PL < PM
P: roots – HP < RA < TO < PA < PL < PM
above-ground organs – RA < PM < HP < PA < TO < PL
K: roots – RA < HP < PA < TO < PL < PM
above-ground organs – HP < PA < RA < PM < PL < TO
Ca: roots – HP < TO < PA < PL < PM < RA
above-ground organs – HP < RA < PA < TO < PL < PM
Mg: roots – HP < PA < TO < PL < RA < PM
above-ground organs – HP < PL < PA < PM < RA < TO.

Presented the above list shows that the weakest bioaccumulation of most of macronutrients in roots was noticed for *Hypericum perforatum* L. and the strongest for *Plantago major* L., whereas for above-ground organs the weakest for *Hypericum perforatum* L. or *Rumex acetosa* L. and the strongest for *Plantago major* L., *Taraxacum officinale* or *Plantago lanceolata*. Translocation factors were typical for macronutrients and ranged from 1.3 to 3.1 for nitrogen, from 0.8 to 2.0 for phosphorus, from 1.3 to 3.3 for potassium, from 1.1 to 3.7 for calcium and from 1.1 to 3.1 for magnesium. The highest translocation was observed for *Taraxacum officinale* (K, Ca) and *Hypericum perforatum* L. (N, P, Mg).

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