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ORIGINAL PAPER

CONTENT OF SELECTED MACROELEMENTS IN THE AERIAL AND UNDERGROUND BIOMASS OF PLANTS FROM OLD STANDS OF THE GENUS *MISCANTHUS*

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Abstract

Old plantations of grasses used for soil remediation or for energy purposes are capable of the uptake and bio-accumulation of macro- and microelements found in soil. The aim of the present research has been to determine the content of calcium, magnesium, sodium and potassium in the aerial and underground parts in three grass species representing the genus *Miscanthus,* derived from a 12-year-old *M. sinensis* plantation and 10-year-old plantations of *M. sacchariflorus* and *M. giganteus*. The content of the elements in the biomass of grasses varied. It depended on a species as well as a place of bioaccumulation in plant organs and it was significantly higher than the soil content of these elements. The aerial parts of grasses, especially leaves, accumulated mostly calcium, potassium and magnesium. In the underground parts, mostly in roots, the plants accumulated potassium, calcium and sodium. The plant rhizomes accumulated magnesium in the amounts comparable to the content of this element in leaves. Depending on the sampling depth in soil, a higher content of calcium and potassium was identified in the 0-15 cm horizon than in the 15-30 cm layer. Magnesium and sodium demonstrated the opposite dependence. To illustrate the effect of the content of the macroelements studied in soil on their content in the grasses analyzed, the bioaccumulation factor was determined to define the ratio of an element's concentration in the plant to its concentration in soil. It shows that the highest capacity for the uptake of the analyzed macroelements from soil was reported in *M. sinensis* and the lowest appeared in *M. sacchariflorus*. Grasses of the genus *Miscanthus* are able to accumulate considerable amounts of macroelements in their organs. After the plantation is terminated, it is a considerable soil-enrichment source.

Keywords: energy grasses, bioaccumulation of macroelements, calcium, magnesium, sodium, potassium, coefficient of bioaccumulation.

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INTRODUCTION

Originating from south-eastern Asia, the genus *Miscanthus* is of increasing importance in the Polish energy sector, as it is able to produce the annual aerial biomass supply from 25 to 35 t ha^{-1}, throughout about 20 years. Mostly three species are used: Amur silver-grass (*M. sacchariflorus* (Maxim.) Hack.), *M. sinensis* (Thunb.) Andersson) and their hybrid – giant miscanthus (*M. giganteus* J. M. Greef & Deuter ex Hodk. & Renvoize). The grasses with their high yielding potential can contribute to the self-sufficiency of agricultural areas in terms of their fuel-and-energy needs (Jeżowski 2003, Majtkowski 2008, Ostrowski et. al. 2009). Strongly developed underground parts, including root systems and rhizomes, with a total weight from 25 to 40 t ha^{-1} each year, constitute a specific soil-erosion preventing system. Old stands can uptake and bioaccumulate large amounts of macro- and microelements from soil; hence their use as plants for remediation of soils fertilized with sewage and sludge (Jeżowski 1999, Martyn et al. 2007, Kabała et al. 2010, Dębska et al. 2013). Numerous authors point that the content of various elements and their adequate ratios also affect the quality of biomass used in the energy sector (Borkowska, Lipiński 2007, Borzęcka-Walker 2010, Kordas, Tasz 2012). They also offer high ornamental qualities, stressed by landscape architects.

The genus *Miscanthus* shows a wide spectrum of tolerance to environmental conditions. Plantations can be set up both on wet soils close to watercourses, and in places with limited moisture, much solar irradiance and high air temperature as well as on soils representing 4 and 5 quality class (Podleśny 2005, Lisowski, Porwisiak 2010). The advantage of grasses representing the genus *Miscantus* is their adaptability to changing climate conditions, mostly solar irradiance and water deficit. As type C-4 grasses, they have the capacity for an effective use of water, nitrogen and other biogenic elements participating in biomass production (Majtkowski et al. 2004). Grasses' growth and development are considerably affected by the richness of soil in macronutrients, mostly Ca, Mg, Na and K, the phytoavailability of which mostly depends on their total content and the form in which they occur in soil. The chemical composition of grasses determines not only the health and condition of the plants, but also their suitability for energy purposes.

The aim of the present research has been to determine the potential bioaccumulation of macroelements, calcium, magnesium, sodium and potassium, in aerial and underground biomass of three grass species representing the genus *Miscanthus*.

MATERIAL AND MEHTODS

The research was performed on experimental plots at the IHAR-BIP Botanical Garden in Bydgoszcz. Long-term collections of three grass species representing the genus *Miscanthus* were analyzed, excluding the question of their genotype-specific traits. The seedlings for the *M. sinensis* plantation, established in 2001, originated from the collection of the Institute of Plant Genetics of the Polish Academy of Sciences in Poznań. The material for *M. sacchariflorus* plantings was received from the IHAR collection in Bydgoszcz, and that for *M. giganteus* – from the VITROPLANT laboratory in Klein Wanzleben, in Germany. Both plantations were established in 2003. Each year, the plantations with grasses covering 30 to 150 m^2 are supplied mineral fertilizers at the doses of N = 88 kg ha^{-1}, P = 64 kg ha^{-1}, K = 96 kg ha^{-1}.

In the autumn of 2012, throughout the inflorescence formation stage, each plantation was randomly sampled, at ten sampling points, from a total area of 1 m^2, to obtain aerial parts of grasses, which were separated into stems and leaves under laboratory conditions. The underground parts were sampled from soil in a form of monoliths, from ten randomly sampled locations, 500 cm^2 and down to 30 cm deep each. Roots and rhizomes were separated from mineral and organic pollutions in each of such soil samples, The plant material was dried at the temperature of 60°C to determine air-dried weight.

The total content of selected macronutrients; Ca, Mg, Na and K was determined separately in leaves, stems, rhizomes and roots of plants as well as in soil. The macroelements were evaluated in three replications, following mineralization with the microwave technique in concentrated HNO_3 and expressed in mg kg^{-1}. The concentration of macronutrients, both in plant parts and in soil, was determined with Atomic Spectrometry Absorption – ASA (Mg and Ca) and Atomic Emission Spectrometry – ASE (Na and K), on a Solaar S4 apparatus. The soil grain size composition was assessed using the hydrometer method, based on the Stoke's law governing the rate of sedimentation of particles suspended in water; the interpretation of the results is based on the World Reference Base for Soil Resources classification (IUSS Working Group WRB 2014). pH was assayed applying the potentiometric method in H_2O (1:2.5 ratio) and in KCl solution at the concentration of 1 mol dm^{-3} (1:2.5 ratio), while C-organic was determined with the Tiurin method in potassium dichromate solution.

To illustrate the effect of the content of the macroelements in soil on their concentrations in the grasses analyzed, the bioaccumulation factor (BF) was determined to define the ratio of the concentration of an element in the plant to the content of this element in soil (Czech et al. 2014).

The research sites were located in soils with the grain size composition of sandy loam (PTG 2011) and with low humus content. The content of C-organic was 6.3 g kg^{-1} in the layer 0-15 cm deep and 7.6 g kg^{-1} in the layer 15-30 cm deep. The reaction of the soils in the surface horizons was pH 7.24

(H_2O) and pH 7.20 (KCl), and in deeper horizons – pH 6.35 (H_2O) and pH 5.88 (KCl). The base saturation (BS) in the soils accounted for 96%.

All the statistical data analyses were performed with Statistica 10. To determine the significance of the differences between the content of macroelements in the biomass of grasses and in soil, the Tukey test was applied at the significance level of $p \leq 0.05$. To define the range of soils and plants' richness in mineral nutrients, the experimental factors were grouped in clusters according to the highest similarity of characters. The cluster analysis was made with the Ward method following data standardization to cover the content of macroelements in soil and in plants.

RESULTS AND DISCUSSION

The analyses of the content of the selected macronutrients in the biomass of grasses representing the genus *Miscanthus* showed that the amount of calcium, magnesium, sodium and potassium varied depending on the species and the plant organs evaluated (Table 1). The highest content of calcium and magnesium was found in the aerial parts, while sodium and potassium were the most abundant in the underground plant parts. Considering the content of all the macronutrients evaluated in the aerial mass, leaves were identified as the organs which were richer in macronutrients than stems. The reason was an incomparably higher intensity of metabolic processes occurring in leaves than in shoots (Starck 2014). A significantly higher content of magnesium in leaves than in stems can be explained by the fact this element is mostly present in the structure of chloroplasts, mainly found in leaves and, additionally, it is the central component of chlorophyll molecules (Starck 2014). On the other hand, calcium plays a different role in the development and functioning of plants. Higher amounts of this element are mostly characteristic for aging tissues, in which it turns into an inactive state and consequently remains in leaves (Wójcik 1998). Potassium, as an element active in the water uptake and decreasing transpiration, becomes easily reused both in cell structures and in plant organs. At the end of the vegetation season of perennials, it is translocated from leaves to shoots or underground parts and it can be secreted through the roots to the ground (Syers 2005). The highest sodium content in all the species tested was reported in the roots, especially in deeper soil layers (15-30 cm). It is an element which is hard to translocate in plants and therefore its considerable amounts are often found to remain in the place of sampling. Interestingly, at respective stages of development, there is a considerable mobility of elements in plant organs. Significant amounts of elements, e.g. sodium, return to soil together with falling leaves, and can be used again by plants in the following growing season (Kahle et al. 2001, Gondek, Filipek-Mazur 2006, Kalembasa, Malinowska 2009).

Table 1

Content of macroelements (mg kg^{-1}) in the organs of grasses representing the genus *Miscanthus*

Macro-elements	Leaves	Stems	Rhizomes	Roots 0-15 cm	Roots 15-30 cm	Soil 0-15 cm	Soil 15-30 cm	LSD$_{p \le 0.05}$ for plant organs
Miscanthus sacchariflorus (*n* = 30)								
Ca	4351	510	562	641	841	217	212	*14.5*
Mg	588	36	490	80	94	201	212	*6.3*
Na	188	44	63	295	450	228	230	*8.4*
K	6636	3172	4990	7289	6870	353	342	*9.1*
Miscanthus sinensis (*n* = 30)								
Ca	3566	1427	1043	1318	1532	262	244	*9.9*
Mg	980	357	927	90	107	349	355	*7.6*
Na	160	40	103	193	353	288	291	*4.7*
K	6483	1497	2891	6970	4634	384	344	*5.3*
Miscanthus giganteus (*n* = 30)								
Ca	4508	1338	1502	3165	3363	220	216	*27.3*
Mg	703	71	426	74	87	246	259	*9.6*
Na	198	50	60	291	325	248	251	*8.0*
K	3700	2519	2537	5198	4715	385	364	*7.3*
LSD$_{p \le 0.05}$ for macroelements								
Ca	27.6	13.4	26.6	14.9	6.4	6.4	5.4	×
Mg	7.7	4.4	11.8	3.8	5.5	9.3	4.2	×
Na	2.5	4.8	5.6	4.3	9.8	5.2	4.0	×
K	9.9	4.7	6.5	6.1	9.3	3.8	3.2	×

With respect to the content of macroelements in aerial parts of grasses, most of them were accumulated in leaves and significantly lower quantities gathered in stems (Table 1). The highest concentrations of calcium and sodium in leaves were accumulated in *M. giganteus* (4508 mg Ca kg^{-1}, 198 mg Na kg^{-1}), while magnesium and potassium accumulated to the highest levels in leaves of *M. sinensis* (980 mg Mg kg^{-1}, 6483 mg K kg^{-1}). The greatest discrepancies in the content of macroelements between leaves and stems occurred for magnesium in *M. sacchariflorus* and *M. giganteus*.

Significant variation in the content of macroelements in leaves and stems depended on the grass species evaluated. On average, three-fold more calcium, magnesium and sodium accumulated in leaves than in stems, whereas potassium is found at such proportions in *M. sinensis*. In *M. sacchariflorus* and *M. giganteus* species, the proportions of the content of potassium in leaves and stems were similar with a slightly higher amount in leaves. Irrespective of the intraspecific variation, most calcium and sodium accumulated in aerial parts of *M. giganteus,* magnesium – *M. sinensis,* and potassium – *M. sacchariflorus.*

The research showed that irrespective of the grass species both soil layers evaluated under the grass had a similar content of macroelements. It should be noted that the soil content was significantly lower than determined in the biomass of grasses (Table 1).

Higher content of calcium (from 217 to 262 mg kg^{-1}) and potassium (from 353 to 385 mg kg^{-1}) was found in soil down to the depth of 15 cm than the layer below 15 cm deep (Ca from 112 to 244 mg kg^{-1}, K from 342 to 364 mg kg^{-1}). Magnesium and sodium showed the opposite dependence. At the depth of 0-15 cm, magnesium was present in levels from 201 to 349 mg kg^{-1}, and at the depth of 15-30 cm the Mg content ranged from 212 to 259 mg kg^{-1}. Sodium in the shallower layer varied from 228 to 288 mg kg^{-1} and reached 230 to 291 mg kg^{-1}at the depth of 15-30 cm.

The varied content of calcium and magnesium in specific horizons of the soil profile can be due to an antagonistic effect of these elements on the uptake by plants (Martyniak 2009). Calcium is an element indispensable for the proper plant growth, which acts as a barrier for the migration of Ca, with soil providing background for its migration (Ostaszewska, Wicik 2012). The form in which calcium occurs in soil, next to the soil's pH, the content of organic matter and richness in antagonistic potassium, can weaken the dependence between soil richness in calcium and its content in the plant. Magnesium is easily leached to the deeper soil layers, hence its content in the upper soil layer is often lower (Franyluebbers, Hons 1996, Fotyma, Gosek 2000, Bednarek et al. 2012). Frequently observed magnesium deficit symptoms, especially in young, shallow-rooted plants are due to the leaching of this element through the surface horizons of soils (Martyniak 2009).

As for sodium and potassium, there is a strict dependence between their content and the uptake by plants. A higher potassium content at a specific depth of the soil profile determines a more intensive sodium uptake by plants. Sodium in soil comes mostly from aluminosilicate minerals, it is poorly sorbed by the solid soil phase, and it easily leaches deep into the soil profile and to groundwater. Interestingly, the ions of the elements found in soil interact with each other, which can involve mutual stimulation or inhibition of the uptake by plants (Filipek et al. 2006).

The analysis of the content of macroelements in the underground parts of grasses showed that the roots contained more calcium, sodium and potassium, but not magnesium, than the rhizomes. Both in rhizomes and in roots, the highest amounts of calcium and potassium were accumulated, while the lowest ones were of sodium. The accumulation of magnesium in rhizomes was even 5-9-fold higher than in roots, especially in *M. sinensis* (927 mg kg^{-1}). Probably this relationship was connected with the presence of the ground-tissue layer in rhizomes and different growth biology of these organs. Interestingly, *M. sinensis* presents compact tuft structure, in contrast to the other plant species which have loose-tuft structure. Most calcium in roots was found in *M. giganteus* (3264 mg kg^{-1}), and sodium and potassium – in *M. sacchariflorus* (Na – 372 mg kg^{-1}, K – 7080 mg kg^{-1}). When exposed to shallower soil layers (0-15 cm), the roots of grasses mostly took up potassium, and its highest amount was reported in the shallow-rooting roots of *M. sacchariflorus* (K - 7289 mg kg^{-1}). Calcium, magnesium and sodium were mostly taken up in deeper soil layers. As for calcium, the highest amount of this macroelement from deeper layers was accumulated in *M. giganteus* (Ca - 3363 mg kg^{-1}), magnesium in *M. sinensis* (107 mg kg^{-1}), and sodium in *M. sacchariflorus* (450 mg kg^{-1}).

In order to explore the soil and plant richness in minerals, the experimental factors were grouped in clusters according to the highest similarity of characters (Figure 1). The cluster analysis for soils revealed two clusters,

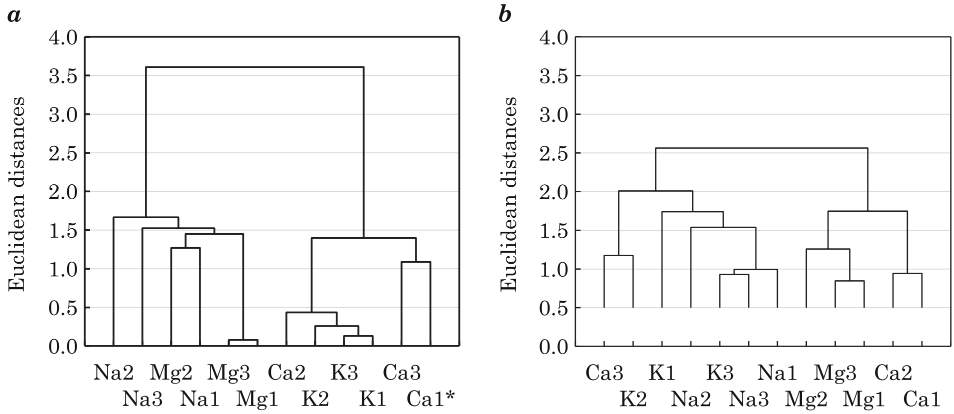

Fig. 1. Dendrogram for macroelements accumulated in soil (*a*), grasses representing the genus *Miscanthus* (*b*). * Successive numbers of stands for grasses representing the genus *Miscanthus*: 1 – *M. sacchariflorus*, 2 – *M. sinensis*, 3 – *M. giganteus*

which comprised comparable contents of respective macroelements, the presence of those elements in soil was manifested by their varied content and it was not closely related to the species of grasses. However, as for the presence of macroelements in plant organs, there was a link to the grass species, which corresponded to the different accumulation of potassium and sodium as well as magnesium and calcium in plants.

The relationships which occurred between concentrations of the elements in the plant and in soil were identified by the bioccumulation factor (BW), and the calculated values confirmed that the plants took up from soil most calcium and potassium and the lowest amounts of sodium (Figure 2). High values of the calcium and potassium uptake were reported both in the aerial and underground mass. The research showed that magnesium was accumulated in considerable amounts not only in leaves but also in plant rhizomes. The highest calcium uptake was found in the plantation of *M. sinensis* and

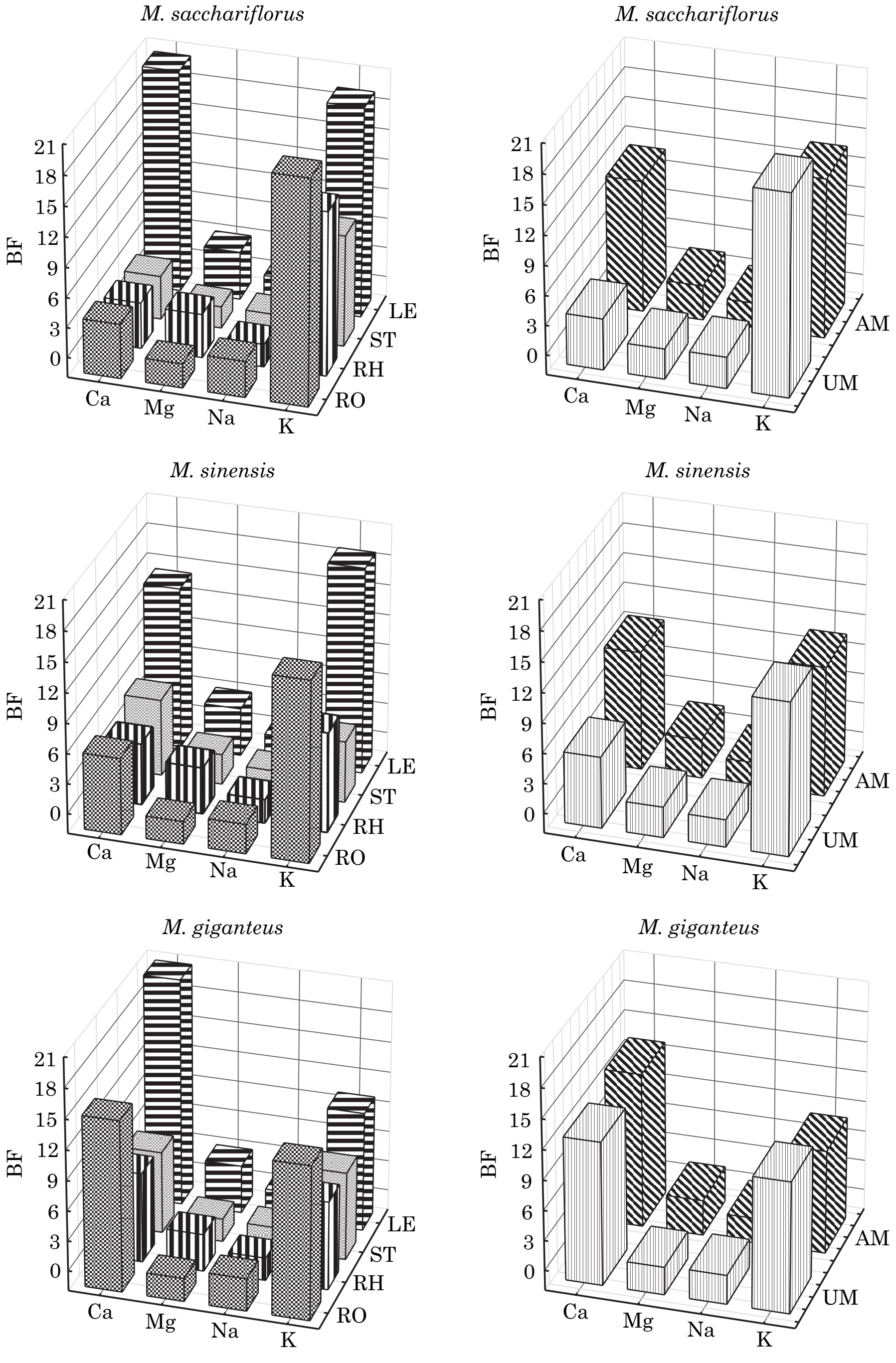

Fig. 2. Values of the bioaccumulation factor in the underground and aerial parts of grasses representing the genus *Miscanthus*: LE – leaves, ST – stems, RH – rhizomes, RO – roots, AM – aerial mass, UM – underground mass, BF – bioaccumulation factor

lower amounts were absorbed by *M. giganteus* plants. Calcium was mostly accumulated in aerial parts of plants. Equally high potassium requirements, with potassium accumulating in delicate roots, were identified in all the plants evaluated, mostly in the *M. sacchariflorus* plantation. The variation in the richness of grasses in macroelements and other organic components (hemicellulose, cellulose, etc.) can be caused by the plants' varied capacity for absorbing mineral nutrients from soil and by their biological and genotype properties (Nowińska et al. 2012, Płażek et al. 2015).

The higher ability of elements to be absorbed by plants leads to a decrease in their soil content. Bearing this in mind, it is unsurprising that the total amount of macroelements in soil occurred in the opposite order than in the plants, *M. sinensis* – *M. giganteus*a – *M. sacchariflorus*.

CONCLUSIONS

1. The content of the analyzed elements in the biomass of grasses representing the genus *Miscanthus* varied, depending on a grass species, but it was definitely higher in grasses than in soil. The highest capacity for the uptake of the macronutrients from soil was demonstrated by *M. sinensis* and the lowest – by *M. sacchariflorus*.

2. The plant elemental content depends on the site of bioaccumulation. The aerial parts of grasses accumulated mostly calcium, potassium and magnesium. The underground parts of plants, especially roots, accumulated mostly potassium, calcium and sodium. Rhizomes accumulated magnesium in the amounts comparable to those which occurred in leaves.

3. The research demonstrated that the grasses representing the genus *Miscanthus* were able to accumulate considerable amounts of macroelements in their organs, therefore differentiated fertilization should be applied. Once a plantation is terminated, Miscanthus plants are a source enriching soil with these valuable nutrients.

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