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ISSN: 0190-4167 (Print) 1532-4087 (Online) Journal homepage: http://www.tandfonline.com/loi/lpla20

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**To cite this article:** Irina Shtangeeva, Solomon Tesfalidet & Lars Lövgren (2017) Comparison of nutrient concentrations in leaves of five plants, Journal of Plant Nutrition, 40:2, 239-247, DOI: 10.1080/01904167.2016.1237647

**To link to this article:** http://dx.doi.org/10.1080/01904167.2016.1237647

Accepted author version posted online: 11 Oct 2016.
Published online: 11 Oct 2016.

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JOURNAL OF PLANT NUTRITION
2017, VOL. 40, NO. 2, 239–247
http://dx.doi.org/10.1080/01904167.2016.1237647

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# Comparison of nutrient concentrations in leaves of five plants

Irina Shtangeeva [a], Solomon Tesfalidet [b], and Lars Lövgren [b]

[a]Chemical Department, St. Petersburg University, St. Petersburg, Russia; [b]Department of Chemistry, Umeå University, Umeå, Sweden

**ABSTRACT**

The paper describes investigation on bioaccumulation of mineral elements and identification of plants based on the concentrations of the elements in the plant leaves. Five native plant species (*Elytrigia repens, Plantago major, Urtica dioica, Chelidonium majus, and Taraxacum officinale*) were studied. To exclude the effects from different growth conditions and developmental stages, the plants were collected simultaneously from the same site (park in St. Petersburg, Russia). It was found that for all plants high concentrations of potassium, sodium, phosphorus and magnesium (K, Na, P, and Mg) were typical, while concentrations of zinc (Zn) and copper (Cu) were the lowest. The most significant difference was found between concentrations of elements in monocots and eudicots. Among other species, *T. officinale* had the highest concentrations of almost all elements. Excellent separation of the plants into different groups which was due to different element concentrations in the plant leaves was demonstrated.

**ARTICLE HISTORY**
Received 25 June 2014
Accepted 10 November 2014

**KEYWORDS**
Grass; leaf nutrient concentrations; monocots and eudicots; ICP-OES

## Introduction

Mineral nutrition is a fundamental phenomenon common to all plants. Since inorganic nutrients participate in biochemical reactions as structural components, activators, and cofactors, the presence of all ions at certain concentrations as well as certain relationships between the ions is necessary for normal plant development. Efficiency of utilizing one or another mineral element is related to genetic specificity of plants. One of the possible reasons for separation of plant species at physiological and biochemical level may be difference in concentrations of macro- and trace elements in the plants since plants are capable of maintaining rather stable cytosolic concentrations of nutrients in their tissues even under different environmental conditions (Mengel and Kirkby, 2001). This is achieved through a delicate balance between uptake, compartmentalization, and storage of the elements.

During recent years, significant progress has been made in the understanding of the processes of uptake and pathways of various chemical elements in plants. It was shown that different genotypes may differ in the demand for mineral element supply and capacity of the element uptake, transport and involvement in the plant metabolism (Ramage and Williams, 2002; Epstein and Bloom, 2005; Herencia et al., 2007; Lovkova et al., 2008; White and Brown, 2010; Fageria et al., 2011). It was also reported that different plants growing in the same place frequently show different concentrations of trace and macro-elements (Reimann et al., 2003; Kataeva et al., 2004; Willey et al., 2005; Bourret et al., 2009). Recently a group of UK scientists have published a series of experimental data confirming differences between concentrations of few elements in shoots of plants belonging to different taxa (Hodson et al., 2005; Willey and Fawcett, 2006; Watanabe et al., 2007; Broadley et al., 2008; Willey and Wilkins, 2008; Broadley and White, 2012). However, the researchers did not pay particular attention

**CONTACT** Irina Shtangeeva shtangeeva@gmail.com Institute of Earth Sciences, St. Petersburg University, Universitetskaya nab, 7/9, St. Petersburg 199034, Russia.
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to relationships between macro- and trace elements. Meanwhile, it may be assumed that relationships between elements in different plant species growing in the same environment may be different, thus suggesting that this can also serve as a peculiar feature of the plants.

As was reported, concentrations of essential minerals in leaves need to be maintained within a certain range since mineral deficiency limits growth and mineral excesses can be toxic (Broadley et al., 2004). Thus, it may be assumed that concentrations of elements in this plant part (leaves) are more stable and may show rather insignificant variation even in spite of significant variations of the element concentrations in the environment. If we compare a range of one or another element in roots and leaves, it may be seen that root element concentrations can vary more significantly as compared to variations in the concentrations of the same elements in leaves (Qian et al., 1999; Baldantoni et al., 2004; MacFarlane et al., 2007). This probably may be due to more close relationships between roots and soil (and concentrations of elements in the rhizosphere soil can vary significantly with time). Once macro- and micro-nutrients have already been taken by roots and translocated to upper plant parts (leaves), concentration of the nutrients should be maintained at more or less stable level in order to provide normal physiological activity of a plant.

For this research, nine elements sodium, magnesium, aluminum, phosphorus, potassium, calcium, iron, copper and zinc (Na, Mg, Al, P, K, Ca, Fe, Cu, and Zn) were chosen. These macro- and trace elements are critical components of various biochemical processes in plants and play different roles in the plant life. In most terrestrial plants $K^+$ is the major cationic inorganic nutrient. It is highly mobile in plants. Although K is not assimilated into organic matter, its deficiency has a strong impact on plant metabolism (Amtmann and Rubio, 2012). Till now, Na has been studied more for its negative effect at excess levels (salt stress), while studies on beneficial or essential role of the element were more scarce (Pilon-Smits et al., 2009). Sodium and K are chemically and structurally very similar monovalent cations. However, there is major discrimination in uptake between Na and K through ion channels (Marschner, 1995). The principal electrolyte for plants is K, and even in ecosystems where there is a predominance of Na, plants still exhibit a strong preference for K (Walker et al., 1996). Phosphorus is a component of key molecules such as nucleic acids, phospholipids, and adenosine triphosphate (ATP) (Raghothama, 1999), and thus, plants cannot grow without a reliable supply of this nutrient. The most well-known function of Mg in plants is its role as a central atom in the tetrapyrrole ring of both the chlorophyll a and chlorophyll b molecules within plant leaf chloroplasts (Wilkinson et al., 1990). Calcium is a unique essential plant macro-nutrient with various fundamental physiological roles in plants (Gilliham et al., 2011). It is required for structural roles in the cell wall and membranes, as a counter−cation for inorganic and organic anions in the vacuole, and as an intracellular messenger in the cytosol (Marschner, 1995). Iron functions as an electron carrier in respiration and photosynthesis, in the production and detoxification of oxygen radicals, oxygen transport and numerous reduction and monooxygenase reactions (Buckhout and Schmidt, 2013). Copper ions act as cofactors in many enzymes. Under normal conditions, Cu is a structural element in regulatory proteins and participates in photosynthetic electron transport, mitochondrial respiration, oxidative stress responses, cell wall metabolism and hormone signalling (Marschner, 1995; Yruela, 2009). Aluminum is a complicated ion in its chemical form and biological function (Matsumoto, 2000). Low concentrations of Al can increase plant growth or induce other desirable effects (Rout et al., 2001; Pilon-Smits et al., 2009). Zinc is typically the second most abundant transition metal in organisms after Fe, and the only metal represented in all six enzyme classes (Broadley et al., 2007). As a component of proteins, Zn acts as a functional, structural, or regulatory cofactor of a large number of enzymes. Recent evidences suggest that Zn plays a key role in stabilizing ribonucleic acid (RNA) and deoxyribonucleic acid (DNA) structure, in maintaining the activity of DNA synthesizing enzymes and controlling the activity of RNA degrading enzymes (Stefanidou et al., 2006).

The goal of the present work was to study accumulation of several essential plant nutrients in different botanical taxa. Since results of experiments performed with plants grown under artificial conditions (in particular, in green-house) often hardly may be the same as results of experiments conducted in a field where often certain problems may arise from stressful field situations it is more important to measure the level of mineral elements in the different plants growing in a field. In the

present study a field test was performed to compare nutrient use strategies and better understand the difference in the plant mineral nutrition.

## Materials and methods

### Sampling

Five native plant species widely distributed in most part of Europe, Asia, North America and northern Africa: couch grass [*Elytrigia repens* (L.) Nevski], plantain (*Plantago major* L.), common nettle (*Urtica dioica* L.), celandine (*Chelidonium majus* L.), and dandelion (*Taraxacum officinale* F.H. Wigg) were harvested simultaneously from a small outdoor site of limited (2.5 × 2.5 m) size with relatively little environmental heterogeneity (in a small park in St. Petersburg, Russia) in the end of October 2013. Autumn was chosen for this experiment because the nutrient absorption by plants can fluctuate considerably during the year; however, by the middle of autumn the development of plants is usually completed, so that we can exclude, at least partially, significant variations in physiological state of the plants and in uptake of nutrients which may occur at the initial stages of the plant growth. Several plants of each species were taken to provide the reproducibility of the element analyses.

### Elemental analysis

The plants were carefully washed by water just after sampling and air dried up to constant weight. Then leaves of the plants were taken for analysis. The mass of each leaf sample was approximately 100 mg. Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES Thermo Fisher Scientific, Waltham, MA, USA) was used to determine element concentrations. For digestion, a CEM MARS 5 Microwave System with Teflon (Matthew, NC) reactors was used. Each plant sample was placed into the microwave digestion vessel, then 10 ml of Suprapur® nitric acid ($HNO_3$, 65% v/v; Merck, Darmstadt, Germany) was added, the vessels were closed and the samples were heated in the microwave oven (program: heating for 10 min to 180°C and holding at 180°C for 9:30 min). After that, the samples were diluted to 25 ml with Milli-Q water. Inductively coupled plasma optical emission spectrometer, Optima 200 DV (PerkinElmer, Überlingen, Germany), equipped with Cross-flow nebulizer and double spray chamber was used for elemental analysis. Stock solutions, 1000 $\mu$g mL$^{-1}$ of Mg, Al, Ca, Fe, Cu and Zn and 10000 $\mu$g mL$^{-1}$ of Na, K, and P, all purchased from CPI international (Amsterdam, Netherlands), were used for calibration. The standard solutions were prepared by further dilution of the stock solutions with appropriate volume of 2% $HNO_3$.

### Data analysis

For multivariate statistical analysis, Statistica for Windows 6.0 software packages (StatSoft, Tulsa, OK, USA) were used. The calculation of mean concentrations of elements and analysis of variances to estimate statistically significant differences between groups of samples were carried out. In addition, cluster analysis was applied to the datasets to classify the plants according to their ability to uptake different macro- and micro-nutrients and to assess the relationships between elements typical for each plant species.

## Results and discussion

### Distribution of elements in different plants

All the determined elements may be divided into three groups according to the element concentrations in plants (Table 1). For all plants, high concentrations of K, Na, P, and Mg were typical, while concentrations of Zn and Cu were the lowest. Calcium, Fe, and Al were usually intermediate between these two groups (with exception of *C. majus*; concentration of Al in the plants was lower than concentrations of Zn and Cu). This decrease in leaf element concentrations correlated well with increase of atomic number of the elements.

In leaves of all the plant species, concentration of K was the highest (it was at least 5 times higher than the concentrations of Na, P, and Mg). This is due to the specific role which this nutrient plays in the plant

**Table 1.** Mean concentrations of elements (mg $kg^{-1}$) ±SD in the plant leaves.

| Class | Clades | Species | Na | Mg | Al | P | K, % | Ca | Fe | Cu | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Monocot | Commelinids | *E. repens* | 268 ± 94 | 65.7 ± 39.0 | 3.52 ± 1.75 | 203 ± 129 | 0.20 ± 0.14 | 26.1 ± 14.1 | 10.8 ± 5.3 | 0.93 ± 0.49 | 2.70 ± 1.54 |
| Eudicot | Asterids | *P. major* | 749 ± 129 | 535 ± 69 | 112 ± 57 | 545 ± 74 | 0.66 ± 0.08 | 673 ± 59 | 137 ± 17 | 4.15 ± 1.62 | 12.1 ± 2.7 |
| Eudicot | Rosids | *U. dioica* | 1257 ± 39 | 3687 ± 201 | 57.7 ± 15.0 | 1459 ± 318 | 1.93 ± 0.24 | 413 ± 63 | 167 ± 41 | 4.21 ± 0.38 | 6.77 ± 1.34 |
| Eudicot | Ranunculales | *C. majus* | 1591 ± 30 | 787 ± 67 | 5.06 ± 2.67 | 3340 ± 556 | 2.42 ± 0.30 | 377 ± 82 | 59.1 ± 3.7 | 6.32 ± 2.48 | 13.1 ± 1.2 |
| Eudicot | Asterids | *T.officinale* | 8018 ± 511 | 2548 ± 20 | 138 ± 68 | 4040 ± 412 | 5.69 ± 0.98 | 1075 ± 6 | 277 ± 103 | 14.0 ± 1.5 | 24.7 ± 3.1 |

physiology. Rather high concentrations of Na and P in leaves were also typical for the plants. Concentrations of both these nutrients were the lowest in *E. repens* and increased in the following order: *E. repens* < *P. major* < *U. dioica* < C. majus < *T. officinale*. It is important to note that one of the most notable features of Na in plant nutrition is remarkable difference among species in their ability to either accumulate or exclude Na from their tissues (Subbarao et al., 2003). This was also demonstrated on the example of our data: leaf Na concentrations differed significantly between different plant species (Table 1).

Although plants were collected simultaneously and from the same site, different plant species varied in concentrations of many elements in their leaves. The most significant differences were observed between *E. repens* (monocot) and other plant species (eudicots). For example, concentrations of all elements studied were statistically significantly ($P < 0.001$) lower in *E. repens* than in *U. dioica* and *T. officinale*. The same considerable differences (except only Al) were observed between *E. repens* and *C. majus*. As for Ca, it has been reported that generally concentrations of Ca are much higher in eudicots than in monocots because of the difference in the cell wall structure between these two groups of plants (Mengel and Kirkby, 2001). Concentrations of Ca and Cu were rather similar for *P. major, U. dioica*, and *C. majus*, but differed considerably from concentrations of these elements in *E. repens* and *T. officinale*. Concentration of Al was almost the same in Asterids (*P. major* and *T. officinale*). *Elytrigia repens* (monocot) and *C. majus* (eudicot) also had similar leaf Al concentrations; the levels of Al in the plants were much lower as compared with concentrations of Al in Asterids. As was previously reported, considerable variations in Al tolerance between species and between varieties of the same species can occur (Andersson, 1988).

## *Cluster analysis of the experimental data*

Application of cluster analysis to the datasets demonstrated excellent separation of plants into different groups (Figure 1). It might be expected because of the differences between concentrations of nutrients

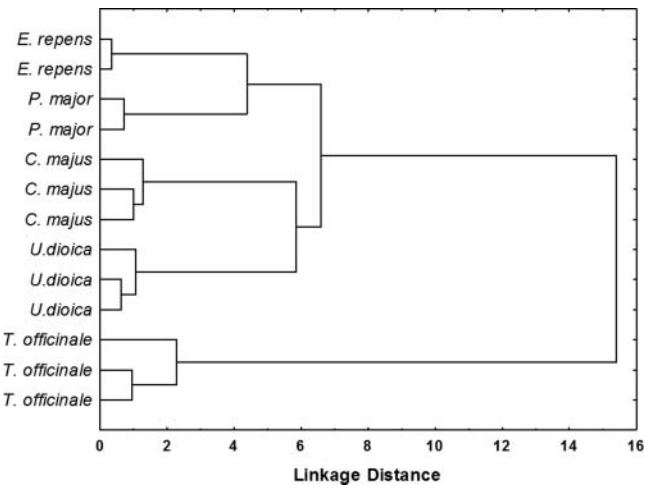


**Figure 1.** Dendrogram of hierarchical cluster analysis (Ward's method) of different plant species. Levels of similarity between different plants are indicated by a linkage distance.

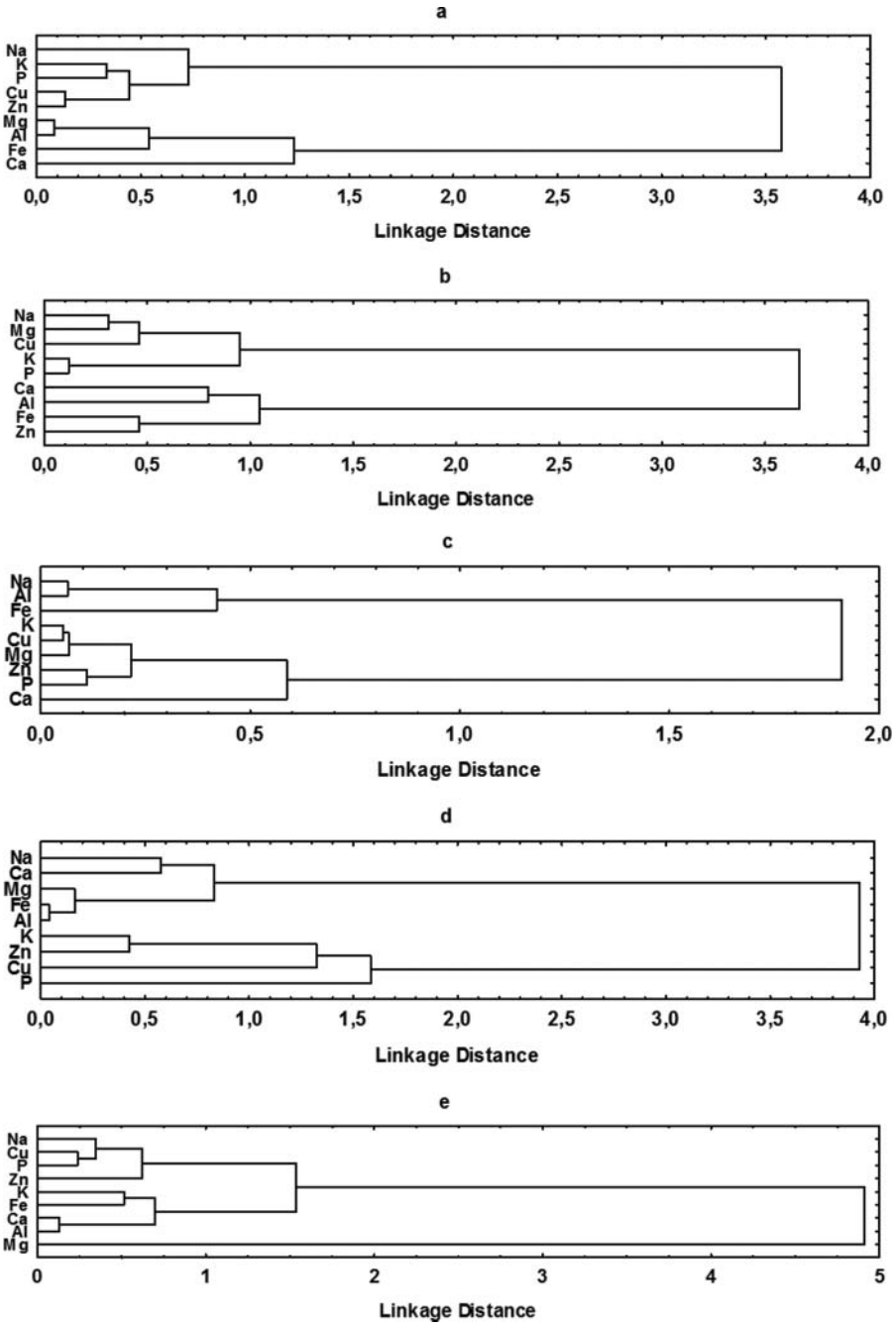


**Figure 2.** Cluster analysis (Ward's method) of elements in different plant species. A) *T. officinale*, B) *P. major*, C) *C. majus*, D) *E. repens*, E) *U. dioica*. Levels of similarity between different elements are indicated by a linkage distance.

in the different plant species. As can be seen from Figure 1, *T. officinale* was well separated from other plant species. This may be explained by the fact that among other species, *T. officinale* had the highest concentrations of almost all elements, especially Na (Table 1).

Comparison of results of cluster analysis of elements in different plant species demonstrated both differences and – in some cases – similarities (Figure 2). Common to each plant species was separation of nine elements determined in the plants into two groups. Among other species, the situation with

*U. dioica* was somewhat different as compared to other plants. Only in the case of *U. dioica* Mg was separated significantly from other elements (Figure 2e).

Interestingly, *T. officinale* (Figure 2a) and *P. major* (Figure 2b) demonstrated similar results. Like for other plant species, here elements were separated into two groups. The first group included Cu-Zn-K-P-Na (*T. officinale*) and K-P-Na-Mg-Cu (*P. major*). The second group of elements consisted of Mg-Al-Fe-Ca (*T. officinale*) and Fe-Zn-Ca-Al (*P. major*). Both *P. major* and *T. officinale* are eudicots, but compared to other tested in this work eudicots (*C. majus* and *U. dioica*), these plants belong to the same clade, Asterids.

Relative to differences between two groups of elements which were specific for other plant species, the differences between two groups of elements in *E. repens* was not so significant (Figure 2c). Linkage distance between these groups of different nutrients was less than for other plants.

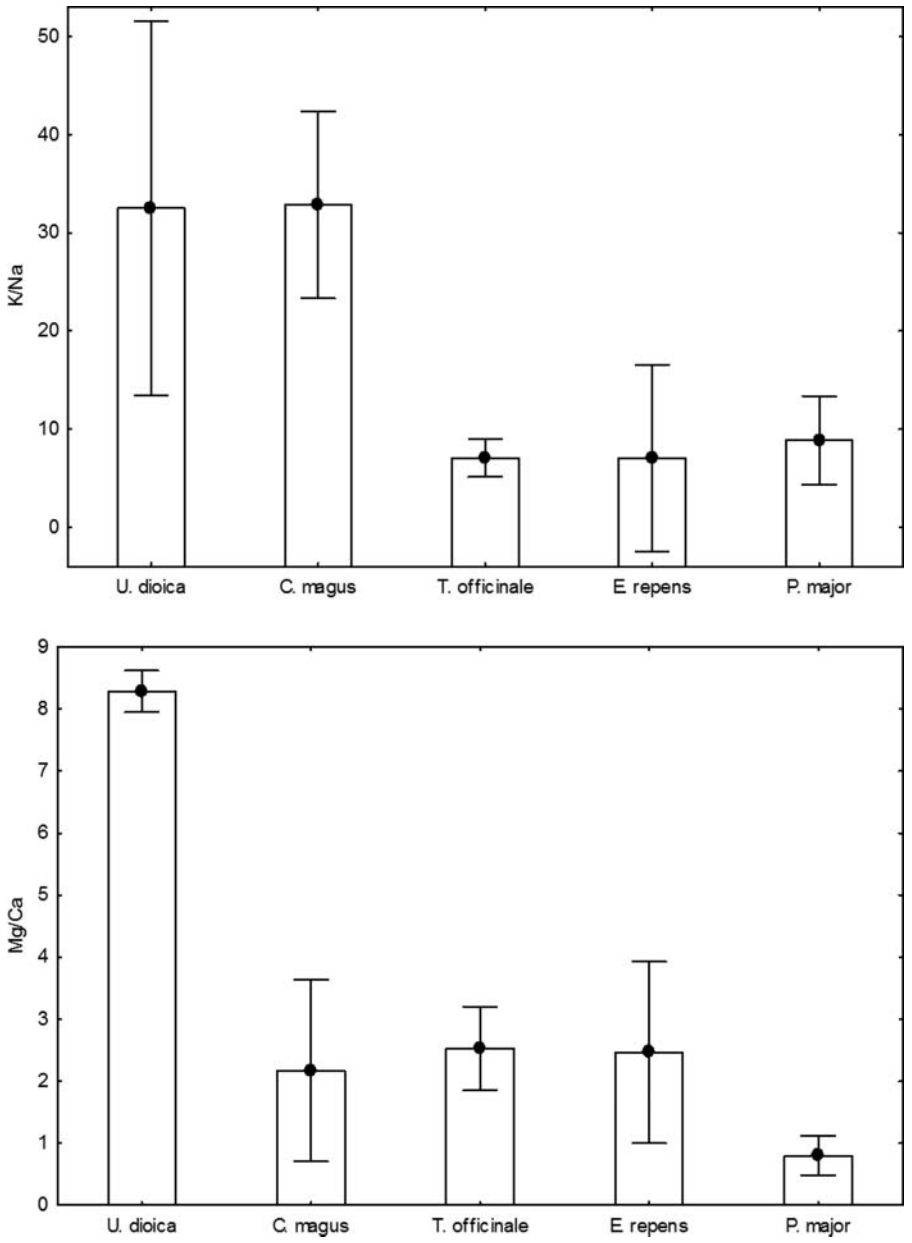


**Figure 3.** Ratios of K/Na and Mg/Ca in leaves of different plant species.

Variations in the element concentrations of plants can also be caused by various growth conditions and differences in the developmental stages. As was reported, the surrounding environment may have a greater influence on the concentrations of elements in leaves compared with the effect of belonging of the plant to one or another taxonomic group (Zhang et al., 2012). Probably, when plants grow in different environmental conditions and harvested at different developmental stages the significant differences in the element concentrations between plant species which were observed in our experiment (when plants grow at the same place and collected simultaneously) may be not so evident.

### *Variability of ratios of some nutrients*

Much evidence has been presented to show that the growth of plants is markedly affected by the proportions of the exchangeable cations which are present in soil. It was demonstrated that ratios of main nutrients in plants remain constant and typical for a particular plant species (Marschner, 2012). In our work, rather significant differences between ratios of chemically similar elements (K/Na and Mg/Ca) in leaves of different plant species were observed (Figure 3). The highest values for both K/Na and Mg/Ca ratios were found for *U. dioica* and the lowest ratios were observed for *T. officinale, E. repens*, and *P. major*. Thus, the ratios can also be used as specific indicators of the particular plant species.

## Conclusions

Data on cycling of different elements through ecosystems has been increased recently. It may be assumed that elements do not cycle independently in vegetation because they are involved in the basic structure and function of cells. This brings up the question as to whether the elemental composition of the plants is typical for particular plant species. On the one hand, we can certainly say "yes." Plants differ widely in their absorption of cations even from the same soil. As was shown in this work, a large difference between concentrations of elements in monocot *E. repens* and eudicots (other plant species studied in the work) may be a good evidence for this hypothesis. On the other hand, we hardly can state with assurance that this is universally true. It is evident that mineral nutrient requirements of all plants are not the same. The level of concentration of one or another element in a particular plant species may be initially determined by the demand of the plant in a specific amount of this element. However, an important question is whether the differences in concentration of this element between species grown under different field conditions will be the same as in the case when the plants are grown simultaneously and in the same environmental conditions. Besides, more research needs to be done to identify and understand the mechanisms by which plants control the concentration levels of elements in leaves.

## Acknowledgements

We would like to acknowledge PhD Åsa Bengtsson, Swedish University of Agriculture, for providing the equipment used in the digestion of samples.

## Funding

Irina Shtangeeva is grateful to the Nordic Council of Ministers Arctic Cooperation program for financial support of her travel to Sweden.

## ORCID

Irina Shtangeeva http://orcid.org/0000-0001-9555-2702
Solomon Tesfalidet http://orcid.org/0000-0002-8175-6883
Lars Lövgren http://orcid.org/0000-0003-0725-5236

## References


Amtmann, A., and F. Rubio. 2012. *Potassium in Plants*. Chichester, UK: John Wiley & Sons, Ltd.

Andersson, M. 1988. Toxicity and tolerance of aluminium in vascular plants. *Water, Air, and Soil Pollution* 39: 439–462.

Baldantoni, D., A. Alfani, P. Di Tommasi, G. Bartoli, and A. V. De Santo. 2004. Assessment of macro and microelement accumulation capability of two aquatic plants. *Environmental Pollution* 130: 149–156.

Bourret, M. M., J. E. Brummer, and W. C. Leininger. 2009. Establishment and growth of two willow species in a riparian zone impacted by mine tailings. *Journal of Environmental Quality* 38: 693–701.

Broadley, M. R, H. C. Bowen, H. L. Cotterill, J. P. Hammond, M. C. Meacham, A. Mead, and P. J. White. 2004. Phylogenetic variation in the shoot mineral concentration of angiosperms. *Journal of Experimental Botany* 55: 321–336.

Broadley, M. R., J. P. Hammond, G. J. King, D. Astley, H. C. Bowen, M. C. Meacham, A. Mead, D. A. C. Pink, G. R. Teakle, R. M. Hayden, W. P. Spracklen, and P. J. White. 2008. Shoot calcium and magnesium concentrations differ between subtaxa, are highly heritable, and associate with potentially pleiotropic loci in *Brassica oleracea*. *Plant Physiology* 146: 1707–1720.

Broadley, M. R., and P. J. White. 2012. Plant Mineralse. In: *Phytonutrients*, eds. A. Salter, H. Wiseman and G. Tucker, pp. 254–298. Oxford: Wiley-Blackwell.

Broadley, M. R., P. J. White, J. P. Hammond, I. Zelko, and A. Lux. 2007. Zinc in plants. *New Phytologist* 173: 677–702.

Buckhout, T. J., and W. Schmidt. 2013. *Iron in Plants*. Chichester, UK: John Wiley & Sons, Ltd.

Epstein, E., and A. J. Bloom. 2005. *Mineral Nutrition of Plants: Principles and Perspectives*, 2nd ed. Sunderland, MA: Sinauer Associates.

Fageria, N. K., V. C. Baligar, and C. A. Jones. 2011. *Growth and Mineral Nutrition of Field Crops*, 3rd ed.. Boca Raton, FL: CRC Press, Taylor & Francis Group.

Gilliham M., M. Dayod, B. J. Hocking, B. Xu, S. J. Conn, B. N. Kaiser, R. A. Leigh, and S. D. Tyerman. 2011. Calcium delivery and storage in plant leaves: exploring the link with water flow. *Journal of Experimental Botany* 62: 2233–2350.

Herencia, J. F., C. Ruiz-Porras, S. Melero, P. A. Garcia-Galavis, E. Morillo, and C. Maqueda. 2007. Comparison between organic and mineral fertilization for soil fertility levels, crop macronutrient concentrations, and yield. *Agronomy Journal* 99: 973–983.

Hodson, M. J., P. J. White, A. Mead, and M. R. Broadley. 2005. Phylogenetic variation in the silicon composition of plants. *Annals of Botany* 96: 1027–1046.

Kataeva, M. N., N. V. Alexeeva-Popova, I. V. Drozdova, and A. I. Beljaeva. 2004. Chemical composition of soils and plant species in the Polar Urals as influenced by rock type. *Geoderma* 122: 257–268.

Lovkova, M., G. N. Buzuk, and S. M. Sokolova. 2008. Genetic aspects of the interrelation between alkaloids and chemical elements in *Atropa belladonna* L. and *Glaucium flavum* Crantz plants. *Applied Biochemistry and Microbiology* 44: 416–419.

MacFarlane G. R., C. E. Koller, and S. P. Blomberg. 2007. Accumulation and partitioning of heavy metals in mangroves: A synthesis of field-based studies. *Chemosphere* 69: 1454–1464.

Marschner, H. 1995. *Mineral Nutrition of Higher Plants*, 2nd ed. London: Academic Press.

Marschner, P. 2012. *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed. San Diego: Academic Press.

Matsumoto, H. 2000. Cell biology of aluminum toxicity and tolerance in higher plants. *International Review of Cytology* 200: 1–46.

Mengel, K., and E. A. Kirkby. 2001. *Principles of Plant Nutrition*, 5th ed. Dordrecht: Kluwer Academic Publishers.

Pilon-Smits, E. A. H., C. F. Quinn, W. Tapken, M. Malagoli, and M. Schiavon. 2009. Physiological functions of beneficial elements. *Current Opinion in Plant Biology* 12: 267–274.

Qian, J.-H., A. Zayed, Y.-L. Zhu, M. Yu, and N. Terry. 1999. Phytoaccumulation of trace elements by wetland plants: III. Uptake and accumulation of ten trace elements by twelve plant species. *Journal Environmental Quality* 28: 1148–1455.

Raghothama, K. G. 1999. Phosphate acquisition. *Annual Review of Plant Physiology and Plant Molecular Biology* 50: 665–693.

Ramage, C. M., and R. R. Williams. 2002. Mineral nutrition and plant morphogenesis. *In Vitro Cellular & Developmental Biology - Plant* 38: 116–124.

Reimann, C., F. Koller, B. Frengstad, G. Kashulina, H. Niskavaara, and P. Englmaier. 2003. Total sulphur in leaves of several plant species from nine catchments within a 1 500 000 $km^2$ area in northern Europe: Local vs. regional variability. *Geochemistry: Exploration, Environment, Analysis* 3: 205–215.

Rout, G. R., S. Samantaray, and P. Das. 2001. Aluminum toxicity in plants: A review. *Agronomie* 21: 3–21.

Stefanidou, M., C. Maravelias, A. Dona, and C. Spiliopoulou. 2006. Zinc: A multipurpose trace element. *Archives of Toxicology* 80(1): 1–9.

Subbarao, G. V., O. Ito, W. L. Berry, and R. M. Wheeler. 2003. Sodium—a functional plant nutrient. *Critical Reviews in Plant Sciences* 22: 391–416.

Yruela, I. 2009. Copper in plants: Acquisition, transport and interactions. *Functional Plant Biology* 36: 409–430.

Walker, N. A., D. Sanders, and F. J. M. Maathuis. 1996. High-affinity potassium uptake in plants. *Science* 273: 977–978.

Watanabe, T., M. R. Broadley, S. Jansen, P. J. White, J. Takada, K. Satake, T. Takamatsu, S. J. Tuah, and M. Osaki. 2007. Evolutionary control of leaf element composition in plants. *New Phytologist* 174: 516–523.

White, P. J., and P. H. Brown. 2010. Plant nutrition for sustainable development and global health. *Annals of Botany* 105: 1073–1080.

Wilkinsoin, S. R., S. Ross, M. Welch, H.F. Mayland, and D. L. Grunes. 1990. Magnesium in plants: uptake, distribution, function, and utilization by man and animals. In: *Metal Ions in Biological Systems*, eds. H. Sigel and A. Sigel, pp. 34–56. New York: Marcel Dekker, Inc.

Willey, N., and K. Fawcett. 2006. A phylogenetic effect on strontium concentrations in angiosperms. *Journal of Environmental and Experimental Botany* 57: 258–269.

Willey, N. J., S. Tang, and N. R. Watt. 2005. Predicting inter-taxa differences in plant uptake of cesium-134/137. *Journal of Environmental Quality* 34: 1478–1489.

Willey, N. J., and J. Wilkins. 2008. Phylogeny and growth strategy as predictors of differences in cobalt concentrations between plant species. *Environmental Science & Technology* 42: 2162–2167.

Zhang, S.-B., J.-L. Zhang, J. W. F. Slik, and K.-F. Cao. 2012. Leaf element concentrations of terrestrial plants across China are influenced by taxonomy and the environment. *Global Ecology and Biogeography* 21: 809–818.

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