Response of wheat and barley seedlings on soil contamination with bromides

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Abstract Environmental pollution is becoming one of the most important global problems. Understanding the main factors affecting accumulation of toxic trace elements in consumed crops is of particular value. Unfortunately, possible toxicity of many trace elements is still poorly studied. The development of measures on identification of new potentially toxic trace elements is critical for high quality and safety of food. In the research, we performed greenhouse pot experiments with two major crops, wheat and barley, that were grown in the soil contaminated with bromides of ammonium and neodymium. The concentrations of elements in the plants and soil were determined by ICP-MS/ICP-OES after leaching the samples with tetramethyl ammonium hydroxide. Additionally, variations in the biomasses and concentrations of pigments in the plant leaves were studied. Although wheat and barley are botanically similar and were grown under the same conditions, concentrations of several elements in the plants were rather different. Both wheat and barley were capable of accumulating high concentrations of bromine (Br) when the plants grow in the soil contaminated with this trace element, but demonstrated different response on the soil contamination. The Br concentrations were always higher in barley, while the concentrations of pigments in barley leaves were lower than in leaves of wheat. During first days, biomass of the plants grown in the soil contaminated with bromides was slightly lower than biomass of the wheat and barley grown in uncontaminated soil. However, with time the bromides exhibited positive effect on the plant biomass.

Keywords Crops; Bromides; Soil contamination; Macronutrients; Trace elements; Pigments

Introduction

Cereals are an important group of crops. Among other cereals, wheat and barley are very popular in many countries (Giraldo et al. 2019). It is known that the plants are source of nutrients and natural bioactive compounds (Fageria et al. 2012; Koistinen and Hanhineva 2017). Wheat is one of the main cereal crops, which accounts for nearly 30% of the world's grain production (Shewry 2009). Approximately 70% of total production of barley is used for animal feed. The rest is mainly used for making beer (McKevith 2004). Recently, barley has become more popular for human food and has partially replaced wheat (Barron et al. 2017).

Both wheat and barley are members of the tribus *Triticeae*. However, wheat belongs to the genus *Triticum*, while barley to *Hordeum* genus. This could result in certain distinctions between these cereals including differences in their elemental composition (Koehler and Wieser 2013). Considering that nutrition of the plants occurs in different ways (Glencross et al. 2012), we can expect that the elemental composition of the two plant species can also differ. It has been reported that under similar soil conditions barley accumulated much less Cd than wheat (Adams et al. 2004). Besides, it was also found that compared to barley wheat had higher amounts of Mn and Pb, but lower concentrations of Al, As, and Co (Barłóg et al. 2020).

Application of various fertilizers plays an important role in agricultural practice. However, it is also known that fertilizers can have certain negative impact on plants and soil. It is important to take into account not only benefits of fertilizers but also their harmful effects. Previously, bromine (Br) compounds were extensively used in agriculture (Fields and White 2002). For our research, we chose two bromides – bromide of ammonium (NH_4Br) and bromide of neodymium ($NdBr_3$). Until recently, not so much experimental data on effects of these two bromides on plants and soils were reported, especially this concerns $NdBr_3$.

Ammonium bromide has found many applications in various industrial fields (Tachikawa et al. 2005). Until now, however, little is known about benefits or toxicity of Nd_3Br for the environment. There are publications about phytotoxicity of some other Nd compounds.

Rezaee et al. (2018) reported that low concentrations of Nd (applied as Nd_2O_3) stimulated the development of leaves of *B. chinensis* L. and also increased the concentration of chlorophyll. At high concentrations of Nd in the nutrient medium toxicity symptoms were clearly visible and plant growth was suppressed. Tang et al. (2017) found that application of $NdCl_3$ reduced the toxicity of Cd for *H. tuberosus* seedlings.

The plant roots release into the rhizosphere low- and high-molecular-weight compounds. This often can take place as a result of biotic and abiotic stresses (Bertin et al. 2003). The root exudates can influence on metabolic processes in plants and also on uptake of different macro- and trace elements (Canarini et al. 2019). Although wheat and barley are botanically similar, their root exudates can differ (Vančura and Hanzlíková 1972). It may be assumed that the differences between chemical compounds that roots of the two plants release into the rhizosphere can lead to certain differences in the uptake of nutrients by the plants.

Chlorophylls are pigments involved in the process of photosynthesis (Blankenship 2014). The group of chlorophylls includes tetrapyrrolic pigments that have common functions and structures (Milenković et al. 2012). In higher plants, chlorophyll a (Chl *a*) and chlorophyll b (Chl *b*) are main forms of chlorophyll that enable plants to absorb energy of light. Carotenoids (Ccar) are essential for protecting pigments (Niroula et al. 2019).

The present study was carried out to examine the effects of NH_4Br and $NdBr_3$ on accumulation of Br and some macro- and trace elements in wheat and barley and to determine the impact of the bromides on the plant biomass and concentration of pigments. The main aims of the research were the following: (1) to evaluate the mobility and availability of Br in the rhizosphere soil and ability of wheat and barley to accumulate this trace element, and (2) to study the differences in the soil chemistry, plant development and uptake of nutrients by wheat and barley seedlings grown in uncontaminated soil and in the soil contaminated with bromides.

Materials and methods

Experimental design, plant material, and growth conditions

The greenhouse pot experiment was performed in June 2018. Seeds of wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) were germinated on a wet filter paper during 5 days. Then germinated seedlings were transferred to ceramic pots (20 cm top diameter) filled with soil (6 kg of soil in a pot). For our experiment we used artificial fertile soil Terra Vita produced by Nord Palp (Russia). The soil consisted of peat (30%), chernozem (30%), sand (10%), compost (20%), and manure (10%). The pH of the soil was 6.0. Scheme of the experiment is shown in Fig. 1. Before planting, the soil in the pots was watered by ordinary tap water (control) and spiked with either NH_4Br or $NdBr_3$. Concentration of Br in the solutions was 100 mg L^{-1}. The chemicals were acquired from Roschimreactive, St. Petersburg (Russia) as pure standards (99 % of purity). Then the soil was mixed and kept in the pots for 24 hours. The experiment was performed in triplicate. The plant and soil samples (soil was taken from the rhizosphere zone of the plants) were collected 2 times, within 4 and 10 days after planting. Plants were washed carefully just after sampling with deionized water. Then plant and soil samples were air-dried up to constant weight.

Elemental analysis

Concentrations of Br, chlorine (Cl), and iodine (I) were determined by ICP-MS and concentrations of sodium (Na), magnesium (Mg), phosphorus (P), potassium (K), calcium

(Ca), and zinc (Zn) were determined by ICP-OES after leaching the plant and soil samples with tetramethyl ammonium hydroxide at mild temperature using the method described by Tagami et al. (2006). Detailed description of the procedure is given in our previous publications (Shtangeeva et al. 2015; Shtangeeva et al. 2017). Quality control was performed through analysis of standard reference material (SRM) Tomato leaves 1573a (National Institute of Standards and Technology, USA). The results of determination of the elements in the SRM well agreed with the certified and informative values.

Determination of chlorophylls and carotenoids

Chlorophylls and carotenoids were isolated from dry plant samples by 90% acetone solution. We used double extraction procedure described by Castle et al. (2011). The concentrations of photosynthetic pigments were determined with VIS-spectrophotometer PE-5300VI (ECROS, St. Petersburg, Russia). The concentrations of Chl *a*, Chl *b*, and Ccar in the acetone solution were calculated using the following formulas:

$$\text{Chl } a = (2.44\,(D_{664} - D^{A}_{664})/D_{664})) \text{ x } (11.85 D_{664} - 1.54\,D_{647} - 0.08\,D_{630}),$$

$$\text{Chl } b = 21.03\,D_{647} - 5.43\,D_{664} - 2.66\,D_{630},$$

$$\text{Ccar} = 4\,D_{480},$$

$$I_{430/664} = D_{430}/\,D_{664},$$

where D_{664} and D^{A}_{664} are absorption of solutions in Bells at λ = 664 nm before and after their acidification; D_{430}, D_{480}, D_{630}, and D_{647} are absorption of solutions in Bells at λ =430, 480, 630 and 647 nm, respectively; $I_{430/664}$ is pigment index.

The concentration calculation considered solution value (*V*s, mL), aliquot value (*V*al, mL), and cuvette length (*l*, cm). The absorption included in the formulas was taken with the correction equal to the absorption at λ = 750 nm. This correction was subtracted from the measured absorption. The result of the determinations was taken as a single result.

Data analysis

STATISTICA for Windows 6.0 Software package (StatSoft, Tulsa, OK, USA) was applied for interpretation of results of the experiments. Mean concentrations of elements were calculated and analysis of variances was applied to estimate statistically significant ($P<0.05$) differences between groups of samples. Pearson correlation analysis and principal component analysis were used to assist in better understanding the distribution of Br, macro- and trace elements in the rhizosphere soil and in plants.

Results and discussion

Variations in the plant biomass

When plants were collected first time (within 4 days after planting), the dry leaf biomasses of the wheat seedlings grown in uncontaminated soil and in the soil spiked with NH_4Br were higher than the leaf biomass of the wheat seedlings grown in the soil spiked with $NdBr_3$. The biomass of the barley seedlings grown in uncontaminated soil was slightly higher as compared with the biomasses of the barley seedlings grown in the soil spiked with bromides (Fig. 2a).

The growth of the seedlings in the soil for 6 more days resulted in an increase of the dry leaf biomass (Fig. 2b). Compared to the plants grown in uncontaminated soil, a larger increase was observed when the seedlings were grown in the soil spiked with bromides. The positive effect was greater for barley than for wheat.

Effects of bromides on the concentrations of pigments in leaves of wheat and barley

Figure 3 illustrates the variations in the Chl *a*, Chl *b*, and Ccar concentrations in leaves of wheat and barley seedlings collected on 2nd sampling date (within 10 days after planting). In wheat, the values of Chl *a*, Chl *b*, and Ccar were higher than in barley. Such differences were typical for the plants grown both in the soil amended with bromides and in the uncontaminated soil.

The positive effect of $NdBr_3$ and especially NH_4Br on the Chl *b* and Ccar was observed for both plant species. The concentration of Chl *a* in leaves of the wheat seedlings grown in the soil spiked with $NdBr_3$ decreased compared to that in leaves of the wheat grown in uncontaminated soil. Li et al. (2008) examined the effects of tetrabromobisphenol (widely used brominated flame retardant) on wheat (*Triticum aestivum*). The researchers also found a small decrease of chlorophyll content in wheat leaves that was caused by growth of the wheat in the soil that contained higher concentration of Br. In our opinion, the decrease of Chl *a* in wheat leaves may be a result of common action of Br and Nd. In leaves of the barley seedlings grown in the soil contaminated with $NdBr_3$ the concentration of Chl *a* was similar to that observed in leaves of the wheat seedlings grown in the soil spiked with this bromide and was almost the same as Ch *a* content in leaves of the barley seedlings grown in the soil contaminated with NH_4Br.

The correlation analysis showed a statistically significant ($P<0.05$) positive correlation between Chl *a* and Chl *b*, Chl *a* and Ccar in leaves of wheat seedlings. This can indicate possible simultaneous variations in the concentrations of different pigments in the plant. On the other hand, no correlation between these pigments in leaves of barley was found. Other researchers reported about positive correlation between chlorophylls and carotenoids in sweet basil cultivars (Kopsell et al. 2005) and between these pigments in maize (Ndukwe et al. 2016). Niroula et al. (2019) observed a statistically significant positive correlation between Chl *a*, Chl *b*, and Ccar in wheat and barley, but the authors calculated the coefficients of correlations for both these plants without their separation into two different groups - barley and wheat.

Concentrations of macro- and trace elements in plants and rhizosphere soil

Mean concentrations of macro- and trace elements in soil and in wheat and barley seedlings are present in Table 1 and Table 2. The concentrations of Na in roots and leaves of wheat and barley seedlings were 3.4 – 6.4 times lower than concentration of the nutrient in soil. Similar trend was also found for Ca and I. On the other hand, concentrations of Mg, P, and Cl were higher in plants than in soil. The concentration of K in roots of wheat and barley was similar to the K content in soil. Leaves of both plant species accumulated much more K than roots. This is due to essential role that K plays in different physiological processes (Cakmak 2005).

Although wheat and barley were grown under the same conditions and were collected simultaneously, there were certain differences in the concentrations of several elements in the plants. When the plants were grown in uncontaminated soil, the concentrations of P, K, and Ca in roots of wheat were statistically significantly ($P<0.05$) higher as compared to concentrations of the elements in roots of barley. When wheat and barley were grown in the soils spiked with bromides, the concentration of Cl in roots of wheat was lower as compared with concentration of Cl in roots of barley. The concentration of Cl in leaves of wheat was lower than in leaves of barley regardless of where the plants were grown. In both the last cases the differences between wheat and barley were statistically significant ($P<0.05$).

K/Na and Mg/Ca ratios in wheat and barley

Nutrient ratios are important characteristics of the physiological state of plants. A balanced combination of nutrients is a key factor that can affect the plant development (Fageria 2001). It has been hypothesized that the ratios of nutrients in different plants may be similar (Knecht and Göransson 2004). In nature, however, we usually observe a variety of nutrient ratios that are typical for each plant species.

During the process of uptake by roots and also translocation inside the plant the ions that have similar chemical properties, for example, Ca^{2+} and Mg^{2+} or K^+ and Na^+ can compete with each other (Fageria 2001). The ratios of K/Na and Mg/Ca in roots and leaves of the wheat and barley seedlings grown in uncontaminated soil and in the soil spiked with NH_4Br and $NdBr_3$ are shown in Table 3.

It is known that under ordinary conditions plant cells have a high K^+/Na^+ ratio (Blumwald 2000). In soil, the K/Na ratio was equal 1.0. In plants, the K/Na ratios were much higher than in soil. In roots, the ratios were always lower as compared to leaves owing to higher concentration of K in leaves. In roots of both the plant species the K/Na ratios were similar. With the only exception (wheat seedlings grown in the soil spiked with NH_4Br) the K/Na ratios in leaves of wheat were lower than in leaves of barley. Lower K^+/Na^+ ratios in wheat as compared to barley were also reported by Izadi et al. (2014).

In soil, the Mg/Ca ratio was equal 0.09. In plants, the Mg/Ca ratios were lower in leaves than in roots and were always higher in barley than in wheat. Compared to the K/Na ratios, a fairly clear effect of the soil contamination with bromides on the Mg/Ca ratios was observed, especially for barley. The variations in the Mg/Ca ratios in the barley seedlings grown in the soils contaminated with bromides were mainly caused by decrease of Mg concentration in roots and increase of Mg in leaves. In wheat, a decrease of Mg/Ca ratio was found only in leaves of the plants grown in the soil contaminated with $NdBr_3$. The variations also resulted from decrease of Mg in leaves of the plants grown in the soil spiked with $NdBr_3$.

Variations in the Br concentration in plants

The growth of wheat and barley in the soil contaminated with bromides resulted in statistically significant ($P<0.05$) increase of Br concentrations in roots and especially in leaves of both the plant species (Table 2). Barley accumulated much more Br than wheat. The adverse effect of the bioaccumulation of Br was observed only in roots of the wheat seedlings grown in the soil enriched with Br. In this case the concentration of Cl (chemical analogue of Br) decreased statistically significantly ($P<0.05$) compared with concentration of Cl in roots of the wheat seedlings grown in non-contaminated soil.

The concentration of Br in the plant roots increased with time, but the increase was different for wheat and barley (Fig. 4). During the first 4 days after planting, the concentration of Br in roots of barley increased ~80 times (in comparison with concentration of Br in roots of the plants grown in uncontaminated soil), while in roots of wheat the increase was less significant (~35 times as compared with Br content in roots of the wheat seedlings grown in uncontaminated soil). During 6 following days, the rate of accumulation of Br in roots of wheat seedlings was higher than in roots of barley seedlings (Fig. 4a). Larger amount of Br was accumulated in roots of the barley grown in the soil amended with NH_4Br than in roots of the barley grown in the soil amended with $NdBr_3$. One of the reasons may be the following: when one or another macro- or trace element is present in the soil as part of different compounds, plants can uptake it in different ways (Halka et al. 2018). Our previous experiments also demonstrated that level of accumulation of Br in plants depended on the Br compound presented in the growth medium (Shtangeeva et al. 2015; Shtangeeva et al. 2017).

The transfer of Br from roots to upper plant parts was different for wheat and barley and depended on the bromide compound applied to soil. The concentration of Br in leaves of the barley seedlings grown in the soil spiked with NH_4Br continued to increase with time. Thus, in this case not only roots of barley were capable of taking large amounts of Br from soil, but translocation of Br to leaves was also enhanced. We may assume that the presence of ammonium in the soil was favourable for Br accumulation in barley. On the other hand, we did not observe the same effect in wheat seedlings. Moreover, when wheat was grown in the soil amended with NH_4Br, the concentration of Br in leaves of the wheat seedlings collected on 2nd sampling date slightly decreased compared to the Br content in leaves of the plants collected on 1st sampling date. More significant decrease was observed when the wheat seedlings were grown in the soil spiked with $NdBr_3$ (Fig. 4b). In leaves of barley seedlings grown in the soil contaminated with $NdBr_3$ the concentration of Br increased slightly during last 6 days. This means that the uptake of Br from soil depended on both bromide compound and plant species.

Principal component analysis (PCA) of soil and plant samples

Figure 5 shows the results of the PCA of soil samples. The first two principal components (PCs) summarized 63% of the total variances. Bulk (initial) soils were well separated from the soil taken from roots of wheat and barley (rhizosphere soil). The PC1 was responsible for the separation. Magnesium, Cl, and P were highly correlated with the PC1 (factor scores were 1.90, -1.09, and -0.95, respectively). Uncontaminated bulk soil and the rhizosphere soil of the wheat and barley seedlings grown in the uncontaminated soil were separated from initial (bulk) soils spiked with bromides and the soil samples taken from roots of the plants grown in the contaminated soils. The PC2 was responsible for the separation. Main loading values in the PC2 were obtained for Br (factor score was 2.03) and also for Zn and Cl (factor scores were -1.45 and -0.87, respectively).

Figure 6a illustrates results of the PCA of roots of wheat. The first two PCs accounted for 64% of the total variances. Roots of wheat seedlings were separated into two groups: roots of the plants collected on 1st and 2nd sampling dates. The PC1 was responsible for the separation. Potassium, P, and Mg were highly correlated with the PC1, and the factor scores were 1.61, 1.30, and -1.21, respectively. Roots of barley (Fig. 6b) were also separated by the PC2 into groups of the samples collected at different dates. Magnesium and K had the main contribution to the separation with factor scores of 2.43 (Mg) and -0.82 (K). As an example, Fig. 7 illustrates the variations in the concentration of K in roots of wheat and barley. The concentration of K in roots of both plants increased with time. On the other hand, concentration of Mg decreased. The first PC was responsible for separation of barley roots into groups of roots of the plants grown in uncontaminated and contaminated soils. Bromine, Cl, and P were highly correlated with the PC1 with factors scores 1.73, 1.53, and -1.11, respectively. Roots of wheat seedlings were not well separated into groups of the samples grown in contaminated and uncontaminated soils.

Figure 6 also shows results of the PCA of leaves of wheat and barley seedlings. Leaves of both plant species were well separated accordingly to the date of sampling. The PC1 (43% of the total variances) was responsible for the separation of wheat leaves and main contribution to the PC1 provided P, Cl, Mg, and Na (factor scores were -1.56, 1.46, 1.33, and -1.19, respectively). The PC2 (33% of the total variances) was responsible for separation of leaves of barley by the date of sampling of the plants. Zinc and I (factor scores -1.84 and -1.12, respectively) had main contribution to the PC2. The PC1 (47% of the total variances) was responsible for separation of barley leaves into groups of the plants grown in non-contaminated and contaminated soils. Bromine (factor score -1.44), P (factor score 1.42), and Mg (factor score -1.27) were highly correlated with the PC1. As in the case of roots of wheat, there was no clear separation of wheat leaves into groups of the samples grown in contaminated and uncontaminated soils. Possible explanation of the fact might be that the increase of Br in roots and leaves of the wheat grown in the soil contaminated with bromides was less significant than in barley.

Correlation analysis of element concentrations in plants

The correlation analysis was used to study the ability of wheat and barley to translocate a particular element from roots to upper plant parts. There was a poor correlation between concentrations of most part of macro- and trace elements in roots and leaves of both plant species. In barley, a statistically significant ($P<0.05$) correlation between concentrations of Br ($r=0.75$) and K ($r=0.63$) was observed. In wheat, no statistically significant correlation between concentrations of elements in roots and leaves was found. This may point to differences between these two plant species in their capability to transfer elements from roots to upper plant parts.

Conclusions

The experimental results demonstrated certain differences in the biogeochemistry of wheat and barley. Although the plants are botanically similar, they exhibited a number of distinctions in concentrations of several elements in different plant parts. Wheat and barley had a certain set of macro- and trace elements, and in each species these elements were present in the combinations typical of either wheat or barley. Each plant species was also unique in its response to the soil contamination. Both wheat and barley were able to transfer Br from roots to upper plant parts and tolerate high concentrations of this trace element. Barley was capable of accumulating larger amounts of Br than wheat, but had lower concentrations of pigments.

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Declarations

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Figure captions

Fig. 1 Schematic diagram of the experimental work

Fig. 2 Dry leaf biomass of wheat and barley seedlings grown in uncontaminated soil (1) and in the soil spiked with NH_4Br (2) and $NdBr_3$ (3). a – 1st sampling (plants were collected within 4 days after planting), b – 2nd sampling (plants were collected within 10 days after planting)

Fig. 3 Concentration of Chl *a* (a), Chl *b* (b), and Ccar (c) in leaves of the wheat and barley seedlings grown in uncontaminated soil (1) and in the soil spiked with NH_4Br (2) and $NdBr_3$ (3)

Fig. 4 Variations in the Br concentrations in roots (a) and leaves (b) of wheat (W) and barley (B) seedlings grown in the soil spiked with NH_4Br (1) and $NdBr_3$ (2)

Fig. 5 Score plot of the first and second principal components of the PCA of soil samples.

in – initial (bulk) soil, w – soil was taken from roots of wheat, b – soil was taken from roots of barley. 1 – uncontaminated soil, 2 and 3 – the soil was spiked with NH_4Br and $NdBr_3$, respectively

Fig. 6 Score plot of the first and second principal components of the PCA of roots of wheat (A) and barley (B) and leaves of wheat (C) and barley (D) seedlings

Plants were grown in uncontaminated soil (c) and in the soil spiked with NH_4Br (a) and $NdBr_3$ (n). 1 and 2 – 1st and 2nd samplings, respectively

Fig. 7 Variations in the concentration of K in roots of wheat (a) and barley (b)

Table 1 Mean concentrations ± SD (n=3) of elements in uncontaminated bulk soil.
* Concentration of Br in the soils spiked with NH_4Br and $NdBr_3$

Element	Mean concentration ± SD
Na, %	1.4±0.3
Mg, %	0.17±0.02
P, %	0.074±0.008
Cl, %	0.14±0.01
K, %	1.4±0.3
Ca, %	1.9±0.1
Zn, mg kg^{-1}	11±2
Br, mg kg^{-1}	17±3
Br, mg kg^{-1}*	100±6
I, mg kg^{-1}	6.4±1.1

Table 2 Mean concentrations ± SD (n=3) of elements in roots and leaves of wheat and barley seedlings grown in uncontaminated soil (control) and in the soil spiked with NH_4Br and $NdBr_3$ and collected on 1st sampling date (within 4 days after planting)

* Differences between wheat and barley grown under the same conditions are statistically significant (P<0.05). [a] Differences between plants grown in uncontaminated soil and in the soil spiked with NH_4Br are statistically significant (P<0.05). [b] Differences between plants grown in uncontaminated soil and in the soil spiked with $NdBr_3$ are statistically significant (P<0.05)

	Roots					
	Wheat			Barley		
Element	control	NH_4Br	$NdBr_3$	control	NH_4Br	$NdBr_3$
Na, %	0.40±0.02	0.30±0.14	0.34±0.08	0.30±0.03	0.38±0.15	0.37±0.17
Mg, %	3.2±0.2	2.4±0.7	2.5±0.3	4.5±1.3	3.6±1.1	3.2±0.5
P, %	0.45±0.02*	0.35±0.15	0.40±0.05	0.30±0.04	0.31±0.06	0.36±0.01
Cl, %	0.61±0.03[ab]	0.45±0.01*	0.44±0.09*	0.81±0.23	1.0±0.1	0.83±0.06
K, %	2.0±0.2*	1.4±0.3	1.7±0.1	1.4±0.04	1.6±0.1	1.5±0.1
Ca, %	0.16±0.01*	0.12±0.06	0.15±0.11	0.073±0.015	0.085±0.006	0.075±0.02
Zn, mg kg^{-1}	36±7	30±11	45±19	31±2	23±10	29±7
Br, mg kg^{-1}	11±1[ab]	362±77*	423±34*	20±9 [ab]	799±57	818±38
I, mg kg^{-1}	1.8±0.8	0.68±0.19	0.84±0.13	0.85±0.01	1.0±0.4	0.81±0.17
	Leaves					
Na, %	0.41±0.12	0.26±0.06	0.42±0.22	0.26±0.06	0.30±0.03	0.22±0.01
Mg, %	0.51±0.14	0.69±0.44	0.28±0.02	0.78±0.62	1.1±0.1	1.0±0.3
P, %	1.1±0.1	1.1±0.09	1.1±0.1	0.91±0.08	0.94±0.07	0.95±0.06
Cl, %	1.6±0.2*	1.5±0.1*	1.7±0.2*	3.4±0.1	3.1±0.8	2.8±0.8
K, %	6.2±1.2	7.3±0.4	7.2±0.4	7.3±0.4	7.5±0.4	6.2±0.9
Ca, %	0.062±0.01	0.071±0.034	0.083±0.053	0.068±0.034	0.048±0.010	0.056±0.011
Zn, mg kg^{-1}	5.0±0.1	5.1±0.1	6.1±0.7	6.2±1.5	6.1±0.1	7.2±0.3
Br, mg kg^{-1}	45±7 [ab]	1519±234	1829±78	54±34 [ab]	2489±406	2233±340
I, mg kg^{-1}	0.26±0.22	0.51±0.41	0.16±0.08	0.39±0.28	0.43±0.32	0.78±0.45

Table 3 Ratios of concentrations of macro-nutrients in roots and leaves of wheat and barley seedlings grown in uncontaminated soil (control) and in the soil spiked with NH_4Br and $NdBr_3$

	Roots					
	Wheat			Barley		
	control	NH_4Br	$NdBr_3$	control	NH_4Br	$NdBr_3$
K/Na	5.0	4.7	5.0	4.7	4.2	4.0
Mg/Ca	20	20	17	62	42	43
	Leaves					
K/Na	15	28	17	28	25	28
Mg/Ca	8.2	9.7	3.4	11	23	18

Fig. 1

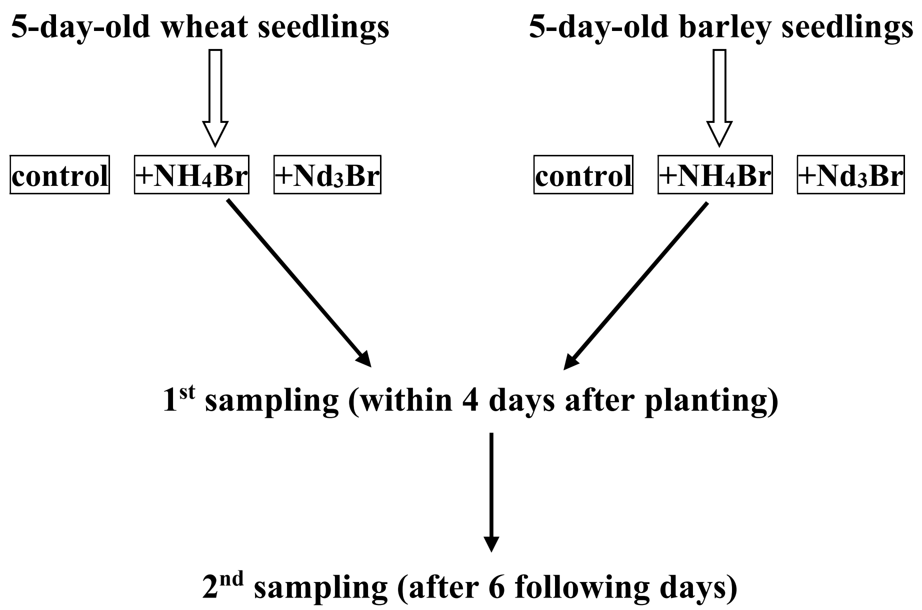

5-day-old wheat seedlings
5-day-old barley seedlings
control
+NH_4Br
+Nd_3Br
control
+NH_4Br
+Nd_3Br
1^{st} sampling (within 4 days after planting)
2^{nd} sampling (after 6 following days)

Fig. 2

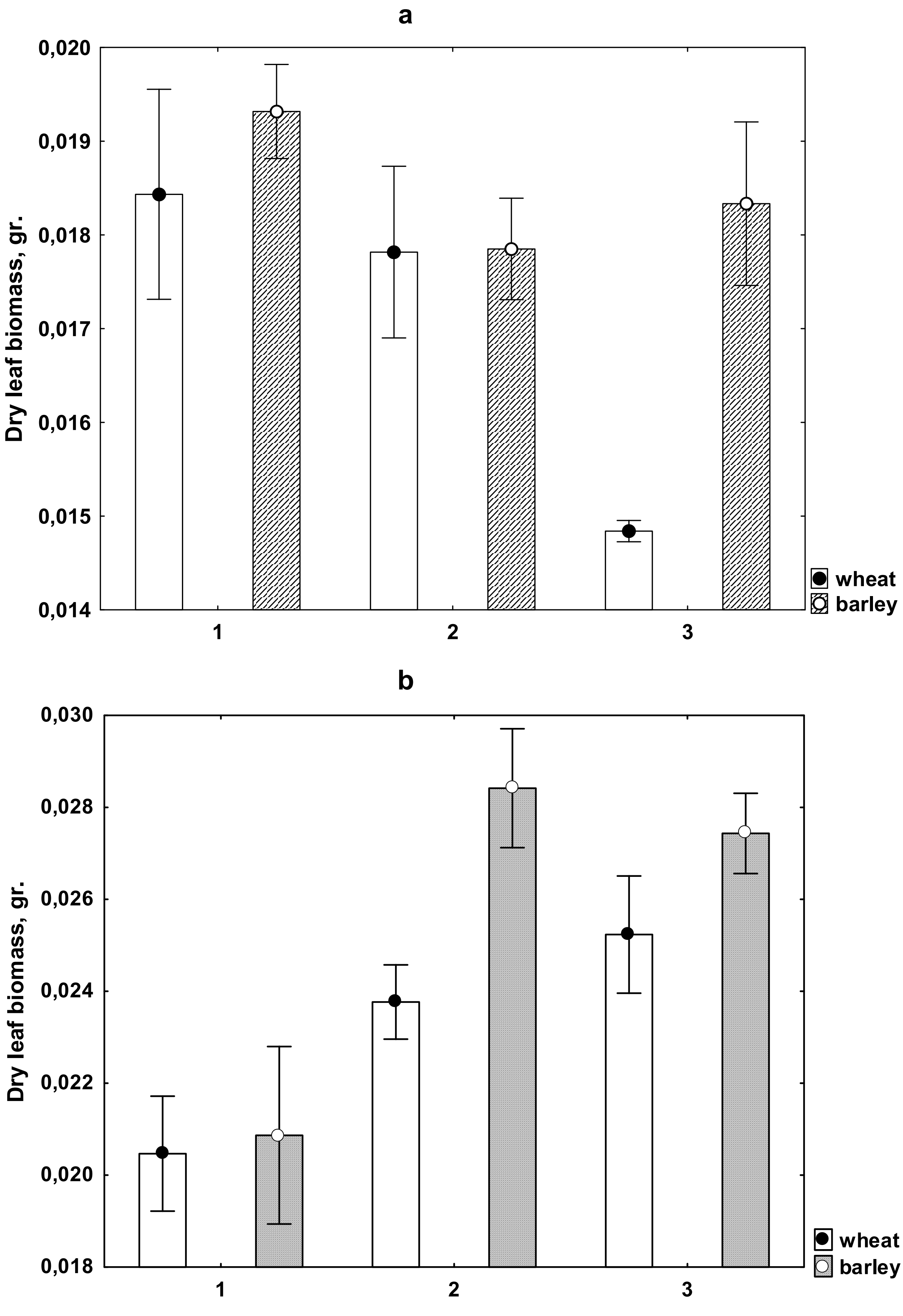

a
0,020
0,019
0,018
0,017
0,016
0,015
0,014
Dry leaf biomass, gr.
1
2
3
wheat
barley
b
0,030
0,028
0,026
0,024
0,022
0,020
0,018
Dry leaf biomass, gr.
1
2
3
wheat
barley

Fig. 3

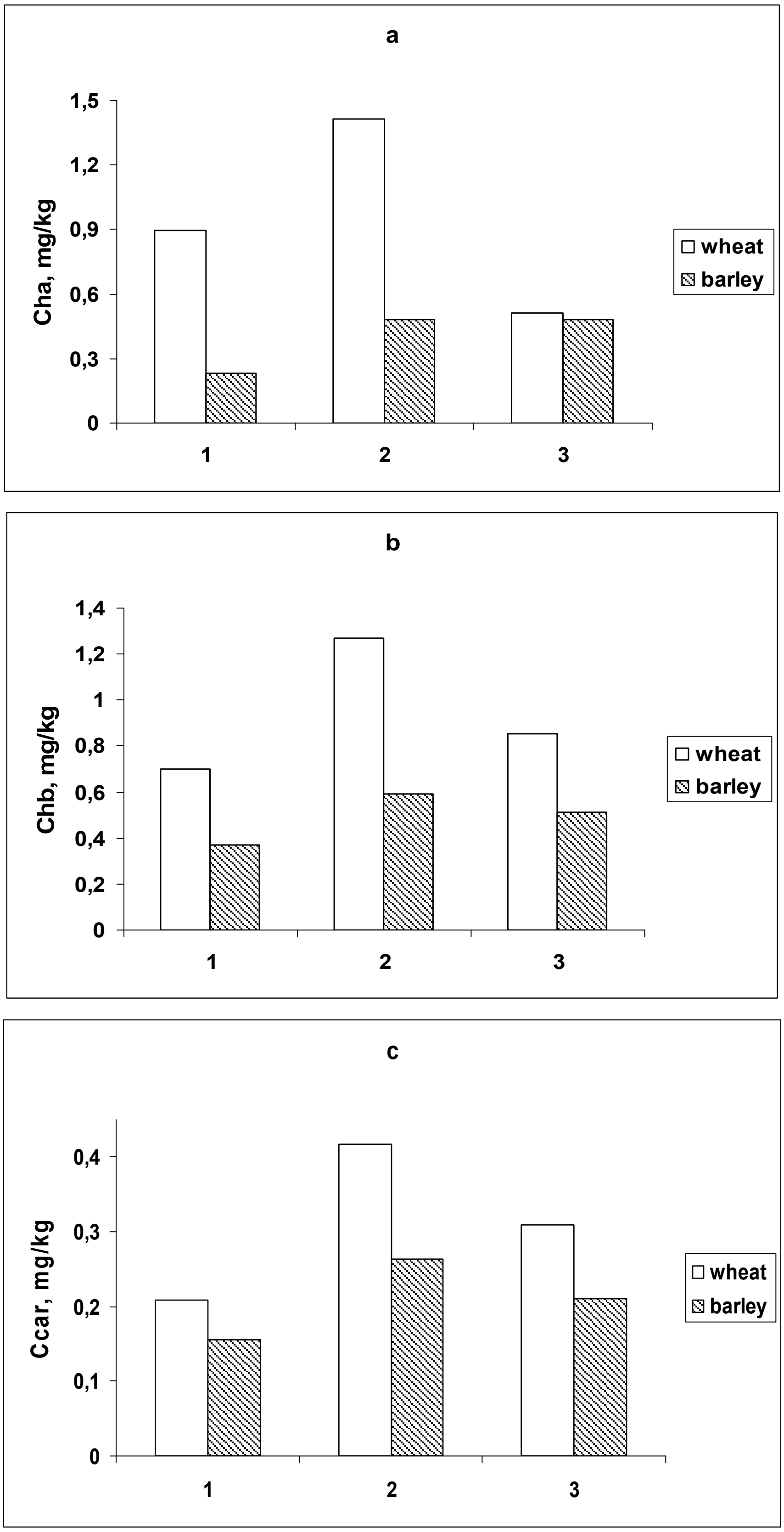

a
Cha, mg/kg
1,5
1,2
0,9
0,6
0,3
0
1
2
3
wheat
barley
b
Chb, mg/kg
1,4
1,2
1
0,8
0,6
0,4
0,2
0
1
2
3
wheat
barley
c
Ccar, mg/kg
0,4
0,3
0,2
0,1
0
1
2
3
wheat
barley

Fig. 4

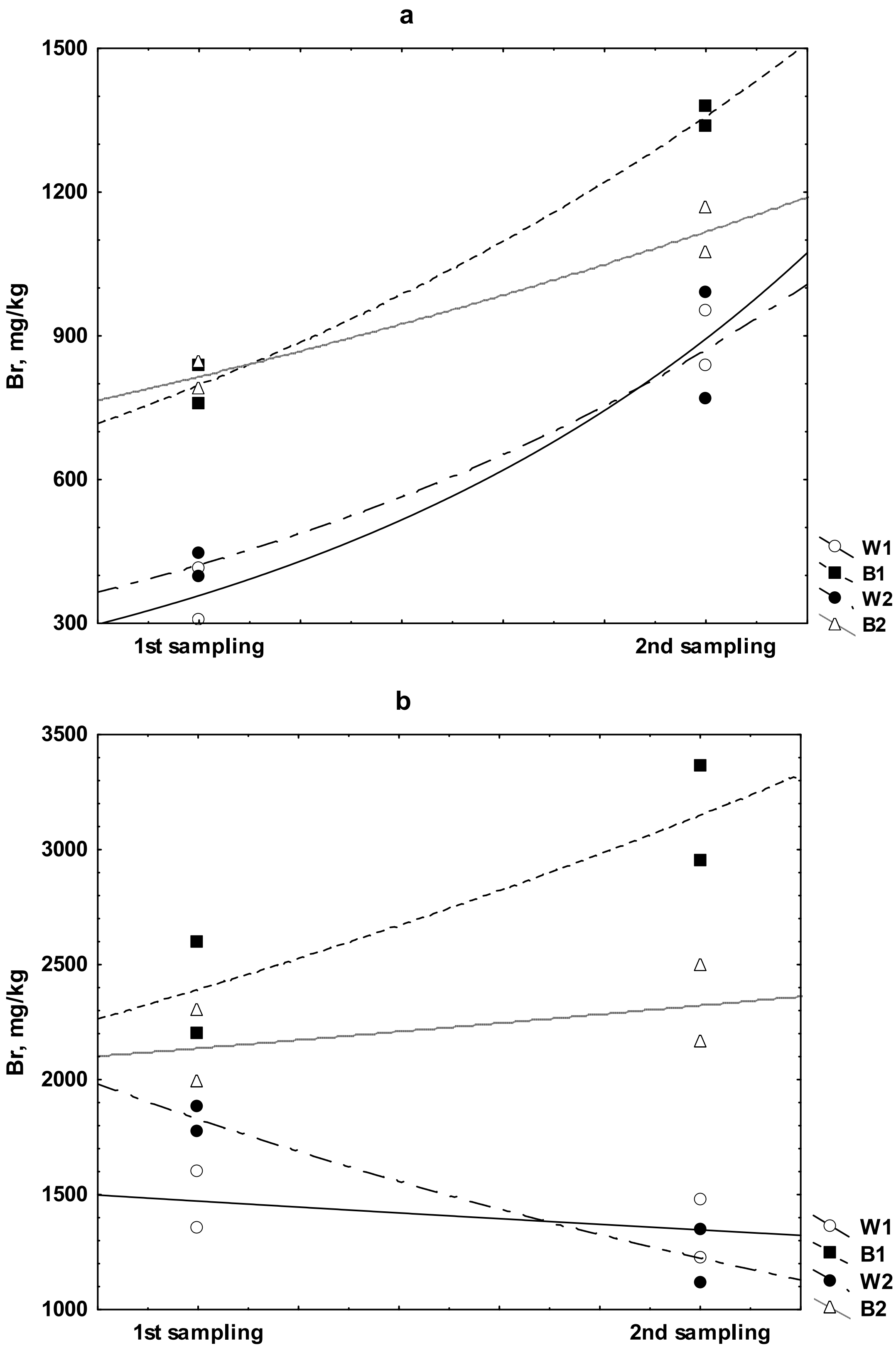
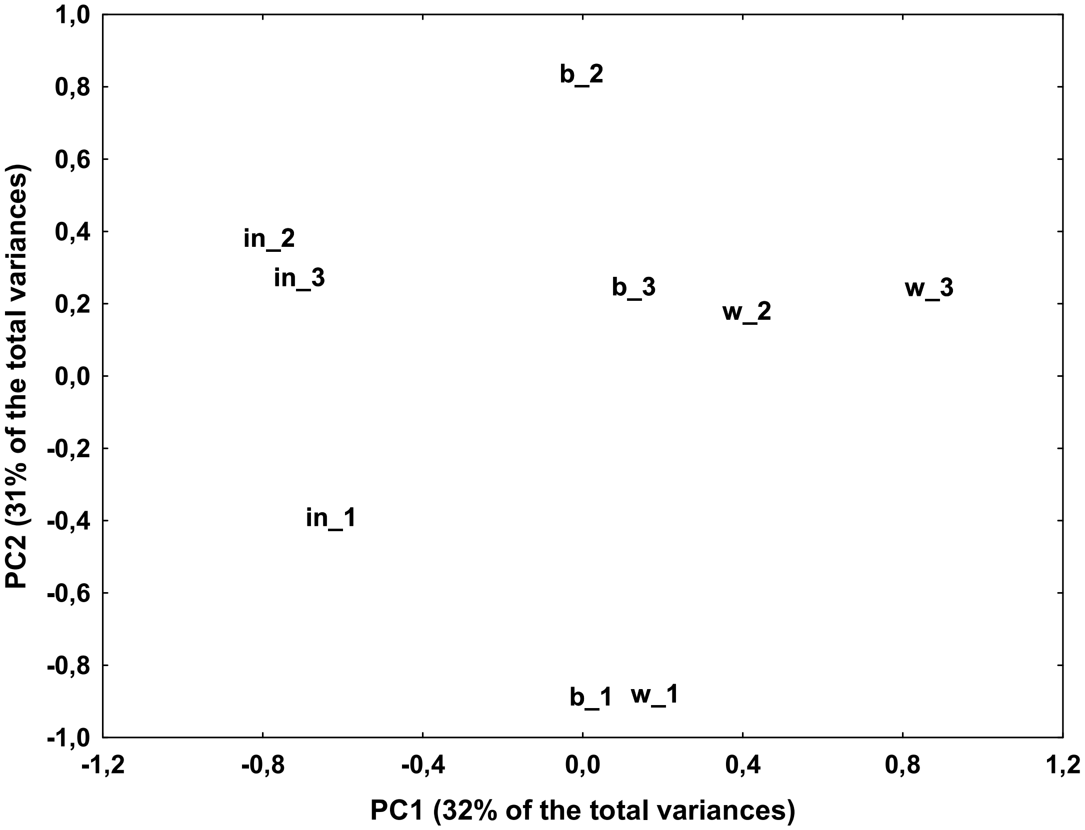
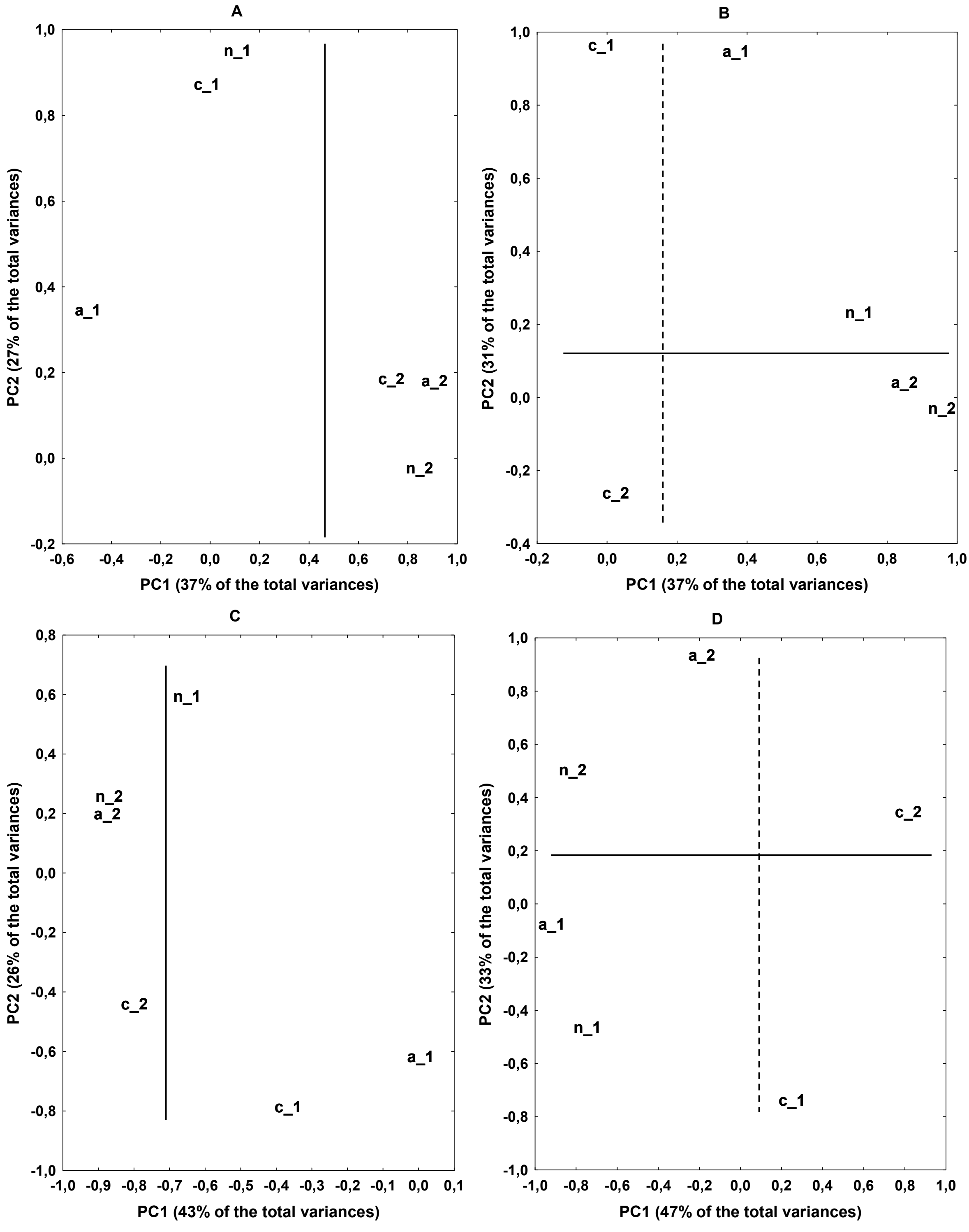

a
1500
1200
900
600
300
Br, mg/kg
1st sampling
2nd sampling
W1
B1
W2
B2
b
3500
3000
2500
2000
1500
1000
Br, mg/kg
1st sampling
2nd sampling
W1
B1
W2
B2

Fig. 5



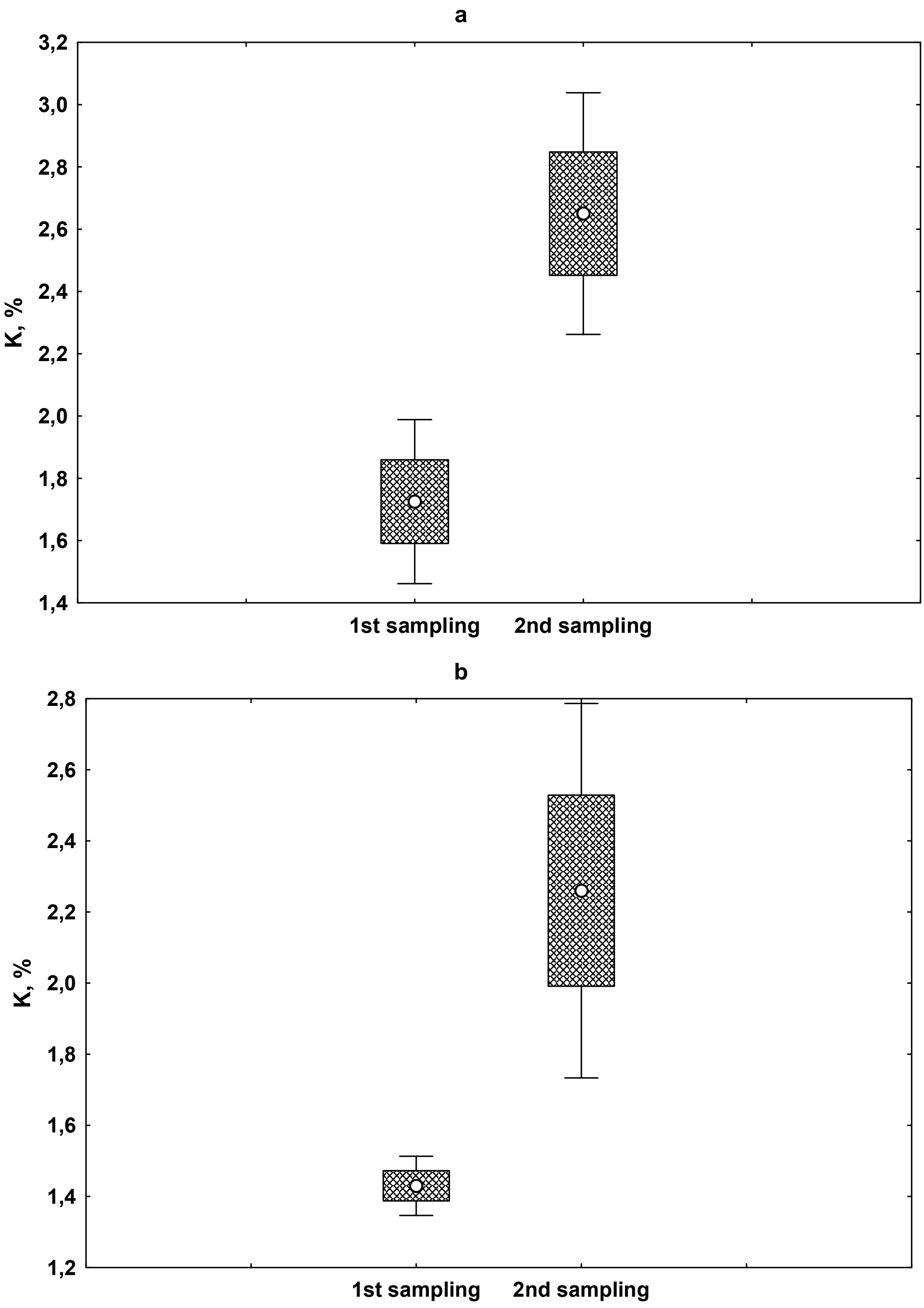
1,0
0,8
0,6
0,4
0,2
0,0
-0,2
-0,4
-0,6
-0,8
-1,0
-1,2
-0,8
-0,4
0,0
0,4
0,8
1,2
PC2 (31% of the total variances)
PC1 (32% of the total variances)
b_2
in_2
in_3
b_3
w_2
w_3
in_1
b_1
w_1

Fig. 6



A
PC2 (27% of the total variances)
PC1 (37% of the total variances)
n_1
c_1
a_1
c_2
a_2
n_2
B
PC2 (31% of the total variances)
PC1 (37% of the total variances)
c_1
a_1
n_1
a_2
n_2
c_2
C
PC2 (26% of the total variances)
PC1 (43% of the total variances)
n_1
n_2
a_2
c_2
a_1
c_1
D
PC2 (33% of the total variances)
PC1 (47% of the total variances)
a_2
n_2
c_2
a_1
n_1
c_1

Fig. 7


a
3,2
3,0
2,8
2,6
2,4
2,2
2,0
1,8
1,6
1,4
K, %
1st sampling
2nd sampling
b
2,8
2,6
2,4
2,2
2,0
1,8
1,6
1,4
1,2
K, %
1st sampling
2nd sampling