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Long-term wildfire effect on nutrient distribution in silver birch (*Betula pendula* Roth) biomass

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Abstract

This study aimed to evaluate the long-term effects of wildfire on nutrient distribution in a silver birch (*Betula pendula* Roth) biomass. Two stands (post-fire and control) of the same age (27 years) were studied in the Cierpiszewo Forest District (central Poland). The stands were located on Brunic Arenosols developed from aeolian sands. The soil and birches were sampled in 10 replicates per stand. The soil samples were taken from depths of 0–10, 10–20, 20–40 and 20–40 cm using a corer. Samples of fine roots, coarse roots, stemwood, stem bark, coarse branches, fine branches and leaves were taken from the trees. The basic soil characteristics were determined using standard procedures. In addition, the carbon (C), nitrogen (N), sulfur (S), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn) contents were analyzed in the soil and biomass samples. The soils were strongly acidic and poor in the studied elements. The nutrient content in the biomass varied strongly among the organs. The most abundant elemental contents were usually in the leaves, followed by the fine roots and fine branches or bark. The lowest nutrient contents occurred in the stemwood. Statistically significant differences were recorded between the post-fire and control stands for some elements. There were higher P, K and Zn contents in most of the biomass fractions in the post-fire stand, as well as Mg and Mn in the roots and stemwood. The control stand had mostly higher contents of N and Ca. The effects of fire on the Fe and Cu accumulations varied among the organs and was not clear for S. Generally, birch showed the highest bioaccumulation intensity for N and the lowest for Fe. Among all the studied nutrients, the bioaccumulation factors were usually the highest in the leaves and the lowest in the stemwood. It can be concluded that fire is an important factor in influencing nutrient management in silver birch stands, even a few decades after its occurrence.

1. Introduction

Wildfire is both a natural and human-induced phenomenon that strongly influences the functioning of terrestrial ecosystems, particularly forests and other associations of permanent vegetation. The effects of fire depend on its severity, duration, and dynamics, and they influence ecosystem structure, and ecological processes and functions (Lobert and Warnatz, 1993; Johnson and Miyanishi, 2001; Adams, 2013). The loss of biodiversity and the simplification of feedbacks between ecosystem components are typical direct effects in areas affected by fire (Syaufina et al., 2018). However, such areas then become specific ecological niches that enable the dispersal of new species of plants and animals. Thus fire constitutes an important factor in ecosystem instability and evolution (Kutiel, 1997; Orgeas and Andersen, 2001; Pyne, 2010).

Wildfires can strongly influence soils, including their morphology (Dziadowiec, 2010), physical properties (DeBano et al., 1998), water repellency (DeBano, 2000), pH (Augusto et al., 1998; Heydari et al., 2012; Chungu et al., 2020; Han et al., 2021), elemental content and form (Knoepp et al., 2008; Verma and Jayakumar, 2012; Schaller et al., 2015; Jonczak et al., 2019), sorptive capacity, soil sorption complex composition (Barrow, 1984), and, in particular, organic-matter stocks and quality (Almendros et al., 1990; Gonet, 2010). Fire effects in soils are most apparent in the ectohumus, the components of which are susceptible to high temperatures. In the mineral topsoil, this effect depends on the soil thermal resistance (Fernandez et al., 2001). The transformation of soil nutrients is a very important aspect of wildfires in terms of ecology, environmental protection and forestry (Torres-Rojas et al., 2020). Due to the high temperatures, reaching 1500°C (Saharjo and Munoz, 2005), the components of the soil organic matter and also some minerals are transformed into gases and ash. Most of the organic carbon (C) and nitrogen (N) volatize into the atmosphere, whereas potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn), among many other elements, constitute the components of ash and are subsequently released into the soil (Grier, 1975). In terms of trace elements, this may result in an environmental hazard. Their accumulation as a result of fire can cause long-term effects due to their potential for increased mobilization (Campos et al., 2016). The transformation of some elements, such as phosphorus (P) and sulfur (S), strongly depends on temperature. Ash constitutes a pool of mineral forms of elements that can significantly increase their bioavailability to plants and microorganisms in a short amount of time (Pereira et al., 2015). However, from the longer perspective, wildfires contribute to nutrient losses from the soil due to leaching (Fisher and Binkley, 2000), erosion (Shakesby et al., 1993; Thomas et al., 1999; Abney et al., 2017) and accelerated mineralization (Schoch and Binkley, 1986).

The effects of wildfire on nutrient uptake by plants has already been the subject of many studies (e.g., Kutiel and Shaviv, 1992; Raison et al., 2009). However, most of these have been focused on short intervals of time following the occurrence of fire. Studies on the long-term effects have been conducted less frequently. Data on the effects of wildfire (both short and long term) on nutrient contents and their distribution in tree biomass are scarce. Meanwhile, this is an important issue because post-fire areas are regenerated (afforestation or spontaneous development) with trees. Soils that have been strongly modified by fire can influence their growth. Moreover, some trees have great potential to accumulate elements in their biomass (Wisłocka et al., 2006). This process is the basis for soil phytoremediation (Grobelak, 2016). In areas affected by fire, this can be used as an effective tool for stabilizing labile forms of elements, which constitute contaminants.

This study aimed to evaluate the long-term effects of wildfire on nutrient (N, P, K, Ca, Mg, S, Fe, Mn, Cu, and Zn) bioaccumulation in silver birch (*Betula pendula* Roth) biomass. Based on data available from the literature, it can be assumed that wildfire can strongly modify certain links in the biogeochemical cycling of elements in forest ecosystems, including their uptake by plants and their accumulation in the biomass, over the long term. Studies on the bioaccumulation of nutrients in vegetation on post-fire stands are not new, but so far they have focused mainly on the short-term effects after the fire. The results presented in this paper extend the knowledge base on the long-term effects of fire. Studies such as this one also have more utilitarian importance because birch is often used for the afforestation of post-fire areas.

2. Material and methods

2.1. Stand characteristics

This study was carried out in the Cierpiszewo Forest District (central Poland). The average annual temperature for this area is 7.7°C, with the lowest values being in January (–2.5°C) and the highest in July (18.2°C) for the years 1871–2010. The mean annual sum of precipitation for this period ranged from 304.1 to 844.0 mm (Pospieszyńska and Przybylak, 2013). The study was performed on two stands of silver birch (*Betula pendula*) aged 27 years, comprising a post-fire area (52.944053 N, 18.458913 E) and a control stand (52.96824 N, 18.409505 E). Both stands represented nutrient-poor habitats and were located on the same complex of Brunic Arenosols (IUSS Working Group WRB, 2015) developed from aeolian sands. The wildfire that affected the first stand occurred in 1992 was moderately intensive (ground and top), covering 2,868 ha of forest, in which the dominant species was pine (*Pinus sylvestris L.*). Various tree species, including silver birch, were used for the afforestation of the burned area. The major characteristics of the stands are included in Table 1.

2.2. Soil sampling and analysis

The soil sampling was performed in June 2021. Ten average trees per stand were chosen for these purposes. One soil core was taken from under each tree approximately 1 m from the stem. The soil samples were collected from depths of 0–10 cm, 10–20 cm, 20–40 cm and 40–80 cm. A total of 40 soil samples were collected from each stand. In addition, one core was taken from the central part of each stand for the purposes of soil description and classification. The soil samples were air-dried and sieved through at 2.0-mm sieve to remove the gravel-sized particles. Then part of each sample was milled into powder for the purposes of chemical analysis. The soil analysis included determination of the particle size distribution using the Polish Soil Science Society's mixed pipette and sieve method (Polskie Towarzystwo Gleboznawcze [PTG], 2009) and classification of textural fractions and groups, as well as the pH, derived potentiometrically in a suspension with water at a soil:water ratio of 1:2.5, the total C, N and S contents by dry combustion (Vario MacroCube, Elementar, Germany) and the P, K, Ca, Mg, Fe, Mn, Cu, and Zn using inductively-coupled plasma optical emission spectrometry (ICP–OES, Avio 200, Perkin Elmer, United States) after sample digestion in aqua regia (microwave digestion system, ETHOS UP, Milestone Analytical, Italy).

2.3. Birch biomass sampling and analysis

The following biomass fractions were collected from the birch trees: second-order roots (RII); first-order roots (RI); stemwood (S); and stem bark (B) from a height of approximately 130 cm; first-order branches (BrI); second-order branches (BrII); and leaves (L) from the central part of the crown. The biomass was dried at 65°C and milled into powder. The analysis included the C, N, and S contents by dry combustion, whereas contents of P, K, Ca, Mg, Fe, Mn, Cu, ,and Zn being determined using the ICP–OES after sample digestion in 65% nitric acid (ETHOS UP microwave digestion). For quality control of the analyses, MERCK reference materials were used.

Table 1
Characteristics of the studied silver birch stands

	Control stand	Post-fire stand
Age (years)	27	27
Density (pcs ha^{-1})	2600	2960
Height (m)	10	12
Diameter at breast height (cm)	11.1 (±*1.4*)*	9.9 (±*1.9*)*

* Standard deviation

2.4. Statistical analysis and calculation

The statistical analyses included determining the mean values of the soil and biomass characteristics and their standard deviations. The Mann–Whitney U test was applied to analyze the differences between the groups of samples. The bioaccumulation factors (BFs) in the birch biomass were calculated for the studied elements, according to the formula: BF = content of element in biomass fraction/content of element in soil. All statistical analyses were performed using Past software.

3. Results

3.1. Basic characteristics of the soils

The Brunic Arenosols were sandy in texture (Table 2) and characterized by a strongly acidic reaction, with the pH(H_2O) ranging from 3.6 to 4.5 in the control stand and from 3.7 to 4.0 in the post-fire stand, considering all the layers. There was a slight decreasing tendency in the values with depth (Figure 1). The soils were typically poor in organic matter. The highest total organic C (TOC) content was noted in the 0–10-cm topsoil (6.7–49.6 g kg^{-1} in the post-fire stand and 9.2–31.2 g kg^{-1} in the control stand). In the deeper parts of soil profiles, the TOC contents were considerably decreased, reaching minimum values at depths of 40–80 cm (Figure 1).

Table 2
Particle size distribution of the studied soils, based on the Polish Soil Science Society classification (PTG, 2009)

	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural group
Control stand					
A	0–13	89.8	8.0	2.2	sand
Bv	13–45	94.7	3.7	1.6	sand
BvC	45–60	98.1	1.0	0.9	sand
C	60–100	98.0	1.1	0.9	sand
Post-fire stand					
A	0–9	93.5	5.4	1.1	sand
Aes	9–16	96.2	2.5	1.3	sand
Bv	16–35	98.6	0.5	0.9	sand
BvC	35–50	99.4	0.1	0.5	sand
C	50–100	99.2	0.2	0.6	sand

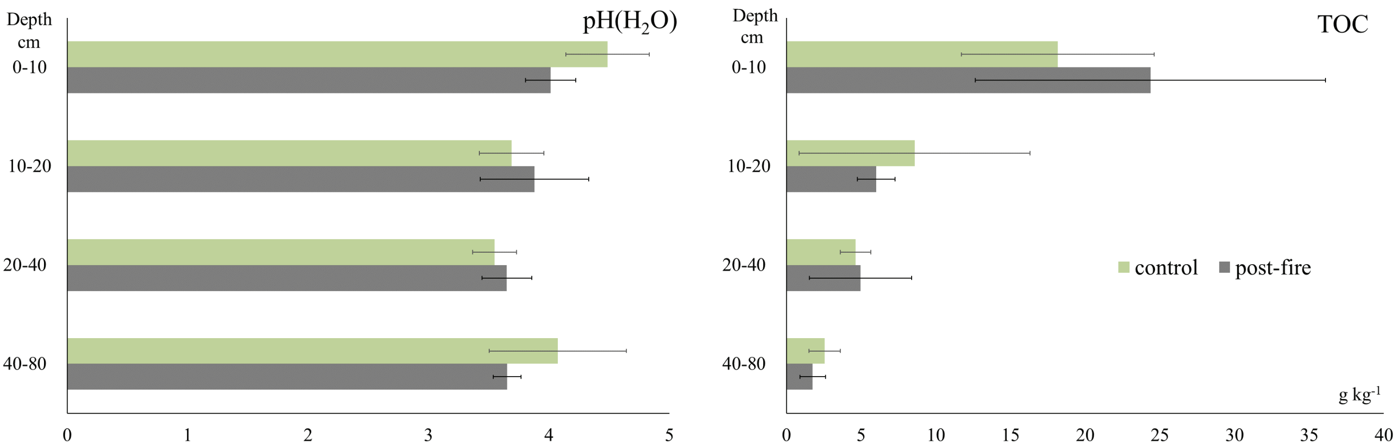


Fig. 1. pH and TOC content in the studied soils

3.2. Nutrients content of the soils

The nutrient content in the soils varied depending on the stand and soil depth. Based on the weighted mean contents in the 0–80 cm soil layer, the elements in the post-fire stand occurred in the order Fe>K>Ca>Mg>N>P>Mn>S>Zn>Cu, whereas, in the control stand, the order was Fe>K>Ca>N>Mg>P>S>Mn>Zn>Cu (Table 3). The soils were generally poor in nutrients, with the observed concentrations being typical of sandy soils on inland dunes (Brożek and Zwydak, 2010). The low Cu, Zn and, Mn contents, in relation to the geochemical background (Pasieczna,

Table 3
Soil mean ± SD elemental contents (mg kg^{-1}) in the control and post-fire stands

	Control stand	Post-fire stand
N	345.2 (±*86.0*)*	356.5 (±*113.3*)*
P[a]	257.2 (±*30.5*)*	215.7 (±*37.4*)*
K[a]	1849.0 (±*181.51*)*	1695.9 (±*106.2*)*
Ca[a]	952.5 (±*88.4*)*	647.0 (±*80.7*)*
Mg[a]	741.1 (±*105.2*)*	315.4 (±*58.0*)*
S[a]	69.7 (±*15.9*)*	81.5 (±*9.9*)*
Fe[a]	5077.3 (±*681.9*)*	2901.5 (±*464.4*)*
Mn[a]	162.0 (±*48.9*)*	71.7 (±*29.0*)*
Cu[a]	0.5 (±*0.2*)*	1.0 (±*0.6*)*
Zn[a]	29.5 (±*10.3*)*	11.3 (±*1.8*)*

[a] Statistically significant at $p<0.05$ differences between the stands, Mann–Whitney U test.
* Standard deviation

2003) confirmed the low environmental contamination with those elements. The studied elements showed various depth tendencies (Figure 2). The N, S, Mn and Cu contents considerably decreased with depth, whereas the P, K, Ca, Mg, Fe, and Zn contents were relatively stable. The average content of elements usually differed between the stands, reaching higher values in the control stand. An opposite tendency was apparent for only Cu and S, as well as for N, Ca and Mg in the 0–10-cm topsoil. These differences between the stands were statistically significant in many cases, as shown in Figure 2.

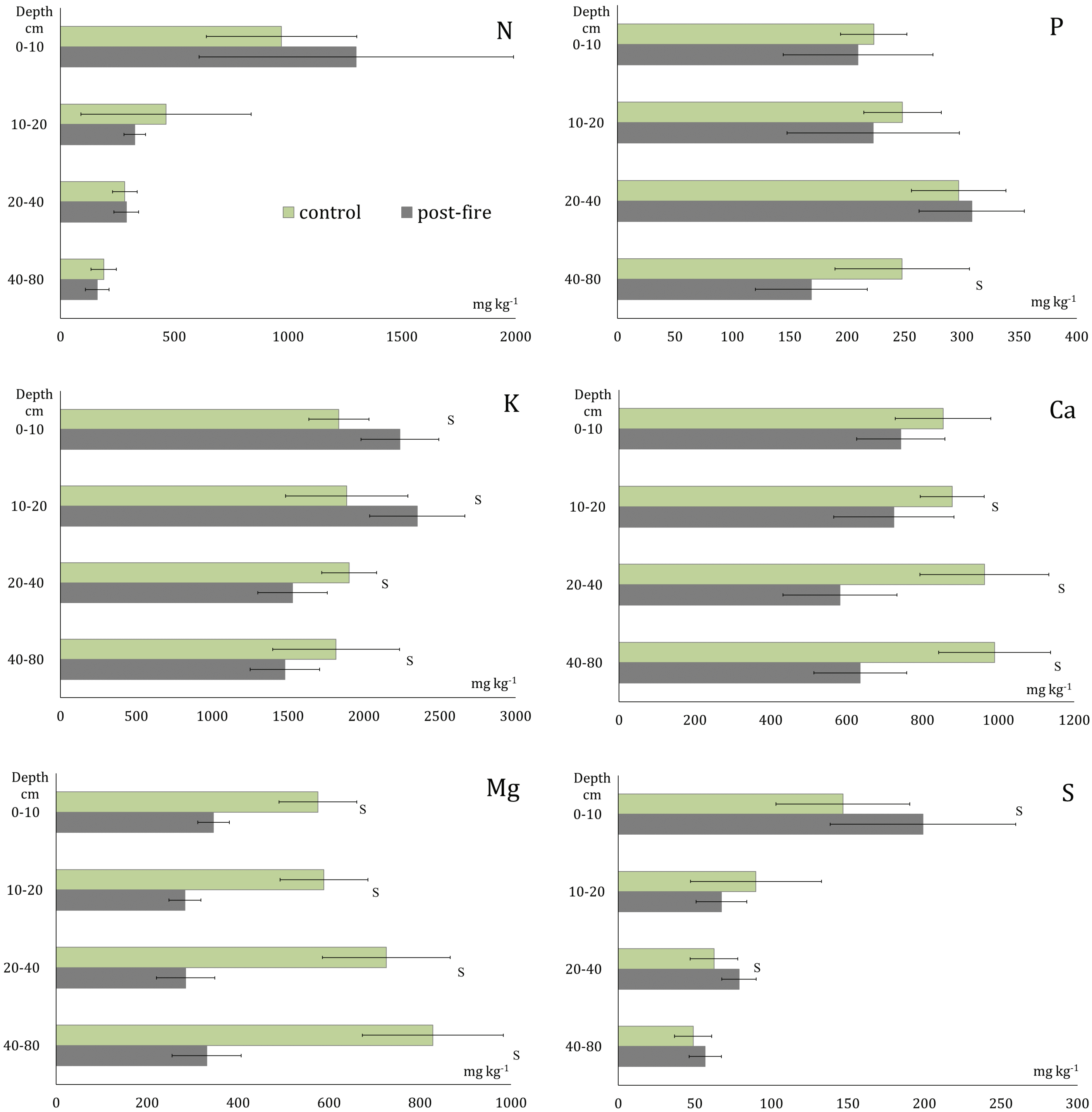


Fig. 2. Mean ± SD elemental content in the soils at depths of 0–10, 10–20, 20–40 and 40–80 cm (S—statistically significant at *p<0.05* differences between the stands, Mann–Whitney U test)

3.3. Nutrient content in the birch biomass

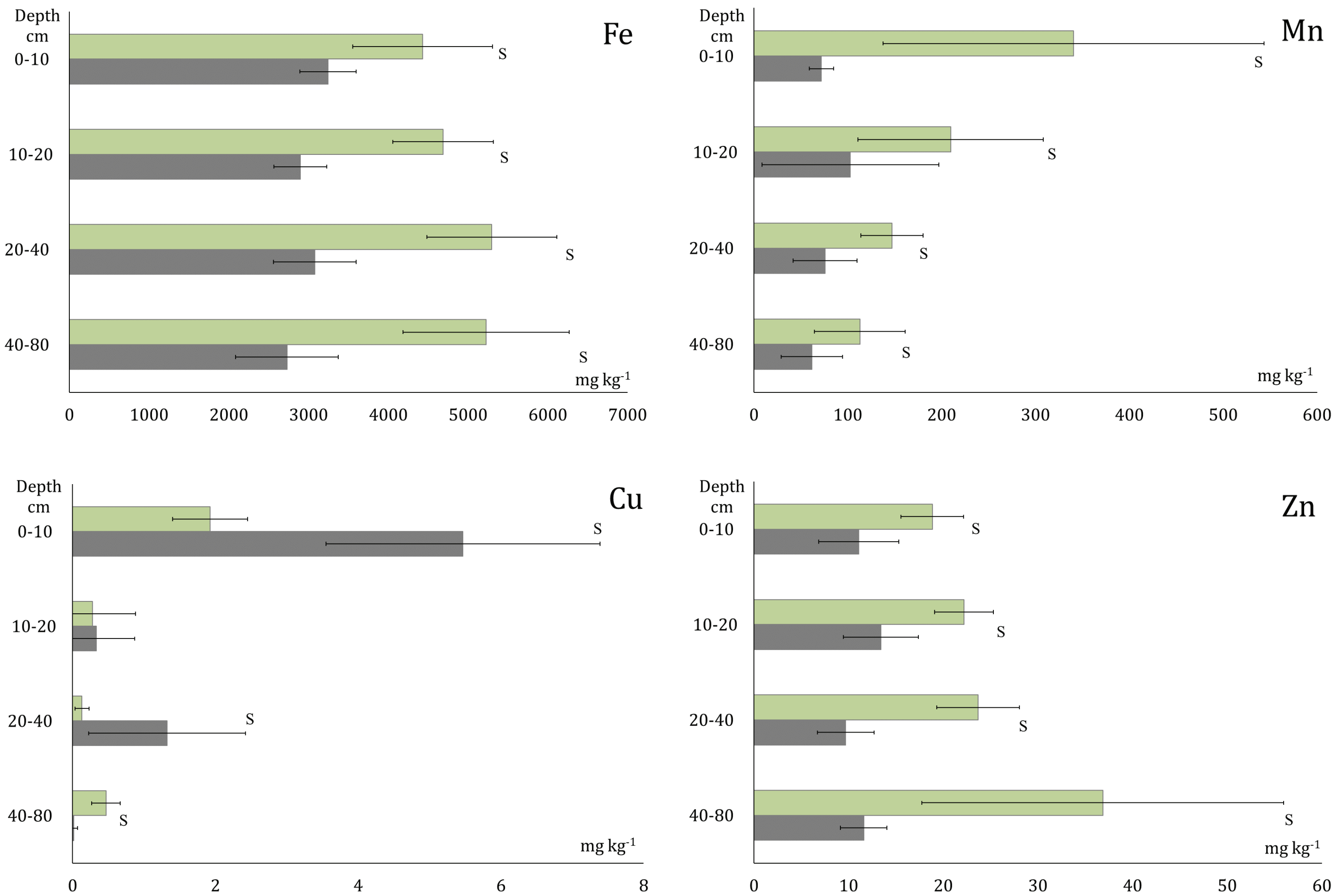
The N content in the birch biomass in the post-fire stand ranged from 1,480.5 ±337.0 mg kg^{-1} in the stemwood to 21,726.4 ±1,374.3 mg kg^{-1} in the leaves and from 2,304.4 ±585.0 to 23,752.2 ±2,527.9 mg kg^{-1}, respectively, in the control stand. The average elemental content in the biomass did not exceed 8,000 mg kg^{-1}, excluding the leaves. In terms of N content, the organs showed similar tendencies in both stands: L>RII>BrII>B>RI>BrI>S in the post-fire stand and L>RII>BrII>RI>B>BrI>S in the control. Differences between the biomass fractions in the stands were not large and were statistically insignificant, except for the fine roots and stemwood (Figure 3).

The opposite tendency was noted for P, for which differences between the stands were statistically significant, especially in the RII, RI and L biomass fractions. In the post-fire stand, the P content ranged from 94.0 ±12.4 mg kg^{-1} in the S fraction to 2,268.3 ±334.1 mg kg^{-1} in the L fraction, whereas in the control stand, it ranged from 1,329.3 ±130.6 mg kg^{-1} to 57.3 ±4.9 mg kg^{-1} in the S and L biomass fractions, respectively. The distribution of P in the biomass in both stands was very similar, with a difference in the roots, and with the post-fire stand RI fraction having a higher P content than the control stand, relative to the RII fraction (Figure 3).

Differences between the stands in terms of the K content were statistically significant, except for the bark. The clearest difference occurred in the leaves, which contained higher concentrations K in the post-fire stand (6,833.4 ±1,395.1 mg kg^{-1}) compared to the control (5,462.3 ±284.0 mg kg^{-1}). The lowest K content was noted in the stemwood, at 573.3 ±187.6 mg kg^{-1} in the post-fire stand and 468.0 ±508.8 mg kg^{-1} in the control.

The Ca content in the birch biomass in the control stand ranged from 1,494.6 ±1,062.3 mg kg^{-1} in the stemwood to 9,643.5 ±3,634.2 mg kg^{-1} in the bark, and from 1,873.8 ±987.6 to 7,887.4 ±1,079.9 mg kg^{-1} in the same fractions in the post-fire stand. The distribution of Ca in the birch organs showed some differences between the stands. In the control stand, the order was B>L>BrI>RII>BrII>RI>S, whereas in the post-fire stand, it was L>B>RII>BrII>BrI>RI>S. These differences were statistically significant only for the RII, B and BrI biomass fractions.

The average Mg contents in the birches reached a maximum of 650 mg kg^{-1}, excluding the leaves, with those values being comparable in both stands, fluctuating around 2,000 mg kg^{-1}. The distribution of Mg in the biomass varied among the stands,



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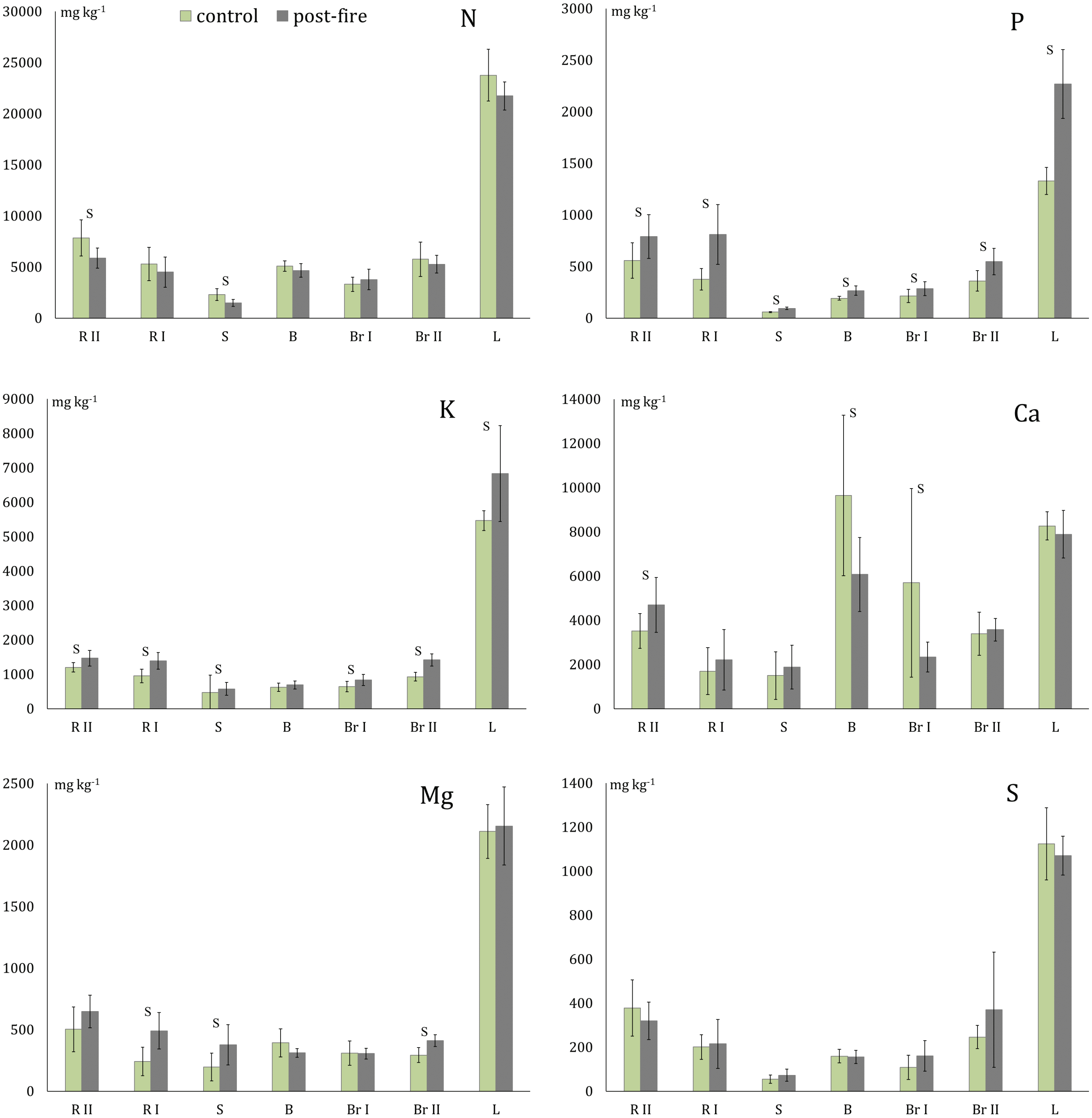

Fig. 3. Mean ± SD elemental content in birch biomass (S—statistically significant at *p<0.05* differences between the stands, Mann–Whitney U test)

and occurred as L>RII>B>BrI>BrII>RI>S in the control stand and L>RII>RI>BrII>S>B>BrI in the post-fire stand. Differences in the Mg content between the stands were generally low and statistically insignificant, in most cases.

The S content did not differ significantly between the stands, considering all the organs. The S content in both the control and post-fire stands was highest in the leaves, amounting to 1,123.4 ±164.2 and 1,069.8 ±88.3 mg kg^{-1}, respectively, while the lowest was in the stemwood, at: 54.7 ±18.5 and 72.4 ±28.2 mg kg^{-1}, respectively.

In contrast to the rest of the elements, Fe had the highest content in the fine roots in both stands, amounting to 274.4 ±95.9 mg kg^{-1} in the control stand and 648.4 ±270.8 mg kg^{-1} in the post-fire stand. In the rest of the organs, the Fe concentrations were low compared to the roots, never exceeding 100 mg kg^{-1}. Differences in the distribution of Fe in the birch organs were observed

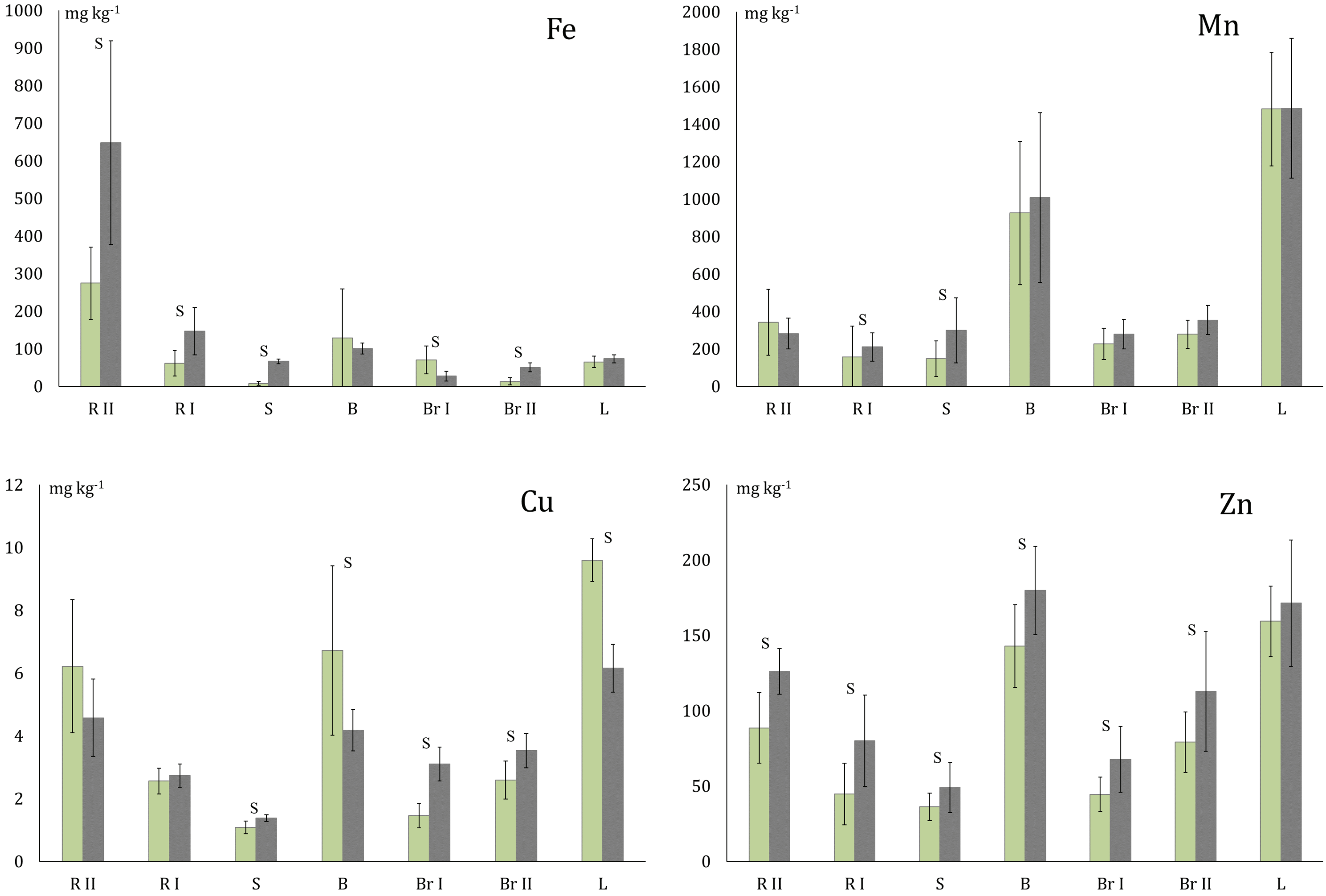

Fig. 3, continue

between the stands. In the control stand, the relative contents were RII>B>BrI>L>RI>BrII>S, whereas in the post-fire stand they were RII>RI>B>L>S>BRII>BrI. Statistically significant differences were observed in most parts of the biomass, excluding the bark and leaves.

In terms of Mn, the differences in the birch biomass between the stands were less and only statistically significant in the coarse roots and stemwood. In both stands, the highest elemental content was noted in the leaves (1,480.5 ±303.4 mg kg^{-1} in the control stand and 1484.0 ±373.2 mg kg^{-1} in the post-fire stand), while the lowest was in the stemwood (148.5 ±95.0 mg kg^{-1}) in the control stand and in the coarse roots (210.4 ±75.2 mg kg^{-1}) in the post-fire stand. As a result of fire, there were several changes in the distribution of the elements in the biomass. In the control stand, the contents were arranged in the sequence L>B>RII>BrII>BrI>RI>S, and in the post-fire stand L>B>RII>S>RII>BrI>RI.

The Cu content in the birch biomass in the post-fire stand ranged from 1.4 ±0.1 mg kg^{-1} in the stemwood to 6.2 ±0.8 mg kg^{-1} in the leaves, and from 1.1 ±0.2 to 9.6 ±0.7 mg kg^{-1}, respectively, in the control stand. The distribution of Cu in the control stand formed the order L>B>RII>BrII>RI>BrI>S, whereas in the post-fire stand, it was L>RII>B>BrII>BrI>RI>S. In most of the birch organs, the differences between the stands were large and statistically significant, except for in the fine and coarse roots.

In terms of the Zn content, the organs showed very similar tendencies in both stands. The highest values in the post-fire stand were recorded in the bark (179.9 ±29.4 mg kg^{-1}), and in the leaves in the control (159.4 ±23.4 mg kg^{-1}). In both stands, the lowest accumulation of Zn was in the stemwood, at 49.1 ±16.7 mg kg^{-1} in the post-fire stand and at 36.3 ±9.1 mg kg^{-1} in the control. A statistical comparison of the Zn content between the stands showed significant differences in all the biomass fractions, except for the leaves.

3.4. Bioaccumulation factors

The intensity of elemental accumulation in the silver birch biomass was evaluated based on the BF (Figure 4). The elements in the different birch biomass fractions occurred in various orders; these details are provided in Table 4. The results show that the leaves had the highest bioaccumulation potential, with respect to the studied elements, whereas stemwood had the lowest. The highest BF was N in the leaves (33.01 ±36.95 in the control and 65.98 ±19.01 in the post-fire stand), followed by Mn (9.67 ±2.91 and 23.17 ±9.93, respectively), Cu (19.41 ±6.28 and 7.11 ±3.07), and Zn (5.87 ±1.69 and 15.81 ±5.54. In addition, Ca (up to 10.21 ±3.96 in the control and 12.44 ±2.77 in the post-fire stand) and S (up to 7.41 ±8.27 and 13.32 ±2.02, respectively) were

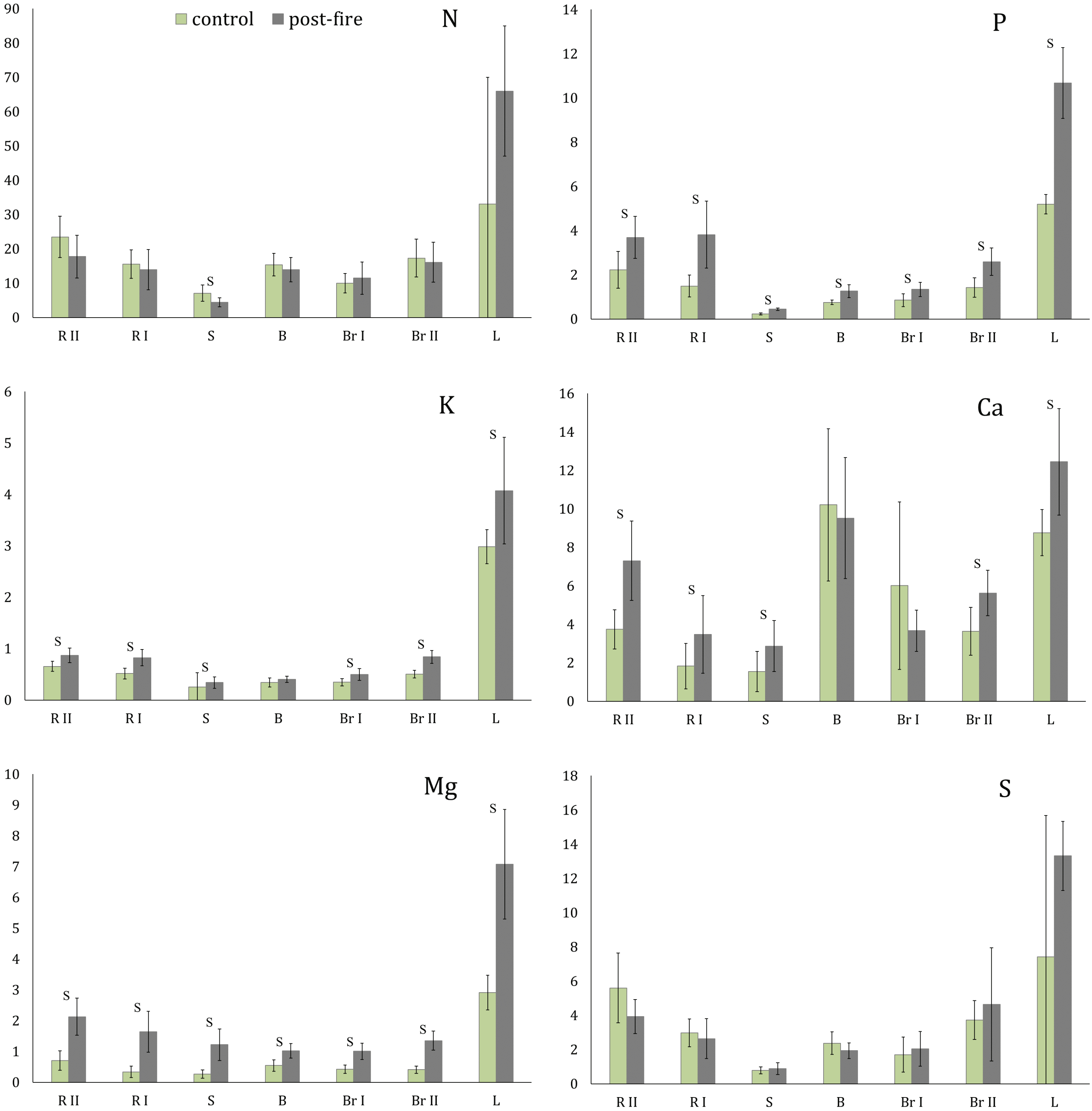

Fig. 4. Mean ± SD of bioaccumulation factors of the studied elements (S—statistically significant at *p<0.05* differences between the stands, Mann–Whitney U test)

strongly accumulated in the majority of the biomass fractions. Then, P (up to 5.19 ±0.44 in the control and 10.67 ±1.60 in the post-fire stand), Mg (up to 2.91 ±0.56 and 7.08 ±1.78, respectively), and K (up to 2.98 ±0.33 and 4.07 ±1.04) were strongly accumulated in the leaves, considerably accumulated in the roots and poorly accumulated in the remaining biomass fractions. The lowest BF was typical for Fe (from 0.002 ±0.001 to 0.013 ±0.003 in the control and 0.01 ±0.01 to 0.22 ±0.08 in the post-fire stand). The statistical significances of the differences between the control and post-fire stands were dependent on the element. Greater differences were generally noted for the micronutrients as opposed to the macronutrients.

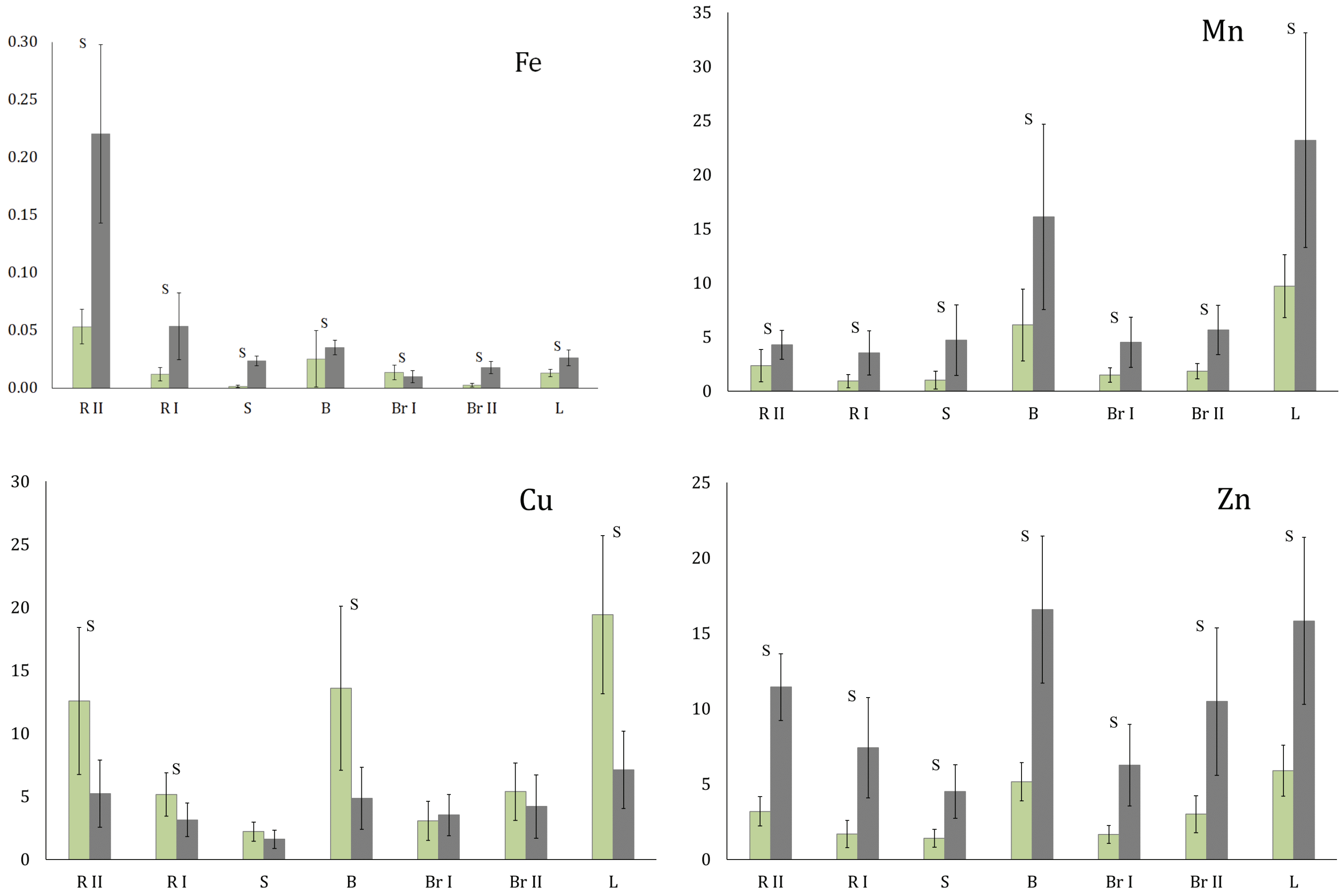

Fig. 4, continue

Table 4
Order of bioaccumulation factor in a silver birch biomass in the control and post-fire stands

Elements	Control stand	Post-fire stand
N	L>RII>BrII>RI>B>BrI>S	L>RII>BrII>B>RI>BrI>S
P	L>RII>RI>BrII>BrI>B>S	L>RI>RII>BrII>BrI>B>S
K	L>RII>RI>BrII>BrI>B>S	L>RII>BrII>RI>BrI>B>S
Ca	B>L>BrI>RII>BrII>RI>S	L>B>RII>BrII>BrI>RI>S
Mg	L>RII>B>BrI>BrII>RI>S	L>RII>RI>BrII>S>B>BrI
S	L>RII>BrII>RI>B>BrI>S	L>BrII>RII>RI>BrI>B>S
Fe	RII>B>BrI>L>RI>BrII>S	RII>RI>B>L>S>BrII>BrI
Mn	L>B>RII>BrII>BrI>S>RI	L>B>BrII>S>BrI>RII>RI
Cu	L>B>RII>BrI>RI>BrI>S	L>RII>B>BrII>BrI>RI>S
Zn	L>B>RII>BrII>RI>BrI>S	B>L>RII>BrII>RI>BrI>S

RII – second-order roots; RI – first-order roots; S – stemwood; B – bark; BrI – first-order branches; BrII – second-order branches; L – leaves.

4. Discussion

Several previous studies have shown that the chemical composition of the tree biomass varies strongly among the organs/fractions, reflecting their physiological functions and processes. The lignified parts, such as stemwood, branches, and roots, are poor in nutrients, whereas the leaves, seeds, and flowers are nutrient-rich in many cases (Finér, 1989; Palviainen and Finér, 2011; Ge, 2015). This observation has been confirmed in this study.

The studies on nutrients distribution in a silver birch biomass have been poorly reported. Gawęda et al. (2014), in a detailed study on young silver birch stands growing on post-arable soils, examined the chemical composition of the biomass and its stock per area unit, estimating that major pools of N, P, and K were allocated to the leaves (372.70 kg ha^{-1}, 38.65 kg ha^{-1}, and 121.57 kg ha^{-1}, respectively), despite their low contribution to the total biomass of the stands. The results of this study support that finding. However, Gawęda et al. (2014) also reported considerable amounts of elements in the stemwood and branches, with low contents in the bark. These findings are not contradictory to the results presented in this paper, rather different units of measurement were used in the studies (mg kg^{-1} in this work and kg ha^{-1} in the cited paper). Also, in the case of S, Ca, and Mg major pools were allocated to the foliage, according to Gawęda et al. (2014). High concentrations of N, P, K, Ca, Mg, Fe, Mn, Cu and Zn in silver birch leaves were reported by Hytönen et al. (2014), who recorded 26,210.0, 2,390.0, 8,010.0, 5,700.0, 1,960.0, 46.0, 1,393.0, 4.5, and 87.0 mg kg^{-1} of those elements, respectively. These results are generally very similar to those obtained in this study. By contrast, Novák et al. (2017) reported contents of N, P, and K in a nutrient-poor stand on Gleysols that were two times lower than the values recorded herein.

The nutrient contents in leaves, as a major component of the plant litterfall in temperate forests, is very important for the functioning of forest ecosystems. It is particularly important in nutrient-poor stands. The chemical compositions of leaves that fall in the autumn and fresh leaves collected from the crowns during the late spring and summer usually differ significantly (Jonczak, 2011; Jonczak et al., 2016). This difference is due to the retranslocation and/or relative accumulation of certain elements before the leaves fall. In addition, leaf litterfall is poorer in the deficient elements (particularly N and P) than fresh leaves. K is usually less intensively retranslocated due to its higher bioavailability in forest soils, whereas Ca and Mg are not retranslocated. Micronutrients, including Mn, Cu, and Zn, occur in soil in low amounts. The studied soils were very poor in those elements (Figure 2). This is typical of sandy soils in uncontaminated areas (Kabata-Pendias and Pendias, 1999; Kalembasa et al., 2006, Brożek and Zwydak, 2010). The low contents of the elements in the soils were reflected in their low contents in the birch biomass in both stands (Figure 3). The BF (or bioconcentration factor) is commonly used as a measure of the intensity of the accumulation of various substances in fresh biomass. The intensity of that process varies strongly among elements and plant species (Parzych et al., 2017; Parzych and Jonczak, 2018; Sut-Lohmann et al., 2020a), and it is also controlled by a complex of site conditions, particularly the form of the elements and the soil pH (Maiti and Jaiswal, 2008; Zeng et al., 2011; Sharma and Pandey, 2014; Gomes et al., 2016). Birch is considered to be a hyperaccumulator of Zn (Gallagher et al., 2008; Dmuchowski et al., 2014). However, most recent studies have also shown large bioaccumulations of cadmium (Cd), Cu, and Mn (Desai et al., 2019). The high potential of birch to accumulate the above-mentioned elements was also confirmed by the present study (Figure 4). These elements were especially strongly accumulated in the leaves and bark. Due to their great susceptibility to trace-element accumulation from the soil and air, leaves/needles and bark have commonly been used as bioindicators of environmental contamination (Sut-Lohmann et al., 2020b; Jonczak et al., 2021). Silver birch has also been used in this context (Butkus and Baltrënaitë, 2007; Ernst and Nelissen, 2008; Supuka et al., 2008; Dadea et al., 2016; Mleczek et al., 2017).

The obtained results indicate that the fire from 30 years ago may have had some effect on the content of some of the elements in the soil, which may also be reflected in the birch biomass. The most significant differences in macronutrient concentrations in the biomass were found in P and K (Figure 3). Their total soil pools were not reduced (Figure 2), which is probably the result of the high threshold temperature at which the volatilization of P and K occurs – that is, above 774°C (DeBano, 1998). The P concentrations in the studied soils were comparable to those obtained by Jonczak et al. (2019) in Brunic Arenosols 21 years after the occurrence of fire. The higher biomass content of K in the post-fire stand is probably strictly related to its higher concentration in the soil. In the case of P, the intensified uptake by the birches may have resulted from an increase in its bioavailability through its conversion to orthophosphate, a form easily available to plants. In addition, the reduced amount of organic matter that often occurs following fire may have contributed to the release of these elements and an increase their uptake (DeBano, 1991). The available literature on the effects of fires on elements, in terms of their bioaccumulation in plants, is sparse and is based on short-term effects. For instance, Kikamägi et al. (2013) conducted a study on the changes in elemental content in silver birch leaves under the effect of the addition of wood ash in peatlands in Estonia. The results showed no effect on the P and K concentrations. Khanna et al. (1994) indicated that most of the K in ash occurs in a water-soluble form, while P is released into solution only in the presence of protons. This may explain their increased content in the biomass in the post-fire stand in this study. Also, a study on changes in the elemental content in the biomass of savanna vegetation after fire in Congo by Laclau et al. (2002) indicated increased P and K concentrations. Kutiel and Naveh (1987) performed an experiment using soils from post-fire pine forest stands to determine changes in the nutrient content of wheat and clover biomass. They found the levels of P and K in the plants to be significantly increased in the post-fire soils compared to the control. The findings of these authors were supported by the results in this paper. However, in another study, DeBano and Conrad (1978) indicated a significant decrease in the nutrient content of the plant biomass after fire.

Negative changes in the Ca and Mg contents in the soils affected by wildfire were very apparent in this study (Figure. 2).

Despite the relatively low sensitivity of those elements to heating (the threshold temperature for Ca is 1,484°C and for Mg 1,107°C), their loss may be a consequence of the erosion of ash and topsoil, which particularly intensely affects elements that are not lost by oxidation or volatilization (Raison et al., 2009). The Ca and Mg contents in the biomass did not show any clear indications that they were affected by fire (Figure 3). In some of the biomass fractions, a decrease in Ca content was noted, although Mg slightly increased after the fire. The variable results reported herein regarding these macronutrients have also been reflected in the works of other authors. Laclau et al. (2002) obtained significantly higher Ca and Mg contents in the aboveground biomass one year after fire, while the concentrations in the roots were at similar levels. In addition, a study by Kutiel and Naveh (1987) highlighted a significant increase in elemental concentrations in the biomass after fire, suggesting consistency with the findings of the present study with respect to the increase in Mg in the biomass after fire. Differences in the intensity of the changes that occurred can be attributed to the different periods of time allowed for the regeneration of the post-fire stands; the aforementioned researchers were reporting on the short-term effects. Calcium demonstrated a different behavior in the present study to the observations of those other authors, but similar to that reported by DeBano and Conrad (1978). Kikamägi et al. (2013) published a further different observation–ash fertilization doubled the Ca concentration in birch leaves compared to the control, while having no affect on Mg.

In this study, there were no differences between the stands regarding soil N (Figure 2). Also, it can be concluded that the effect of fire on the N stocks in the biomass after 30 years was negligible (Figure 3). A similar behavior of N was reported by Kikamägi et al. (2013), who saw no effect of ash on the N content in birch leaves. In addition, Laclau et al. (2002) reported no differences for the aboveground N. However, other researchers have obtained contrasting results regarding the behavior of N. DeBano and Conrad (1978) indicate a significant decrease (by 75%) in N content after fire, while Kutiel and Naveh (1987) found an increase of N in plants. For S, in the present study, there was no effect on its content in either the soil or the biomass.

The effects of wildfire on the micronutrient status in soils is poorly understood (Certini, 2005). Based on the data obtained, it is clear that, among all the micronutrients studied, fire may have contributed to an increase in the content of bioavailable Zn, which was reflected in every silver birch biomass fraction (Figure 3). Birch is considered to be a hyperaccumulator of Zn (Dmuchowski et al., 2012; Szwalec et al., 2018). This increase in the plant-biomass Zn content following fire has also been reported by Reinhart et al. (2016). Compared with the studied elements, with their strongest accumulations occurring in the leaves, it is apparent that the Fe content in the biomass was at its highest in the roots (Figure 3). This might be an effect of the low mobility of Fe (Parzych et al., 2016). However, an increase in the elemental content of the roots could also be the result of biomass contamination with fine soil particles. This is a common problem in root analysis because, even small amounts of soil mineral particles adhering to the root surfaces can affect the analytical results (Hunt et al., 1999). This particularly affects elements such as Fe, which have high contents in the soil, but low contents in the plant biomass.

Differences in the Mn concentrations between the stands, compared with Fe and Zn, were significantly lower, and affected only the RI and S biomass fractions, in which there was a slight increase in accumulation after fire (Figure 3). Similarly to the micronutrients, the pool of soil Mn was lower in the post-fire stand (Figure 2), so the increased biomass content could be the result of the uptake of its mobilized form from deeper soil layers. De Marco et al. (2005) indicated an increase in available Fe and Mn forms in southwestern Italy after the application of experimental fire, which may explain their higher accumulation in the post-fire stand in this study. The organ content of Cu varied between the stands (Figure 3). However, a stronger uptake was highlighted in the control stand, even though the total Cu content in the soil was higher (Figure 2). A similar trend was found by Stankov Jovanovic et al. (2011) in a study on the effects of wildfire on Cu bioavailability in Serbia.

5. Conclusions

Based on the results of this study, it can be concluded that different elements exhibit diverse retention and distribution in silver birch biomass as a consequence of the long-term effect of wildfire. Low, commonly insignificant statistical differences were noted between the post-fire and control stands for N, S, and Mn. For Ca and Cu, higher concentrations were noted in the control stand in the majority of the biomass fractions, whereas the P, K and Zn contents were higher in the post-fire stand. The Mg and Fe trends were organ-dependent. The highest bioaccumulation intensity was typical in the leaves, except for Fe. Certain elements were also strongly accumulated in the bark (Ca, Mn, Cu, Zn) and fine roots (Fe, Cu, Zn). Stemwood was the poorest in all the studied elements. Based on BFs, it was found that the strongest accumulation in each birch organ was N, followed by Mn, Zn, Cu, S, Ca and P. While Mg and K were accumulated mainly in the leaves, the BF for Fe was below 0.3. This study highlighted the importance of wildfire as a factor that influences nutrient management in forest ecosystems dominated by silver birch.

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Długoterminowy wpływ pożaru na rozmieszczenie składników pokarmowych w biomasie brzozy brodawkowatej (*Betula pendula* Roth)

Słowa kluczowe

Brzoza brodawkowata
Pożary
Obieg składników pokarmowych
Bioakumulacja

Streszczenie

Celem badań była ocena długoterminowego wpływu pożaru na rozmieszczenie składników pokarmowych w biomasie brzozy brodawkowatej (*Betula pendula* Roth). Badaniami objęto dwa stanowiska (popożarowe i kontrolne) w tym samym wieku (27 lat), położone na terenie Nadleśnictwa Cierpiszewo (Polska centralna). Stanowiska znajdowały się w tym samym kompleksie gleb rdzawych wykształconych z piasków eolicznych. Próbki gleby i brzozy pobierano w dziesięciu powtórzeniach na stanowisko. Próbki gleby pobierano z głębokości 0–10, 10–20, 20–40 i 20–40 cm za pomocą próbnika rdzeniowego. Z drzew pobrano próbki korzeni drobnych, korzeni grubych, drewna pnia, kory pnia, gałęzi grubych, gałęzi drobnych i liści. Podstawowe właściwości gleby oznaczono stosując standardowe procedury. Ponadto w próbkach gleby i biomasy analizowano ogólną zawartość węgla (C), azotu (N), siarki (S), fosforu (P), potasu (K), wapnia (Ca), magnezu (Mg), żelaza (Fe), manganu (Mn), miedzi (Cu) i cynku (Zn). Gleby były silnie kwaśne i ubogie w badane pierwiastki. Zawartość składników pokarmowych w biomasie była silnie zróżnicowana w poszczególnych organach. Najbardziej zasobne w składniki pokarmowe były liście, następnie drobne korzenie i drobne gałęzie oraz kora. Najmniejszą zawartość składników pokarmowych stwierdzono w drewnie pnia. W przypadku niektórych pierwiastków stwierdzono statystycznie istotne różnice pomiędzy stanowiskiem popożarowym a kontrolnym. Na stanowisku po pożarze odnotowano większe koncentracje P, K i Zn w większości frakcji biomasy, a także Mg i Mn w korzeniach i drewnie pni. Zawartość N i Ca była zwykle wyższa na stanowisku kontrolnym. Wpływ pożaru na akumulację Fe i Cu był zróżnicowany w poszczególnych organach. Nie został on potwierdzony w przypadku S. Generalnie brzoza wykazywała największą intensywność bioakumulacji w odniesieniu do N, a najmniejszą w odniesieniu do Fe. Spośród wszystkich badanych składników pokarmowych współczynniki bioakumulacji były zwykle najwyższe w liściach, a najniższe w drewnie pnia. Można stwierdzić, że pożar jest ważnym czynnikiem wpływającym na gospodarkę składnikami pokarmowymi na stanowiskach brzozy brodawkowatej, nawet kilkadziesiąt lat po jego wystąpieniu.