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Nutrient distribution in silver birch (*Betula pendula* Roth) biomass growing on post-arable soils

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Abstract

The afforestation of former farmland is a common practice on poor-quality soils when traditional production is no longer profitable. To at least maintain, and preferably improve the health and quality of the soil, it is crucial to understand the effects of various tree species on the soil environment. Tracking nutrients, including their contents, bioavailability, bioaccumulation in the biomass, and return to the soil via litterfall is important in this regard. Although silver birch (*Betula pendula* Roth) is often implemented in afforestation, knowledge concerning its ecology is still insufficient, including the nutrient aspects. Hence, we undertook a broad study to determine the bioaccumulation of major nutrients (N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn) in the biomass of silver birch trees growing on post-arable soils, representing various trophic states and degrees of deformation, under temperate climatic conditions. The study covered four stands representing varied soil textures (loamy and sandy) and ages (10 and 35 years). Samples of soil (from depths of 0–10, 10–20, 20–40, and 40–80 cm) and biomass (fine roots, coarse roots, stemwood, bark, coarse branches, fine branches, and leaves) were collected and analyzed using standard procedures. The soils were acidic and moderately abundant in total organic carbon and N, but generally poor in the remaining elements. The elemental contents strongly varied among the birch organs, commonly reaching their highest values in the leaves, followed by the roots (N, P, K, Mg, S), bark (Mn, Cu), and branches (Ca). Iron occurred in its highest amounts in the fine roots, Zn in the bark. Among the macronutrients, the highest bioaccumulation intensity was recorded for N, followed by S, P, and Ca, while the highest intensity among the micronutrients was for Zn. Statistically significant differences were noted in several cases between the stands, in terms of individual biomass fractions and their elemental contents and bioaccumulation factors. Our results highlight the influence of soil properties and the post-arable nature of the stand on the nutrient accumulation in silver birch biomass. We found that silver birch growing on former arable soils shows an increased accumulation of some nutrients, particularly P and S. Moreover, the strong bioaccumulation of Zn and Mn by this species was confirmed.

1. Introduction

Human history is closely linked to progressive deforestation in many areas (Mather et al., 2000). The conversion of forest soils to cropland soils has resulted in significant changes in their properties and functions, which has affected terrestrial ecosystems and biodiversity at various scales (Bezerra et al., 2023), as well as certain global processes (Tinker et al., 1996). The loss of soil organic matter (SOM), accompanied by a deterioration in its quality, and profound changes in the soil's nutrient status and cycling are typical of the transition from forest to arable land use (Murty et al., 2002; Tolimir et al., 2020). Further changes strongly depend on the agricultural practices applied, including crop rotation, cultivation techniques, and fertilization. The impacts of these factors on the soil system have been clearly demonstrated by the results of long-term experiments (e.g., Kaiser et al., 2007; Chahal et al., 2021). Agricultural practices in the past have contributed to soil degradation in many areas and in many ways (e.g., Borrelli et al., 2017; Bednář and Šarapatka, 2018). As a result, the profitability of cultivating soils of some areas has declined considerably, leading to the abandonment of agricultural production.

Soils excluded from agricultural production are characterized by a number of specific features resulting from unsuitable agricultural practices. Compaction, low SOM content and poor SOM quality, acidification or alkalization, salinization, low nutrient contents, nutrient imbalance, and contamination with various substances are the symptoms most typical of soil degradation and reduced productivity (Prăvălie et al., 2021). A significant number of these problems concern sandy soils with naturally low contents of organic matter and clay minerals, these being the components responsible for the mechanisms of internal stabilization and the buffering of external factors (Šimanský et al., 2019). Afforestation is considered to be one of the most effective forms of regeneration of soils degraded by agricultural production. However, the ultimate effects of this process depend on the choice of tree species because it is well known that each species interacts with the soil in their own particular way (Augusto et al., 2002). Identifying these mechanisms is crucial for the successful restoration of degraded soils, including their properties and functions. In addition, the choice of vegetation should consider the initial state of the soil in terms of the form of degradation and the expected final effects. Tracking nutrients in plant–soil systems, including their contents in the soil, their uptake, allocation in the biomass, return to the soil via litterfall, and release during litter decomposition, provides valuable information on the effects of vegetation on the soil cover and its potential for reclamation.

Previous studies have shown that the afforestation of degraded post-arable soils brings many ecological and economic benefits (Łaska, 2014), and is generally in line with a policy promoting the sustainable management of natural resources (Sławski et al., 2020). However, the afforestation of such soils is a challenge to modern forestry due to their specific characteristics (Krawczyk, 2014), particularly considering the key objectives of that process–at least maintaining, and preferably improving, the health and quality of the soil. Being able to meet these expectations requires a detailed diagnosis of the trends and mechanisms pertaining to how individual tree species impact the soil system–its structure, properties, processes, and functions. Tracking essential nutrients, including its elemental content, their forms, bioavailability, leaching in the soil, and uptake, their bioaccumulation in the biomass, return to the soil via litterfall, and release during decomposition, can add highly valuable information to this topic.

Silver birch (*Betula pendula* Roth) is one of the tree species most often used for the afforestation of post-arable and post-industrial areas in the temperate climatic zone. Although it can usually be found on nutrient-poor sandy soils (Sutinen al., 2002; Oksanen, 2021), its tolerance to a variety of site conditions is broad. It is a species with high succession potential, characterized by its rapid growth and large seed fall (Špulák et al., 2010). Hence, it easily colonizes open spaces, such as abandoned fields, post-fire or post-industrial areas, improving site conditions for other, more demanding species. Although silver birch is widely distributed in the forests of the Northern Hemisphere, and its importance has been increasing in the forest economy over the last few decades, there is still insufficient knowledge concerning its impact on the soil system and vice versa (Jonczak et al., 2020). This also concerns nutrients–their status, cycling, and bioaccumulation in the biomass–with the available data differing and often being inconsistent.

The production of biomass in silver birch stands is considered to be large (Uri et al., 2012; Gawęda et al., 2014; Jagodziński et al., 2017), thus suggesting a high demand for soil nutrients. Although this thesis has been confirmed by several authors in relation to nitrogen (N), phosphorus (P), and potassium (K) (Ferm, 1993; Falkengren-Grerup et al., 2006), it seems to be contrary to the opinion of the high tolerance of this tree for poor site conditions. Previous studies have shown that fresh silver birch biomass is relatively rich in nutrients. However, these elemental contents are controlled by their abundance at the site, the soil characteristics, and the stand age, and they vary among the organs, commonly reaching their highest values in the leaves and rarely in the bark or fine roots (Daugaviete et al., 2015; Novák et al., 2017; Rustowska, 2022). Daugaviete et al. (2015) reported higher contents of nutrients in the biomass of silver birch growing on post-arable compared to natural soils. Among the elements, zinc (Zn) and manganese (Mn) are understood to accumulate particularly strongly in the biomass of silver birch (Dmuchowski et al., 2014; Rustowska, 2022). Studies by Hagen-Thorn et al. (2006), Aosaar et al. (2016), and Jonczak et al. (2023a) have shown that essential nutrients, including N, P, and K, are intensively translocated from the senescing leaves to the branches during the late summer and autumn, whereas some (calcium [Ca], iron [Fe], Mn, and Zn) are accumulated. Finally, the nutrient contents in silver birch litterfall are among the highest reported for broadleaved tree species (Brandtberg et al., 2004; Jonczak et al., 2023a) and much higher than for conifers (Berg and Staaf, 1987, Johansson, 1995). Hence, litterfall constitutes an important link in the biogeochemical cycling of elements in birch stands. Leaves, as a major component of litterfall, decompose rapidly (Tripathi et al., 2006; Huttunen et al., 2009). Based on previous studies, no opinion on the impact of silver birch on the nutrient status of soils is unambiguous, with both positive and negative effects having been reported.

Overall, the available literature demonstrates an increasing interest in the study of silver birch and its role in the biogeochemical cycling of elements and the transformation of soils. Hence, we undertook a broad study aimed at determining the bioaccumulation of major nutrients in the biomass of silver birch growing on soils representing various trophic statuses and degrees of deformation.

2. Material and methods

2.1. Study area

The study was performed in central Poland, which, based on the Köppen–Geiger climate classification (Peel et al., 2007), resides in a cold climatic zone, characterized by warm summers and a humid continental climate. The mean annual temperature was 8.3°C and the mean annual sum of precipitation was 541.4 mm yr^{-1} for the period 1951–2020 for the nearest station in Skierniewice. July was the warmest month, while January was the coldest. July was also the month with the highest sum of precipitation, while January was the lowest. Based on the thermal classification of Miętus et al. (2002), the studied year (2021) was characterized as normal, with air temperatures oscillating around the multiannual mean value. The annual sum of precipitation in 2021 amounted to 685.4 mm yr^{-1}, which, referring to the precipitation classification of Kaczorowska (1962) and in relation to the norm for the period 1951–2020, was categorized as humid.

In this paper, we focused on the accumulation of N, P, K, Ca, magnesium (Mg), sulfur (S), Mn, Fe, copper (Cu), and Zn in the biomass of silver birch growing on post-arable soils under temperate climatic conditions. The study covered four stands of silver birch that varied in terms of soil condition, stand age, stand density, and tree diameter at breast height (DBH). Two major sources of variability were included in the study–soil texture (sandy soils and loamy soils) and stand age (10 and 35 years old). The nutrient contents in silver birch organs (fine roots, coarse roots, stemwood, bark, coarse branches, fine branches, leaves) and in the topsoil (0–80 cm) were analyzed. The soil analysis also included several characteristics influencing the nutrient abundances and their bioavailability. All stand characteristics are included in Table 1. Stands C and D were covered by a natural succession of silver birch, while at Stands A and B planting (*without* plowing*)* was carried out.

2.2. Soil and biomass sampling

Soil and biomass samples were collected in July 2021 from 10 locations per stand. Each location represented one average tree, from which the following biomass fractions were taken: second-order roots (RII), first-order roots (RI), stemwood (S), stem bark (B), first-order branches (BrI), second-order branches (BrII), and leaves (L). The samples of stemwood and bark were collected at breast height, while the leaves were taken from the central part of the crown. The soil samples were collected from under each tree (approximately 1 m from the stem) using a 3-cm-diameter corer from soil mineral layers 0–10, 10–20, 20–40, and 40–80 cm deep. In addition, one core was taken from the central part of each stand for the purpose of describing and classifying the soil using the World Reference Base (WRB) for Soil Resources 2022 system (IUSS Working Group WRB, 2022).

2.3. Laboratory analysis

The soil samples were dried at room temperature and sieved through a 2.0-mm-mesh sieve. The samples were subjected to particle size distribution analysis using the mixed pipette and sieve methods and applying the U.S.D.A (Soil Survey Division Staff, 1993) classification of textural classes. The soil pH was determined using the potentiometric method in a suspension with water at a soil:water ratio of 1:2.5. The biomass samples were dried at 65°C and then milled into powder. The total organic carbon (TOC), N, and S contents were determined by dry combustion (Vario MacroCube, Elementar, Germany). The P, K, Ca, Mg, Fe, Mn, Cu, and Zn contents were determined by inductively coupled plasma atomic-emission spectrometry (ICP-OES, Avio 200, Perkin Elmer, USA) after microwave (Ethos Up, Milestone, Italy) digestion in 65% nitric acid.

All the analyses, except for the particle size distribution and pH, were performed in duplicate. Only pure per-analysis reagents and certified reference materials were used for instrument calibration and quality control.

2.4. Statistical analyses and calculations

The statistical analysis included obtaining the mean elemental contents from the soil and biomass samples along with the standard deviations (SDs). We also calculated bioaccumulation factors (BFs) based on the formula BF = element content in the biomass fraction/element content in the soil. To determine the statistically significant differences between the stands, the Kruskal–Wallis test followed by Dunn's test was applied. Relationships between variables were analyzed by principal component analysis (PCA) using Statistica 13 software.

3. Results

3.1. Basic characteristics of the soils

The studied silver birch stands were located on complexes of Cambisols (Stands A and B) and Brunic Arenosols (Stands C and D) based on forest maps. According to the WRB classification (IUSS Working Group WRB, 2022), Stands A and B were on Dystric Cambisol (Loamic, Ochric) developed from fine aeolian sediments over glacial till, whereas Stands C and D were on Eutric Cambisols and Eutric Brunic Arenosols developed on aeolian sediments overlying fluvioglacial sands. The difference in classification of the soils at Stands C and D resulted from the thickness of the silt layer. The presence of an Ap horizon in all

Table 1
Selected characteristics of the studied silver birch stands

Stand name	Coordinates	Forest address	Soil reference group	Age (years)	Density (trees ha^{-1})	DBH (cm)
A	N 51.7085 E 19.9498	06-02-2-09	Dystric Cambisol (Loamic, Ochric)	10	4,000	11.5±2.6
B	N 51.7092 E 19.9474	06-02-2-07-60-C-00	Dystric Cambisol (Loamic, Ochric)	35	1,020	23.7±5.7
C	N 51.8712 E 20.2980	06-18-1-01	Eutric Cambisol	10	3,500	10.7±2.4
D	N 51.8768 E 20.3006	06-18-1-01	Eutric Brunic Arenosol	35	2,640	17.3±4.8

Note: Soil reference group according to the World Reference Base for Soil Resources (2022) classification.

the studied soils confirmed their post-arable character (Table 2). The soils were strongly acidic or acidic, with mean pH-H_2O values of 4.8±0.1 for Stand A, 4.9±0.2 for B, 5.5±0.2 for C, and 5.3±0.4 for D, considering the 0–80-cm layer. The vertical variability in this property was low (Fig. 1). The soils were quite poor in SOM, with the highest TOC contents occurring in the 0–10-cm topsoil, and with the values being 17.2±4.5, 20.0±5.7, 11.0±3.0, and 12.9±2.0 g kg-1 for Stands A, B, C, and D, respectively. The tendency of the TOC content was to decline with depth, with the TOC content in the 40–80-cm layer being no higher than 2.7±2.1 g kg^{-1} (Stand A). Statistically significant differences between the stands, both in terms of pH and TOC, were noted in several cases (Fig. 1).

3.2. Nutrient contents of the soils

The weighted mean nutrient contents in the 0–80-cm soil layer are presented in Table 3. Based on these, in Stands A and B, the elements occurred in the order Fe>K>Mg>Ca>N>Mn>P>S>Zn>Cu and Fe>K>Mg>Ca>N>P>Mn>S>Zn>Cu, respectively. In Stands C and D, they occurred in the order Fe>K>Ca>Mg>N>P>Mn>S>Zn>Cu and Fe>K>Ca>Mg>P>N>Mn>S>Zn>Cu, respectively. The vertical distributions of K, Mg, Fe, and Cu showed low variability, whereas N, P, Ca, S, Mn, and Zn showed a decreasing tendency with depth (Fig. 2). Statistically significant differences were frequent between the stands, especially in the macronutrients. Among these, P, Mg, and S showed the greatest variability.

Table 2
Particle size distribution in the studied soils

Soil horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural group (USDA)
			A		
A(p)	0–20	69.4	29.2	1.4	sandy loam
Bw	20–42	60.8	36.0	3.2	sandy loam
2C	42–150	93.1	3.7	3.2	sand
			B		
A(p)	0–24	59.5	37.5	3.0	sandy loam
Bw	24–55	63.2	34.2	2.6	sandy loam
2C	55–150	60.9	18.7	20.4	sandy clay loam
			C		
A(p)	0–25	67.0	30.9	2.1	sandy loam
Bv	25–45	71.1	26.9	2.0	sandy loam
C	45–150	84.2	13.6	2.2	loamy sand
			D		
A(p)	0–27	80.2	17.6	2.2	loamy sand
Bv	27–60	86.8	11.9	1.3	sand
C	60–150	96.0	3.0	1.0	sand

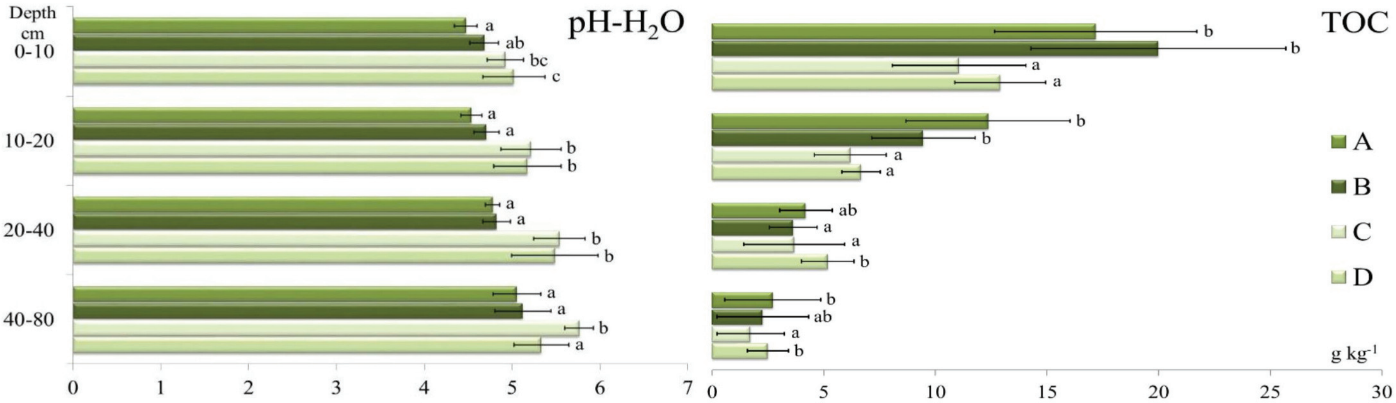

Fig. 1. pH and TOC contents of the studied soils (different letters indicate statistically significant differences between stands at a significance level of $p<0.05$ based on the Kruskal–Wallis test followed by Dunn's test)

Table 3
Soil weighted mean ± SD elemental contents (mg kg⁻¹) in the studied stands in the 0–80-cm soil layers

Element	A	B	C	D
N	428.7 ± 55.2^{b}	436.1 ± 90.1^{b}	327.5 ± 67.2^{a}	338.9 ± 63.4^{a}
P	195.0 ± 23.2^{a}	305.1 ± 41.5^{b}	178.0 ± 35.2^{a}	361.7 ± 34.2^{b}
K	$1,670.5\pm387.9^{b}$	$1,880.9\pm338.4^{bc}$	$2,021.5\pm263.7^{c}$	$1,349.7\pm73.0^{a}$
Ca	830.8 ± 89.2^{a}	932.5 ± 71.8^{b}	$1,001.5\pm82.3^{b}$	910.5 ± 103.1^{ab}
Mg	939.6 ± 211.8^{bc}	983.0 ± 197.4^{c}	783.8 ± 114.4^{ab}	700.4 ± 61.6^{a}
S	121.4 ± 14.4^{c}	96.3 ± 13.6^{b}	68.0 ± 16.2^{a}	77.1 ± 8.4^{a}
Fe	$5,881.1\pm979.6^{b}$	$5,638.6\pm838.2^{ab}$	$5,144.5\pm857.2^{a}$	$5,308.5\pm344.9^{ab}$
Mn	214.8 ± 52.7^{bc}	223.5 ± 45.0^{c}	162.1 ± 27.5^{a}	176.7 ± 31.9^{ab}
Cu	7.8 ± 1.6^{a}	7.3 ± 0.9^{a}	9.2 ± 1.4^{b}	10.3 ± 1.5^{b}
Zn	20.0 ± 1.6^{b}	20.1 ± 3.1^{b}	15.8 ± 2.0^{a}	22.0 ± 3.7^{b}

Note: Different letters indicate statistically significant differences between the stands at a significance level of $p<0.05$ based on the Kruskal–Wallis test followed by Dunn's test.

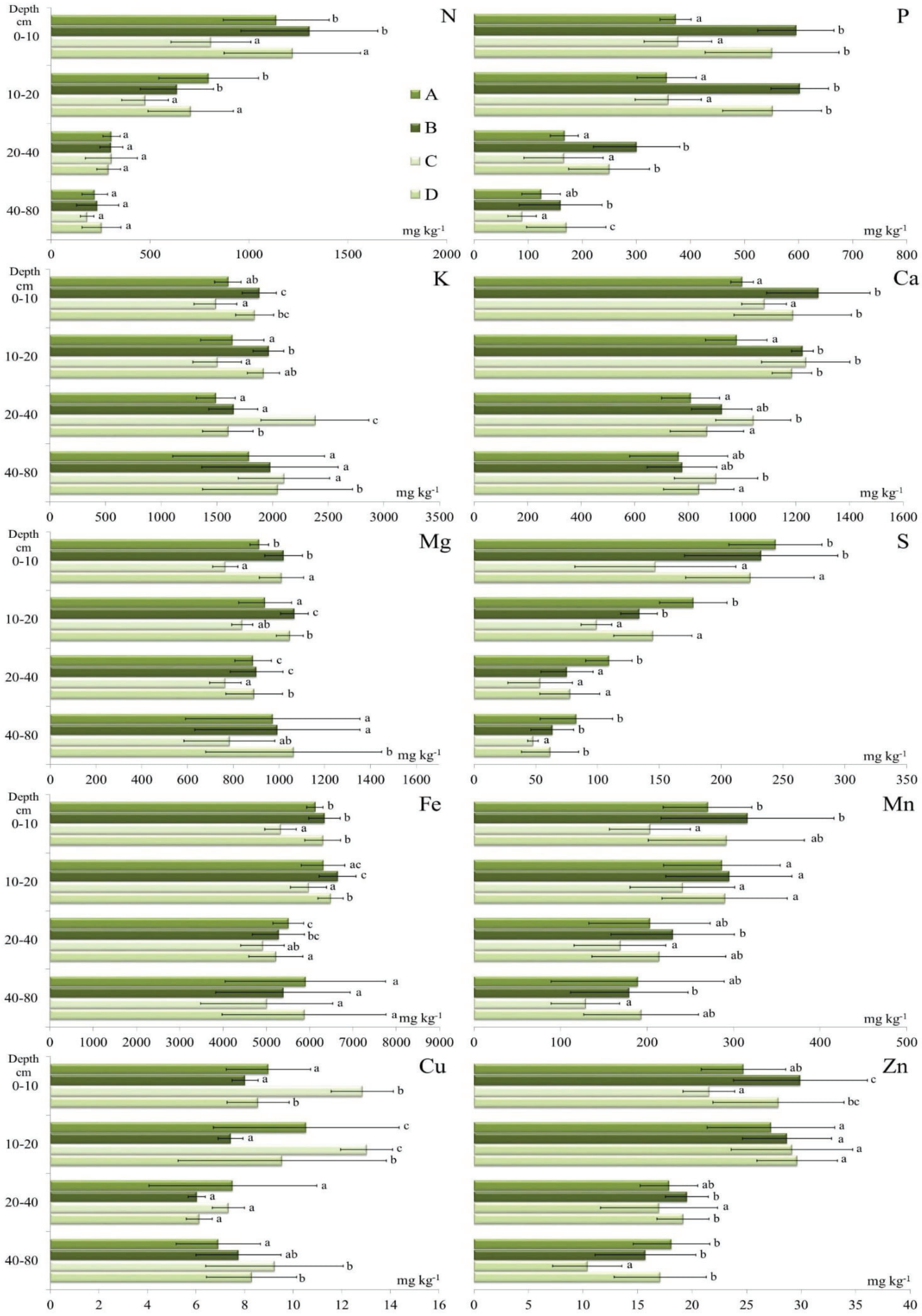

Fig. 2. Mean ± SD elemental content in the soils at depths of 0–10, 10–20, 20–40, and 40–80 cm (different letters indicate statistically significant differences between stands at a significance level of $p<0.05$ based on the Kruskal–Wallis test followed by Dunn's test)

3.3. Nutrient content in birch biomass

As shown in Fig. 3, the distribution patterns varied among the studied elements. The majority of the nutrients occurred in their highest amounts in the leaves (N, P, K, Ca, Mg, S, Mn), followed by the roots (N, P, K, Mg, S), bark (Mn, Cu), and branches (Ca). Zinc had its highest content in the leaves or bark, depending on the stand, whereas Fe was the highest in the fine roots. The stemwood was the poorest in all studied elements, but statistically significant differences in the elemental contents were observed between the stands in several cases (Fig. 3), although no specific trend could be recognized.

A PCA analysis was applied to identify sources of variability and reveal the relationships between the elements in various biomass fractions and their linkage to the soil nutrients and certain characteristics (Figs. 4–10). The observed variability was explained by two major principal components (PC1 and PC2) in 88.9%, 87.2%, 80.5%, 78.2%, 84.1%, 75.2%, and 81.3% of the cases for the RII, RI, S, B, BrI, BrII, and L biomass fractions, respectively. Several correlations were observed between the elements in the biomass fractions and the soil parameters and stand age. The soil TOC content was mostly strongly negatively correlated with the P content and positively with the S, Fe, and Mn contents. The pH-H_2O was mostly positively correlated with

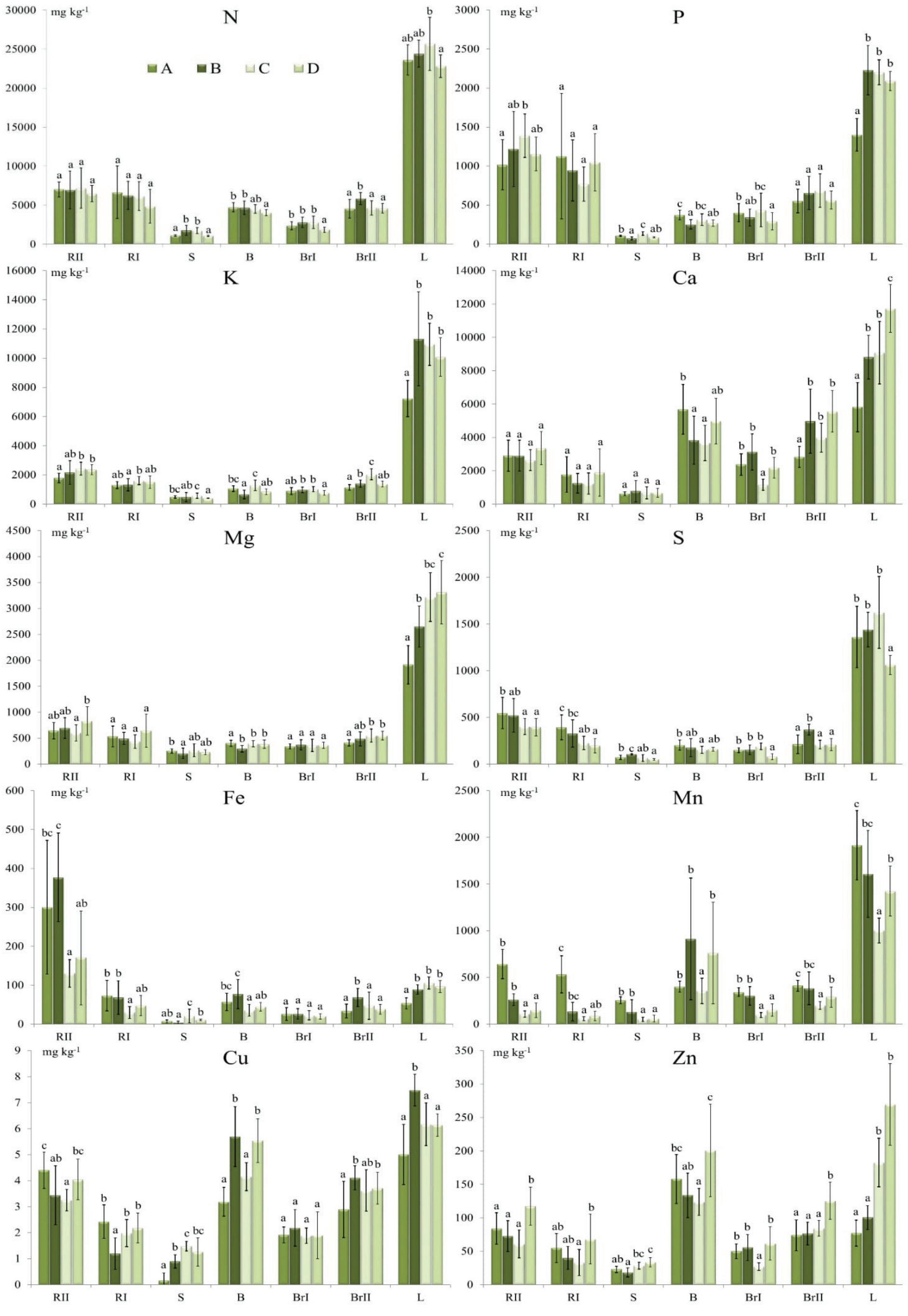

Fig. 3. Mean ± SD elemental content in birch biomass (different letters indicate statistically significant differences between stands at a significance level of $p<0.05$ based on the Kruskal–Wallis test followed by Dunn's test). RII – second-order roots, RI – first-order roots, S – stemwood, B – bark at a height ≈130 cm, BrI – first-order branches, BrII – second-order branches, and L – leaves

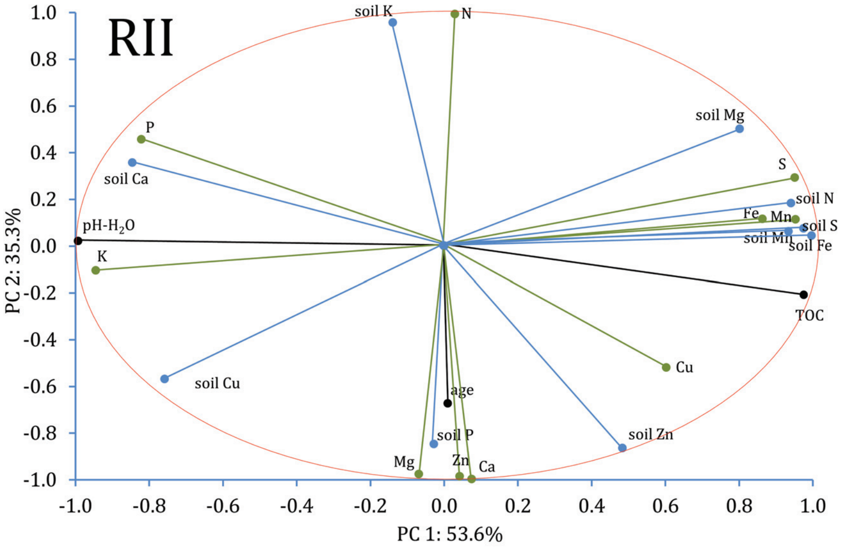

Fig. 4. PCA analysis for RII biomass fraction and soil characteristics (green lines – biomass components/properties, blue lines – soil components/properties, gray lines – stand characteristics). RII – second-order roots

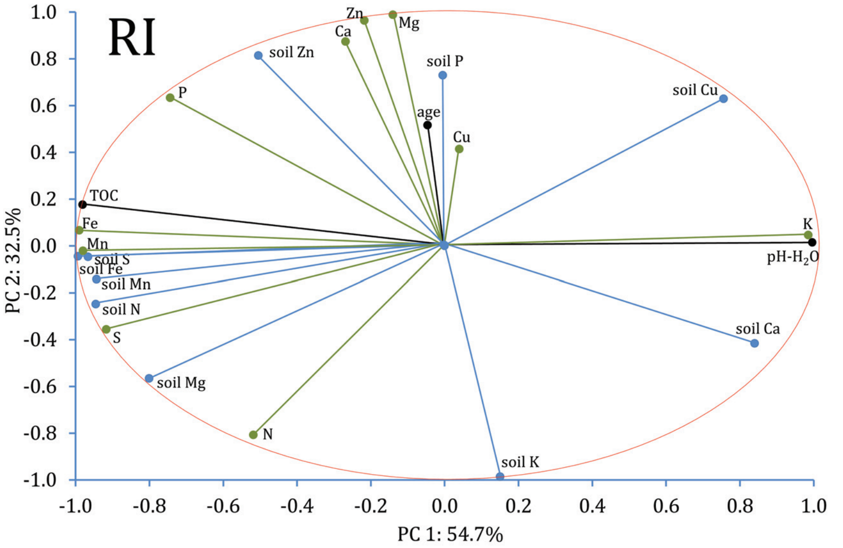

Fig. 5. PCA analysis for RI biomass fraction and soil characteristics (green lines – biomass components/properties, blue lines – soil components/properties, gray lines – stand characteristics). RI – first-order roots

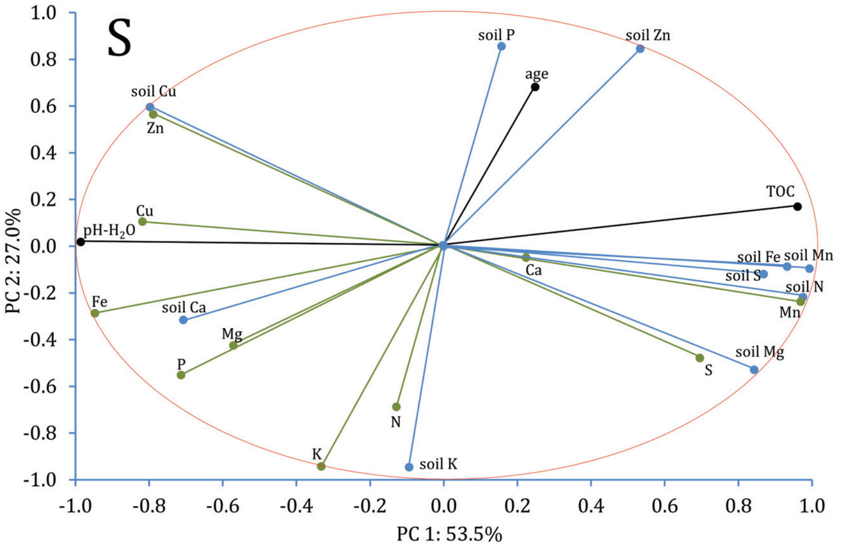

Fig. 6. PCA analysis for S biomass fraction and soil characteristics (green lines – biomass components/properties, blue lines – soil components/properties, gray lines – stand characteristics). S – stemwood

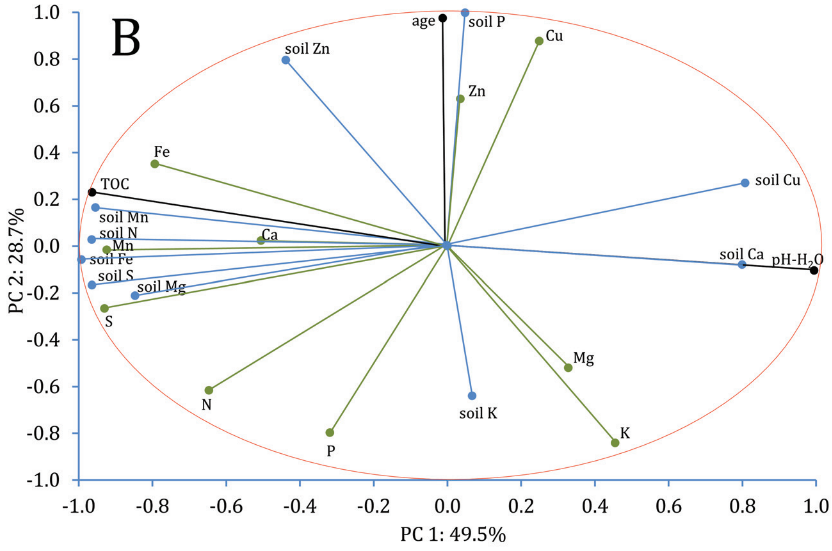

Fig. 7. PCA analysis for B biomass fraction and soil characteristics (green lines – biomass components/properties, blue lines – soil components/properties, gray lines – stand characteristics). B – bark

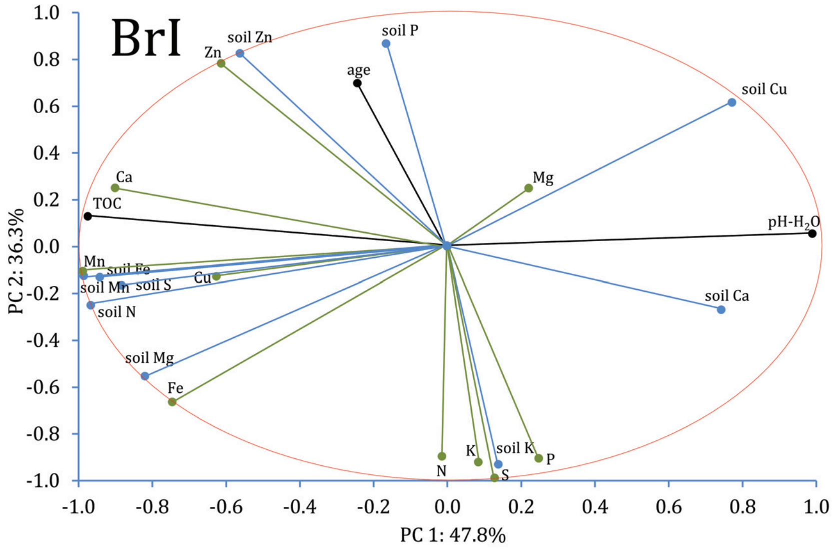

Fig. 8. PCA analysis for BrI biomass fraction and soil characteristics (green lines – biomass components/properties, blue lines – soil components/properties, gray lines – stand characteristics). BrI – first-order branches

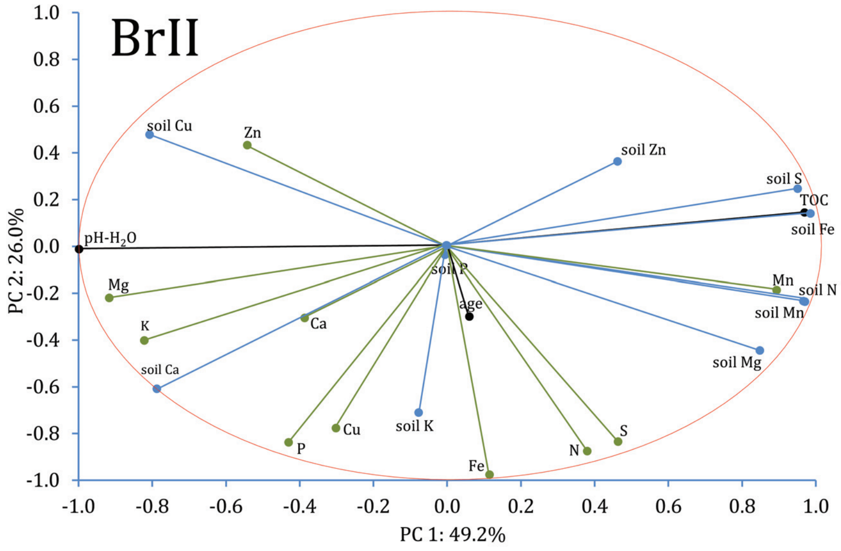

Fig. 9. PCA analysis for BrII biomass fraction and soil characteristics (green lines – biomass components/properties, blue lines – soil components/properties, gray lines – stand characteristics). BrII – second-order branches

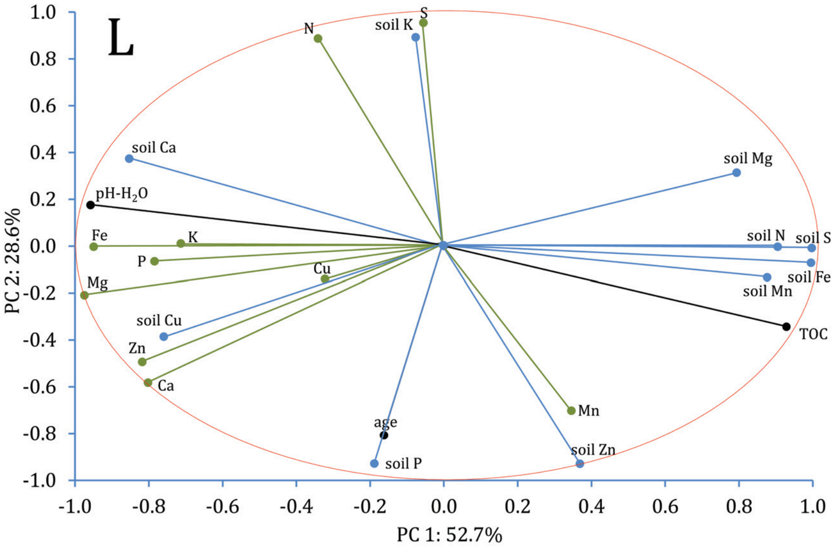

Fig. 10. PCA analysis for L biomass fraction and soil characteristics (green lines – biomass components/properties, blue lines – soil components/properties, gray lines – stand characteristics). L – leaves

the K contents, while negatively with Mn and S contents. Stand age was mainly strongly correlated with Ca (positively).

3.4. Bioaccumulation factor

The intensity of nutrient bioaccumulation was evaluated based on the BF. In all the stands, the highest BF values among the macronutrients were noted for N, and among the micronutrients for Zn (Fig. 11). The order of BF values in regard to particular elements varied (Fig. 11). In general, the highest bioaccumulation was typical of the leaves and/or bark. In most cases, the stemwood was characterized by the poorest bioaccumulation intensity of all the studied elements. The lowest BF value for the macronutrients was mainly for K, while for the micronutrients, it was Fe. Strong variation was also apparent in the occurrence of statistically significant differences, which were noted in several cases between the stands and were usually greater with regard to the macronutrients.

4. Discussion

The soils of the studied silver birch stands represented the typical components of the soil cover of the temperate climatic zone. The differences between the stands mainly concerned the origin of the parent material and its textural characteristics, which was reflected in the physical and chemical properties, and ultimately also the trophic status and productivity of the soils. Generally, all the soils were rather poor in quality, an so their exclusion from agricultural production was not surprising. It should be noted that we captured the present state of the soils in this study, which were only partially developed after the 10 or 35 years of impact from their planting with silver birch. Recent studies have clearly shown that silver birch negatively influences SOM (Jonczak et al., 2023b) and strongly modifies the soil microbiome (Chojnacka et al., 2023). The differences recorded between the studied soils, in terms of pH and elemental content, were generally not large, but they were statistically significant in several cases (Fig. 2). The slightly lower pH in the topsoil compared to the deeper soil zones indicated the initial phases of acidification—a process that typically occurs under forest vegetation in a percolating water regime. The lower TOC contents in the soils of C and D compared to A and B (Fig. 1) were expected, considering differences in texture—a major factor in soil aggregation and the physical protection of SOM (Le Bissonnais and Arrouays, 1997). The soil texture and SOM also strongly determine nutrient occurrences, including their stocks and bioavailability, and ultimately also their uptake and accumulation in the plant biomass (Silver et al., 2000; Gerke, 2022).

The nutrient levels in the silver birch biomass were mainly a function of the biomass fraction. The importance of soil characteristics and stand age were not fully clear. Most of the studied nutrients occurred in their highest amounts in the leaves, and their lowest in the stemwood. This observation well reflects the physiological role of these organs and the one-way solution transport from the root zone to the leaves. This is a typical observation, also noted for silver birch by Rustowska (2022), and by several other authors for other tree species. Some elements (Ca, Zn, Cu, and Zn) occurred in high amounts in the bark. This is also a typical relationship. The ability to accumulate elements in the bark has been widely applied in the bioindicative assessment of environmental contamination with trace elements (Chrabąszcz and Mróz, 2017). Phosphorus, Fe, and Cu occurred at relatively high concentrations in the fine roots. In the case of Fe, this reflects a methodological problem more than the true concentration of the element in the biomass. This is due to contamination of the roots with fine soil particles that cannot be completely removed from the sample during preparation (Hunt et al., 1999). We confirmed the finding of Hellsten et al. (2013) that nutrient concentration decreases with increasing root diameter.

Among the nutrients, N, P, and K are considered of key importance for silver birch growth, as evidenced by the studies of Ovington and Madgwick (1959), Ferm (1993), Miller (1984), and Hynynen et al. (2010). In addition, Possen et al. (2021)

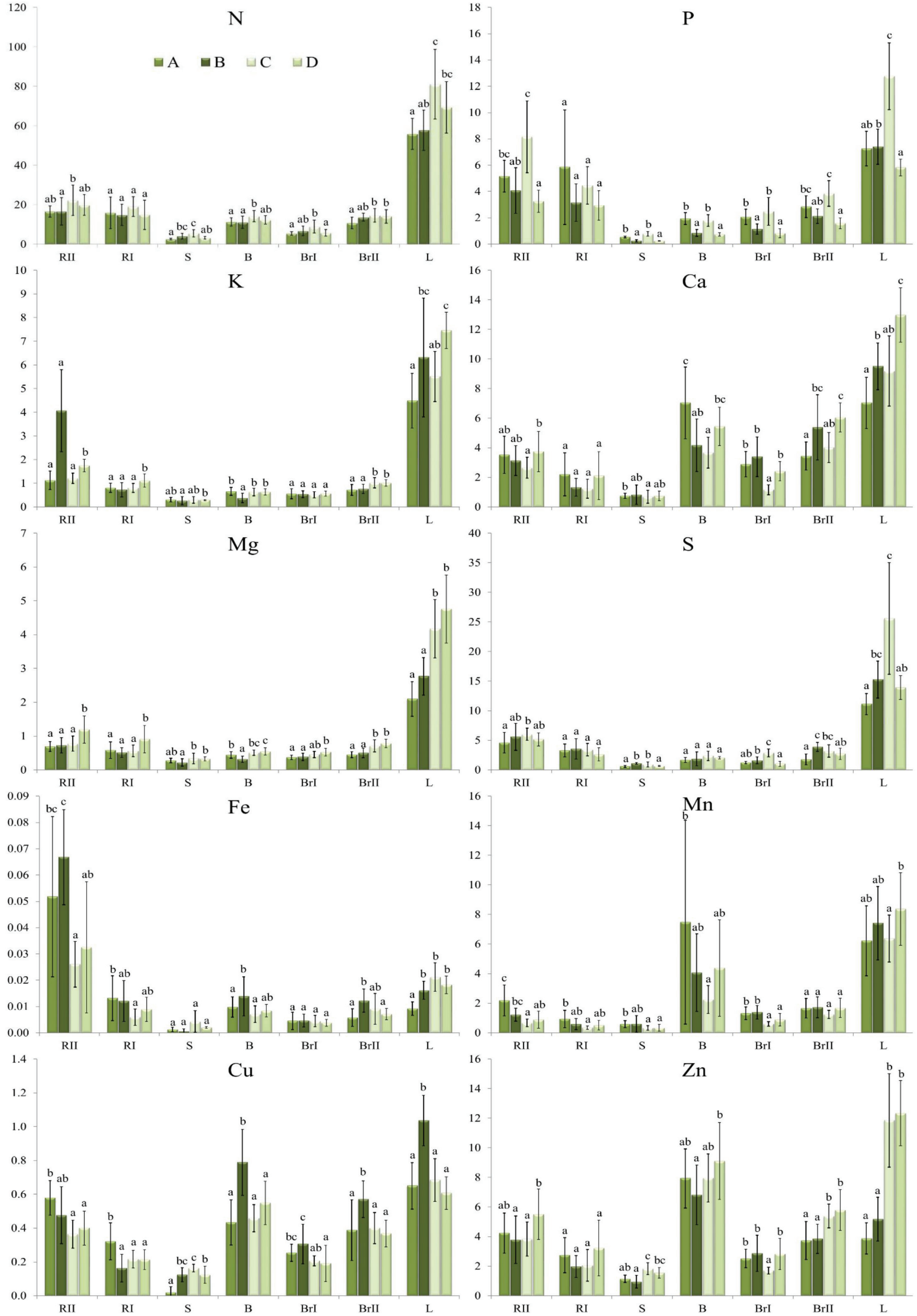

Fig. 11. Mean ± SD of the BFs of the studied elements (different letters indicate statistically significant differences between stands at a significance level of $p<0.05$ based on the Kruskal–Wallis test followed by Dunns's test). RII – second-order roots, RI – first-order roots, S – stemwood, B – bark at a height ≈130 cm, BrI – first-order branches, BrII – second-order branches, and L – leaves

highlighted the role of N in the adaptation of this tree to changes in climate. Jonczak et al. (2023a) stated that silver birch litterfall is relatively rich in these elements, although they are intensively translocated from the senescing leaves to the branches in autumn. The N, P, and K contents recorded in our story in the silver birch biomass were generally comparable with those reported by other authors for post-arable stands (e.g., Daugaviete et al., 2015). However, some differences were apparent when comparing them to stands representing another land-use history. For instance, lower P contents were reported by Rustowska (2022) in natural and post-fire stands on inland dunes, by Novák et al. (2017) on nutrient-poor gleyic soils, and by Hellsten et al. (2013) in Sweden. Contrastingly, Oksanen et al. (2005) noted higher P contents. The higher contents of the studied elements in the post-arable stands in this study seem to compare well to the natural contents reported in the literature, likely reflecting the effect of fertilization on the former arable fields. It might be expected that the importance of this factor would decrease over time, which seems to have been confirmed by our study. We observed higher P contents in the biomass of younger birches than older ones (Fig. 3). This observation is in line with the fact that the nutritional requirements of silver birch are greater in the early phases of growth (Miller, 1984). The differences noted between the studied stands can be partially explained by the soil pH—an important factor in nutrient bioavailability (Tuszyński, 1990). Based on our results and data in the literature, it can be assumed that the post-arable character of the stands influenced the accumulation of N, P, and K in the silver birch biomass.

Calcium and Mg are usually present in soils in amounts that exceed the nutritional demands of the vegetation. Hence, they are not translocated from senescing leaves, including in silver birch (Jonczak et al., 2023a). Although the studied stands were generally comparable in terms of the Ca and Mg contents of the soils (Table 3), some statistically significant differences were found between the biomass fractions (Fig. 3). The distribution of these elements in the leaves indicated the importance of stand age as a factor in the variability. Its role is not clear for other biomass fractions.

Sulfur cycling has been rarely studied in forest ecosystems, although it is a key micronutrient, with an interesting anthropogenic context over the last century. The element usually occurs in European forest soils in low amounts and is strongly taken up by the vegetation. Atmospheric emissions were an important source of the element in the 20th century (Oniawa and Babajide, 1993). However, due to a reduction in such emissions, S has become increasingly deficient in both forest and arable soils over the last several years (Skwierawska et al., 2016; Shukla et al., 2021). The large role of vegetation and SOM in the biogeochemical cycling of S has also been confirmed by its distribution in soil profiles. The highest concentrations have been reported for SOM-enriched horizons, with a decreasing tendency with depth being typical (Tabatabai and Bremner, 1972). This tendency was also confirmed in our study (Fig. 2). Another important factor influencing S is soil texture. Typically, S occurs in higher amounts in fine-textured soils. This tendency was also confirmed in our study (Table 3). The distribution of S in the silver birch biomass showed trends typical of the other studied nutrients, with maximum values noted in the leaves and minimum values in the stemwood. However, there is no literature data on this topic, so it is difficult to say whether the trends observed are typical.

There is more literature available on the Mn, Cu, and Zn contents in silver birch biomass, although this usually concerns industrial or urban areas and has a contamination context (Kosiorek et al., 2016; Szwalec et al., 2018; Kříbek et al., 2020; Sitko et al., 2022). When comparing our data with those reported by Jonczak et al. (2023a) for stands on post-arable soils, and by Oksanen et al. (2005) and Rustowska (2022) for natural stands, the Fe, Mn, Cu, and Zn contents in the biomass were generally similar. Manganese had the highest contents, accompanied by the greatest stand-to-stand variability, among the mentioned elements (Fig. 3). The high potential for Mn accumulation is also typical of other tree species, including Scots pine and Norway maple, as evidenced by Kosiorek et al. (2016). The differences observed between the stands indicate abundance of soil (Table 3), soil texture (Table 2), and TOC content (Fig. 1) as key factors in Mn variability in silver birch biomass. In addition, it is well known that the bioavailability of elements such as Fe, Mn, Cu, and Zn is strongly controlled by soil pH (Gębski, 1998; Gupta et al., 2019).

The BF has commonly been applied as a measure of the intensity of the bioaccumulation of chemical elements in plant organs (e.g., Jonczak and Parzych, 2018; Rustowska, 2022; Yan et al., 2023). This factor has interpretative value in the context of both plant nutrition and environmental contamination. Based on the BF, we can state that the silver birch in the studied stands had a sufficient supply of the majority of nutrients (Fig. 11), particularly N. High BF values for N are typical of forest vegetation due to its intensive uptake and low content in the soil. The major nutrients in our study had BF values comparable to those reported by Rustowska (2022) in silver birch stands growing on post-fire soils. Regarding the micronutrients, typically high BF values were noted for Mn and Zn, which accords with the findings of Gallagher et al. (2008), Dmuchowski et al. (2014), Szwalec et al. (2018), and Desai et al. (2019). The high bioaccumulative potential of silver birch with respect to these elements can be highlighted by comparison with other tree genera, including Avicennia and Rhizopora (Takarina and Pin, 2017), and the 11 pine species studied by Jonczak et al. (2021). In our study, we additionally assumed that nutrient accumulation would also controlled by silver birch age because several previous studies have indicated the importance of this factor (e.g., Alifragis et al., 2001; Rosenvald et al., 2013; Rodríguez-Soalleiro et al., 2018). While significant differences in the content of some elements (mainly K, Cu, and Zn) have been observed between stands differing in age, the trends are not clear.

5. Conclusions

The results of this study highlight the complexity of nutrient bioaccumulation in silver birch biomass and the linkage of the process with the site characteristics, including soil texture, pH, SOM content, and nutrient abundance. The influence of the post-agricultural history on the stands appeared to be marked, but this history's role should be considered in the context of an indirect effect, as a factor shaping the physical and chemical characteristics of the soils. The role of stand age, as a factor influencing the bioaccumulation of nutrients in the biomass of silver birch growing on post-arable soils, was not fully revealed by our study. The elements showed strongly uneven distributions in the organs, reflecting their physiological roles and the one-way solution transport from the fine roots to the leaves. Typically, the leaves were the richest in most of the studied elements, followed by the roots (N, P, K, Mg, and S), bark (Mn and Cu), and branches (Ca). Based on our results, we can state that silver birch strongly accumulates N and P, these being deficient nutrients in forest ecosystems. This supports previous reports. Another typical observation was the strong bioaccumulation of Mn and Zn, which confirms the opinion of the studied tree species as being good accumulators of these elements.

Overall, our findings contribute to a more comprehensive understanding of the ecology of silver birch, with particular emphasis on its functioning on post-arable soils. However, our knowledge on this issue is still far from complete, albeit these results have the potential to be applied in the development of forestry practices for post-arable sites characterized by a number of specific features resulting from their history.

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Rozmieszczenie składników odżywczych w biomasie brzozy brodawkowatej (*Betula pendula* Roth) porastającej gleby porolne

Słowa kluczowe

Brzoza brodawkowata
Obieg biogeochemiczny
Składniki pokarmowe
Bioakumulacja
Gleby marginalne

Abstrakt

Zalesianie dawnych gruntów rolnych jest powszechną praktyką na glebach niskiej jakości, gdy tradycyjna produkcja nie jest już opłacalna. Aby przynajmniej utrzymać, a najlepiej poprawić zdrowie i jakość gleby, kluczowe jest zrozumienie wpływu różnych gatunków drzew na środowisko glebowe. Śledzenie składników odżywczych, w tym ich zawartości, biodostępności, bioakumulacji w biomasie i powrotu do gleby poprzez opad ściółki, jest ważne w tym zakresie. Chociaż brzoza brodawkowata jest często stosowana w zalesieniach, wiedza na temat jej ekologii, w tym kwestia składników odżywczych, jest wciąż niewystarczająca. W związku z tym podjęliśmy szeroko zakrojone badania w celu określenia bioakumulacji głównych składników odżywczych (N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn) w biomasie brzozy brodawkowatej rosnącej na glebach porolnych, reprezentujących różne stany troficzne i stopnie deformacji, w umiarkowanych warunkach klimatycznych. Badaniami objęto cztery drzewostany reprezentujące różne tekstury gleb (gliniaste i piaszczyste) oraz wiek (10 i 35 lat). Próbki gleby (z głębokości 0–10, 10–20, 20–40 i 40–80 cm) i biomasy (drobne korzenie, grube korzenie, drewno pnia, kora, grube gałęzie, drobne gałęzie i liście) zostały zebrane i przeanalizowane przy użyciu standardowych procedur. Gleby były kwaśne i umiarkowanie zasobne w całkowity węgiel organiczny i N, ale ogólnie ubogie w pozostałe pierwiastki. Zawartość pierwiastków była silnie zróżnicowana między organami brzozy, osiągając najwyższe wartości w liściach, a następnie w korzeniach (N, P, K, Mg, S), korze (Mn, Cu) i gałęziach (Ca). Żelazo występowało w największych ilościach w drobnych korzeniach, Zn w korze. Wśród makroskładników najwyższą intensywność bioakumulacji odnotowano dla N, a następnie S, P i Ca, podczas gdy najwyższą intensywność wśród mikroelementów odnotowano dla Zn. Statystycznie istotne różnice odnotowano w kilku przypadkach między drzewostanami, pod względem poszczególnych frakcji biomasy i ich zawartości pierwiastków oraz współczynników bioakumulacji. Uzyskane przez nas wyniki wskazują na wpływ właściwości gleby oraz porolnego charakteru stanowiska na akumulację składników pokarmowych w biomasie brzozy brodawkowatej. Stwierdzono, że brzoza brodawkowata rosnąca na glebach porolnych wykazuje zwiększoną akumulację niektórych składników pokarmowych, zwłaszcza P i S. Ponadto potwierdzono silną bioakumulację Zn i Mn przez ten gatunek.