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ORIGINAL PAPER

Soil properties of Kraków's urban forests with selected alien tree species

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ABSTRACT

With climate change being a pressing issue, the multi-functionality of urban forests can only be ensured by their sustainability, diversity and stable development. Improving our knowledge of the ecological requirements, ecosystem effects and adaptability of non-native tree species in specific urban forest conditions is a foundation for future sustainable forest management. The study involved investigating the impact of selected alien tree species on soil properties in urban forests located in Kraków. Eight tree species were investigated – Douglas fir, Canada hemlock, sweet chestnut, black cherry, horse chestnut, common walnut, box elder, and black locust. The study's primary goal was to determine the impact of selected species on the quantity and quality of soil organic matter, its physicochemical properties, the C/N/P stoichiometry of soil and enzymatic activity. The analyses confirmed different properties of soil under influence of alien deciduous and coniferous tree species. Properties of soil surface horizons of black locust and horse chestnut were different from other examined alien species. Canada hemlock and Douglas fir exerted the most substantial acidifying effect on the surface soil horizons. These results confirm that growing mixed stands and avoiding conifer monocultures is justified. Additionally, research confirmed that soils of different alien tree species characterized by different biochemical activity expressed by enzymatic activity. Our research confirmed that C/N/P stoichiometry is a valuable tool to assess the nutrient cycle in urban forests and that alien tree species have different effects on the C, N, and P content.

KEY WORDS

dissolved organic carbon; ecological stoichiometry; enzyme activity; forest stands; litter characteristics

Introduction

The species composition of tree stands significantly influences the characteristics of soil organic matter (Hobbie *et al.*, 2006; Mueller *et al.*, 2012), soil acidification (Paluch and Gruba, 2012), soil buffer capacity (Hobbie *et al.*, 2006; Gruba and Mulder, 2015) and soil biochemistry (Błońska *et al.*, 2016, 2017, 2018). The soil receives organic matter from litter and root exudates, including soluble sugars, organic acids, amino acids, and starch. Plant cell walls contribute biopolymers, cellulose, and lignin (Baldrian and Šnajdr, 2011; Beven and Germann, 2013). The type of litter

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produced by the trees in a forest affects how quickly organic matter breaks down, as well as the release of nutrients into the soil. This, in turn, can impact the overall properties of the soil (Santa-Regina and Tarazona, 2001). The biogens released during the decomposition of the litter shape the balance of macronutrients in the soil surface horizons, influencing the proportions of acidic and alkaline ions in the soil (Błońska *et al*., 2021). Deciduous tree species release more alkaline cations into the soil, and the faster decomposition rate of the litter of these species favours the release of more mineral nitrogen.

The biochemical properties of soils are sensitive indicators reflecting changes in the soil environment (Uzarowicz *et al*., 2020). Soil enzymes are vital to the nutrient cycle as they are associated with the activity of microorganisms and plant root secretions. They serve as indicators of microbial nutrient demand and metabolic processes (Małek *et al*., 2021). Enzymes such as β-D-cellobiosidase, β-glucosidase, β-xylosidase play a crucial role in soil organic C mineralisation, while N-acetyl-β-Glucominidase and Phosphatase are important in the N and P cycles respectively. Arylsulphatase is essential for the S cycle. Enzyme activity is largely influenced by carbon substrates released during litter decomposition (Adamczyk *et al*., 2014). Microorganisms require mineral substances found in tree litter to affect soil pH, in addition to the carbon substrates needed for enzymatic reactions (Błońska *et al*., 2021). Soils with high organic matter content tend to have higher microbial biomass as they are the preferred energy source for microorganisms (Landgraf and Klose, 2002). Biomass and microbial activity are most often limited by nitrogen availability (Wardle, 1992), which in forest soils may be directly related to the quality of litter supplied to the forest floor. Previous studies confirm that deciduous species support soil microflora more powerfully than coniferous species (Scheu and Parkinson, 1995; Zhong and Makeschin, 2006).

Forest ecosystems are exposed to changes resulting from climate change, and urban forest ecosystems are additionally exposed to the influence of anthropogenic factors, which makes them separate cases that should be managed according to different principles. In order to improve the stability of urban ecosystems, their biodiversity must be taken care of. Introducing various tree species, including alien species, can increase the biodiversity and stability of such ecosystems. Knowledge of the influence of various alien tree species on the soil environment in the context of urban forests will deepen our knowledge to assess their adaptability in the specific conditions of the urban forest environment. The main aim of the research was to determine the properties of the soil environment in the conditions of Kraków's urban forests with alien tree species, especially the physicochemical properties, C/N/P stoichiometry of soils and enzymatic activity. Our research compared soil properties influenced by various alien tree species. This study attempts to explain the influence of litter from selected alien trees species on biochemical activity through the amounts of released components. We suppose that soils under influence of alien tree species differ in C/N/P stoichiometry because they provide different amounts of C and P. It was assumed that among the studied alien species, conifers – Douglas fir *Pseudotsuga menziessi* (Mirb.) Franco and Canada hemlock *Tsuga canadensis* L. – had the most acidifying effect on the soil. Horse chestnut *Aesculus hippocastanum* L., black locust *Robinia pseudoacacia* L. and black cherry *Prunus serotina* Ehrh. improved the quantity of nutrients delivered to the soil with detritus.

Materials and methods

Study site and experimental design. This study was conducted in urban forests in Kraków (50°03'41"N; 19°56'18"E), namely Reduta Forest, Zesławice Forest and Wolski Forest. The area covered by the study is occupied by Luvisols (Skiba and Drewnik, 2013). The soils studied had a similar texture (average 25% sand, 69% silt and 6% clay). The average temperature in the study area was 8.5°C, and the average annual precipitation was about 715 mm. Kraków is the second--largest town in Poland, with an area of 327 km^2. In Kraków, urban forests cover 19.61 km^2.

The study was conducted in 2020. The following alien tree species were included in the research: Douglas fir *Pseudotsuga menziesii*, Canada hemlock *Tsuga canadensis*, black locust *Robinia pseudoacacia*, black cherry *Prunus serotina*, sweet chestnut *Castanea sativa* Mill., horse chestnut *Aesculus hippocastanum*, common walnut *Juglans regia* L. and box elder *Acer negundo* L. The average age of the studied trees was 80 years. In selected forest complexes, study plots have been designated. Each type of study plot was repeated three times. A total of 24 study plots were investigated (8 alien species × 3 repetitions). Soil samples were collected at each study plot for laboratory analysis. These were taken from the humus mineral horizon (A) after removing the litter horizon. Additionally, litter samples were taken from each study plot for column experiments in the laboratory.

LABORATORY ANALYSIS. After air-drying, soil samples were sifted through a sieve with a mesh diameter of 2 mm and analysed further. After air-drying, the litter samples were ground. The particle size distribution was determined with laser diffraction (Analysette 22, Fritsch, Idar-Oberstein, Germany). The soil and litter pH were determined in water using the potentiometric method. C and N were measured with an elemental analyser (LECO CNS TrueMac Analyser Leco, St. Joseph, MI, USA). We used ICP analysis (ICP-OES Thermo iCAP 6500 DUO, Thermo Fisher Scientific, Cambridge, UK) to determine the P content. We determined the P levels after mineralising the mixture with concentrated nitric and perchloric acids at a ratio of 3:1 and calculated the C/N, C/P and N/P ratios on a molecular level. The cation concentrations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were extracted with ammonium acetate and determined through inductively-coupled plasma analysis (ICP-OES Thermo iCAP 6500 DUO, Thermo Fisher Scientific, Cambridge, UK).

To determine enzymatic activity, fresh samples of natural moisture were taken, passed through a sieve with a mesh diameter of 2 mm and stored at 4°C. The activity of extracellular enzymes (β-glucosidase (BG), β-D-cellobiosidase (CB), β-xylosidase (XYL), N-acetyl-β-D-glucosaminidase (NAG), phosphatase (PH) and arylsulphatase (SP)) was determined with fluorescently-labelled substrates (Pritsch *et al.*, 2004; Sanaullah *et al.*, 2016; Turner, 2010). Fluorescence was measured on a multi-detection plate reader (BioTek) with excitation at a wavelength of 355 nm and emission at 460 nm. The soil C:N acquisition ratios were calculated with BG:NAG, BG:PH and NAG:PH for the soil C:P while N:P acquisition ratios, respectively (Lasota *et al.*, 2021). To conduct a model experiment in the laboratory, litter of the tested species was collected using a metal frame measuring 20×20 cm. Litter samples collected in the field were dried, and then weighted (20 g) and placed in glass funnels with filter paper. Litter samples were rinsed with distilled water (250 ml) and the obtained filtrates were subjected to further analysis. Water samples collected during the column experiments were chemically analysed. They were stored at 4°C and filtered with 0.45-μm filters. The water chemistry was analysed with ion chromatography using a DIONEX ICS 5000 unit. The concentrations of total carbon (TC), inorganic carbon (IC), total organic carbon (TOC) and total nitrogen (TN) were determined with a Shimadzu Total Organic Carbon (TOC) analyser (Shimadzu, Japan). The concentration of TOC in filtered water samples was equal to the dissolved organic carbon (DOC). Electrical conductivity (EC) and pH values were also determined.

STATISTICAL ANALYSIS. An one-way ANOVA test was used to assess significant differences between the mean values of properties. The relationships between properties were established with the Pearson correlation coefficient. Principal component analysis (PCA) was used to interpret factors in certain data sets. Differences with $P<0.05$ were considered statistically significant. All analyses were performed in Statistica 12 software (StatSoft, 2012).

Results

Urban forest soils in Kraków, influenced by alien tree species, were characterised by different physicochemical properties and enzymatic activity (Tables 1, 2). The tested soils were characterised by pH in the range of 3.99-6.90 (Table 1). The lowest pH was recorded in soils with Douglas fir and the highest in soils with common walnut. The average C content ranged from 12.78 g kg^{-1} to 114.20 g kg^{-1}, and the N content ranged from 1.35 g kg^{-1} to 6.31 g kg^{-1}. Significantly lower C and N content were recorded in soils with box elder compared to the other tested species. Significantly higher C and N content in soils with black cherry were noted compared to the sweet chestnut, box elder, horse chestnut, common walnut and black locust. Less differentiation was noted for P content and basic cations (Table 1). Black cherry soils had the highest P content, while box elder, common walnut and black locust soils had the lowest P content compared to the other tested species. Less differentiation was noted in the studied soils' enzymatic activity (Table 2). The highest β-D-cellobiosidase (CB) and β-xylosidase (XYL) activity was recorded in Canada hemlock soils. Black cherry soils showed the highest N-acetyl-β-D-glucosaminidase (NAG) and phosphatase (PH) activity. The highest β-glucosidase (BG) activity was found in soils with black locust, and the highest arylsulphatase (SP) activity was recorded in sweet chestnut soils (Table 2). Significant differences were found only for PH activity levels (Table 2). Phosphatase activity in soils with black cherry was statistically the highest compared to other tested species, excluding Canada hemlock. The enzymatic activity of NAG, XYL, SP and PH strongly correlated with the pH of the studied soils and the P content. Meanwhile, the NAG, XYL and PH activity positively correlated with the C and N content and negatively correlated with pH (Table 3).

Wider C/N/P stoichiometry was noted in soils with Douglas fir and Canada hemlock (521/21/1 and 423/18/1, respectively). Narrower C/N/P stoichiometry was noted in soils with box elder (92/8/1). A significantly higher C/N ratio was found in soils with Douglas fir, black cherry and Canada hemlock (24.3, 21.2 and 23.7, respectively) compared to box elder (Fig. 1). Soils with Douglas fir, black cherry and Canada hemlock were characterised by a 5-fold higher C/P ratio compared to soils with box elder. The N/P ratio recorded in soils with Douglas fir and black cherry was three times higher than that of soils with box elder. Box elder soils had the lowest C/N, C/P and N/P ratios (Fig. 1). Analysis of the BG, NAG and PH activity by stoichiometry demonstrates that the studied soil samples differ significantly in their BG/NAG, BG/PH and NAG/PH ratios (Fig. 2). The highest BG/NAG ratio was recorded in soils with black locust (6.5) and the lowest in soils with black cherry (0.4). The highest BG/PH ratio was recorded in soils with common walnut (0.8) and the lowest in soils with sweet chestnut (0.1) and black cherry (0.1). The highest NAG/PH ratio was recorded in soils with Douglas fir (0.3) and black cherry (0.3) and the lowest in soils with box elder (0.1; see Fig. 2).

The analysis confirmed the relationship between the physicochemical properties of the studied soils and the C/N/P stoichiometry. The C/N ratio was strongly negatively correlated with the Ca and Mg content and pH ($r=-0.75$, $r=-0.65$ and $r=-0.84$, respectively) and positively correlated with P content ($r=0.81$; see Table 4). The C/P ratio correlated with N, C and P content. The N/P ratio was negatively correlated with Ca content and pH ($r=-0.43$ and $r=-0.61$, respectively) and positively correlated with the N, C and P content ($r=0.91$, $r=0.85$ and $r=0.56$, respec-

Table 1.

Basic properties of soil under the influence of different alien tree species

Species	pH	C	N	P	Ca	K	Mg	Na
SC	4.47 ±0.08c	52.52 ±5.87bc	3.28 ±0.31c	0.43 ±0.06b	1.85 ±0.27b	0.29 ±0.04b	0.49 ±0.07c	0.01 ±0.00b
DF	3.99 ±0.06c	109.43 ±7.45a	5.25 ±0.38ab	0.54 ±0.06ab	2.82 ±0.31b	0.26 ±0.01b	0.54 ±0.01c	0.02 ±0.01ab
BE	5.84 ±0.57b	12.78 ±2.35d	1.35 ±0.22d	0.36 ±0.05c	15.82 ±8.10a	0.29 ±0.02b	1.28 ±0.14b	0.01 ±0.011b
HC	5.84 ±0.35b	31.33 ±11.10c	2.27 ±0.53cd	0.44 ±0.06b	14.40 ±3.97a	0.53 ±0.16a	1.86 ±0.29b	0.01 ±0.00b
CW	6.90 ±0.02a	21.98 ±2.77c	1.87 ±0.20d	0.38 ±0.04c	15.30 ±1.68a	0.62 ±0.11a	1.54 ±0.08b	0.01 ±0.00b
BL	6.46 ±0.35ab	39.72 ±0.94c	3.21 ±0.05c	0.36 ±0.01c	22.62 ±2.50a	0.47 ±0.07ab	2.90 ±0.55a	0.06 ±0.00a
BC	4.18 ±0.16c	114.20 ±15.02a	6.31 ±0.55a	0.60 ±0.04a	3.91 ±0.93b	0.53 ±0.06a	1.01 ±0.02bc	0.01 ±0.01b
CH	4.08 ±0.34c	87.75 ±31.40ab	4.23 ±0.93bc	0.53 ±0.09ab	2.53 ±0.41b	0.25 ±0.06b	0.47 ±0.07c	0.04 ±0.04ab

Mean ±SD, C, N and P content ($g \cdot kg^{-1}$), Ca, K, Mg and Na content ($cmol(+) \cdot kg^{-1}$), SC – sweet chestnut, DF – Douglas fir, BE – box elder, HC – horse chestnut, CW – common walnut, BL – black locust, BC – black cherry, CH – Canada hemlock; small letters in the upper index of the mean values mean significant differences between species

Table 2.

Enzyme activity (nmol MUB g d.m. h^{-1}) in soil under the influence of different alien tree species

Species	CB	BG	NAG	XYL	SP	PH
SC	2.58 ±3.82	25.23 ±14.91	39.43 ±31.29	0.60 ±1.04	12.58 ±11.22	224.68 ±150.97bc
DF	6.59 ±3.37	59.79 ±28.32	66.22 ±15.81	35.55 ±21.61	3.93 ±1.56	216.75 ±77.37bc
BE	0.47 ±0.81	36.34 ±21.81	9.56 ±5.28	0.00 ±0.00	0.00 ±0.00	79.29 ±75.60c
HC	9.31 ±12.35	83.16 ±44.51	44.14 ±1.50	0.00 ±0.00	0.00 ±0.00	309.53 ±47.39abc
CW	11.12 ±11.51	120.87 ±63.29	48.72 ±45.54	2.05 ±2.58	0.00 ±0.00	143.46 ±43.12c
BL	16.47 ±9.99	136.00 ±24.54	21.20 ±1.06	9.87 ±9.79	2.30 ±1.92	249.81 ±133.14bc
BC	14.46 ±1.77	77.89 ±36.81	203.86 ±87.48	30.64 ±5.30	8.24 ±11.03	608.77 ±179.73a
CH	22.63 ±20.04	96.39 ±70.90	132.65 ±192.00	61.02 ±79.89	4.06 ±3.52	525.27 ±109.37ab

Mean ±SD, CB – ß-D-cellobiosidase, XYL – ß-xylosidase, NAG – N-acetyl-ß-D-glucosaminidase, BG – ß-glucosidase, PH – phosphatase and SP – arylosulphatase, SC – sweet chestnut, DF – Douglas fir, BE – box elder, HC – horse chestnut, CW – common walnut, BL – black locust, BC – black cherry, CH – Canada hemlock, small letters in the upper index of the mean values mean significant differences between species

Table 3.
Relationships between the physicoproperties of the studied soils

	pH	N	C	P
CB	–0.10	0.33	0.35	0.36
BG	0.30	0.02	0.02	–0.02
NAG	–0.47*	0.62*	0.62*	0.62*
XYL	–0.51*	0.57*	0.57*	0.54*
SP	–0.43*	0.36	0.36	0.42*
PH	–0.51*	0.63*	0.63*	0.71*

*$p<0.05$

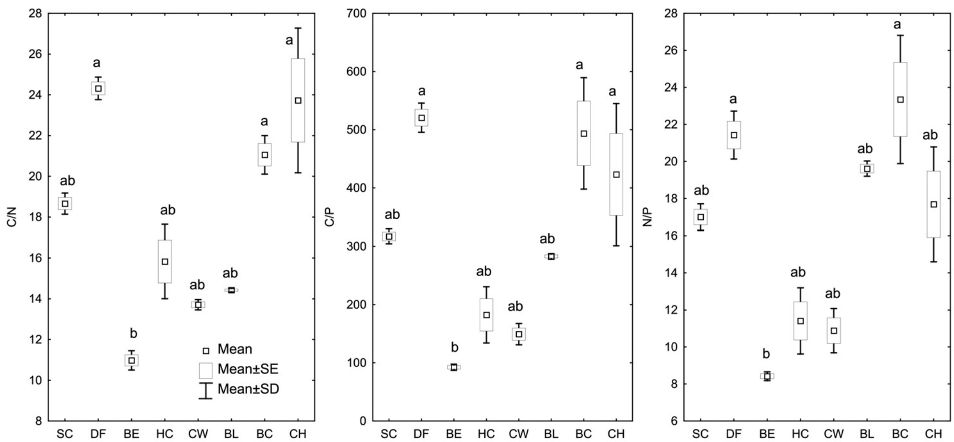

Fig. 1.
C:N:P stoichiometry in soil under the influence of different alien tree species
SC – sweet chestnut, DF – Douglas fir, BE – box elder, HC – horse chestnut, CW – common walnut, BL – black locust, BC – black cherry, CH – Canada hemlock, small letters mean significant differences between species

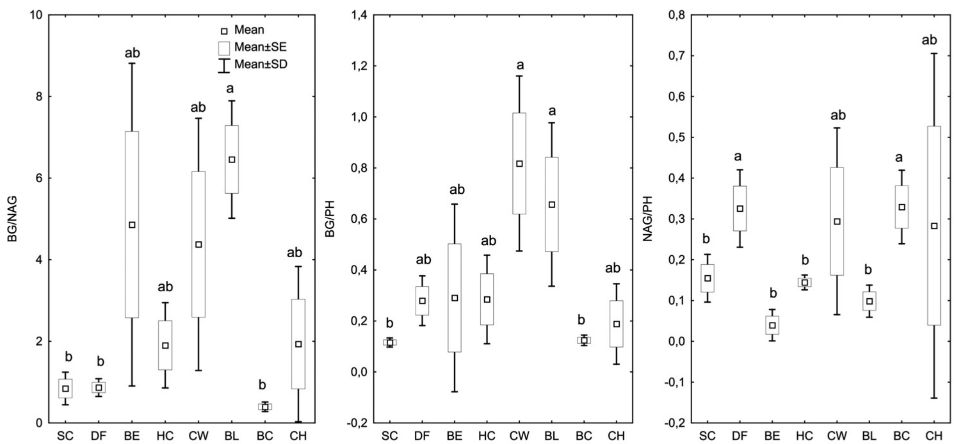

Fig. 2.
Stoichiometry of BG, NAG, and PH activities in soils under the influence of different alien tree species
SC – sweet chestnut, DF – Douglas fir, BE – box elder, HC – horse chestnut, CW – common walnut, BL – black locust, BC – black cherry, CH – Canada hemlock, BG – β-glucosidase, NAG – N-acetyl-β-D-glucosaminidase, PH – phosphatase; small letters mean significant differences between species

tively; see Table 4). The analysis also confirmed the relationship between stoichiometry and the biological activity of the soils, expressed as enzyme activity. The C/N, C/P, and N/P ratios correlated with the NAG, XYL and PH activity.

The studied species' litter analyses confirmed the diversity of their properties (Table 5). The highest pH was found in the litter of black locust and horse chestnut, which was 6.33 and 6.09, respectively (Table 5). Significantly lowest pH was recorded in the litter of box elder (3.76). The litter of the studied species also differed in the content of N and C. Significant differences were noted in the case of the C/N ratio. The Douglas fir and Canada hemlock litter were characterised by the highest C/N ratio (44.3 and 40.03, respectively) (Table 5). The analysis of leachates from the litter of the tested alien tree species confirmed the observed differences in chemical composition. Different properties characterized coniferous species (Douglas fir and Canada hemlock) compared to the other studied species. Conifers' TC, DOC and TN content were ten times lower than the other species (Table 6). At the same time, coniferous species were characterized by the lowest base cation content, especially of Ca, K and Mg (Fig. 3).

PCA analysis explains 62% of the variability of examined properties (Fig. 4). Factor 1 is related to the enzyme stoichiometry. Factor 2 is related to the soil and litter properties. PCA analysis distinguished two groups of species: one dominated by coniferous and the other by deciduous species. Soils with deciduous species were characterized by a higher pH, higher content of basic cations and higher enzymatic activity. PCA analysis confirmed that soils with coniferous species, sweet chestnut and black cherry were characterised by higher C/N, C/P and N/P ratios (Fig. 4).

Discussion

The investigated tree species exert various effects on soils' physicochemical and biochemical properties. The differences in the tested soil properties result from differences in the properties

Table 4.
Relationships between the properties of the studied soils

	Ca	K	Mg	Na	pH	N	C	P	CB	BG	NAG	XYL	SP	PH
C/N	–0.75*	–0.31	–0.60*	0.22	–0.84*	0.84*	0.92*	0.81*	0.34	0.02	0.54*	0.66*	0.35	0.55*
C/P	–0.63*	–0.25	–0.44*	0.31	–0.79*	0.95*	0.97*	0.73*	0.31	0.01	0.56*	0.64*	0.30	0.51*
N/P	–0.43*	–0.11	–0.17	0.37	–0.61*	0.91*	0.85*	0.56*	0.28	0.07	0.46*	0.47*	0.28	0.46*

*$p<0.05$

Table 5.
Chemical properties of litter of the studied tree species

Species	pH	N	C	C/N
SC	4.71 ±0.05b	2.65 ±0.31b	44.69 ±0.71ab	16.9 ±0.9b
DF	4.15 ±0.06b	1.04 ±0.09c	46.21 ±1.21a	44.3 ±2.8a
BE	3.76 ±0.12c	2.25 ±0.17b	42.40 ±2.02b	18.8 ±1.2b
HC	6.09 ±0.51a	2.94 ±0.71b	44.30 ±3.02ab	15.1 ±0.8c
CW	5.06 ±0.08a	3.04 ±0.12a	42.07 ±1.82b	13.9 ±1.1d
BL	6.33 ±0.72a	3.73 ±0.42a	46.88 ±2.42a	12.4 ±0.7d
BC	4.97 ±0.68a	2.24 ±0.11b	43.30 ±3.21ab	19.3 ±1.3b
CH	4.09 ±0.21b	1.14 ±0.09c	46.06 ±2.81a	40.3 ±3.4a

Mean ±SD, C, N content ($g \cdot kg^{-1}$), SC – sweet chestnut, DF – Douglas fir, BE – box elder, HC – horse chestnut, CW – common walnut, BL – black locust, BC – black cherry, CH – Canada hemlock, small letters in the upper index of the mean values mean significant differences between species

Table 6.

Concentrations of total carbon (TC), dissolved organic carbon (DOC) and total nitrogen (TN) of leachates from the litter of different alien tree species

Species	pH	EC	TC	DOC	TN
SC	4.85 ±0.06d	0.85 ±0.18bc	2276.7 ±551.7b	2275.1 ±550.1b	50.2 ±10.2c
DF	4.85 ±0.17d	0.23 ±0.05c	387.5 ±73.5c	387.1 ±73.5c	9.3 ±1.0d
BE	3.75 ±0.06e	2.01 ±0.34a	2675.0 ±554.7b	2674.5 ±554.7b	91.6 ±18.7b
HC	5.45 ±0.05b	1.90 ±0.51a	2446.3 ±108.1b	2442.5 ±103.4b	101.9 ±30.4b
CW	5.34 ±0.18bc	1.67 ±0.54ab	2210.7 ±308.7b	2209.7 ±309.2b	69.9 ±6.5bc
BL	6.32 ±0.02a	1.26 ±0.06ab	1943.3 ±198.8b	1942.1 ±198.6b	200.1±12.7a
BC	5.07 ±0.10cd	2.00 ±0.06a	3864.8 ±52.5a	3864.4 ±52.6a	101.9 ±1.7b
CH	5.69 ±0.19b	0.06 ±0.01c	95.5± 27.9c	94.5 ±27.2c	4.00 ±0.5d

Mean ±SD, EC – electrical conductivity (mS·cm^{-1}), TC – concentrations of total carbon (mg·L^{-1}), TN – total nitrogen (mg·L^{-1}), DOC – dissolved organic carbon (mg·L^{-1}), SC – sweet chestnut, DF – Douglas fir, BE – box elder, HC – horse chestnut, CW – common walnut, BL – black locust, BC – black cherry, CH – Canada hemlock, small letters in the upper index of the mean values mean significant differences between species

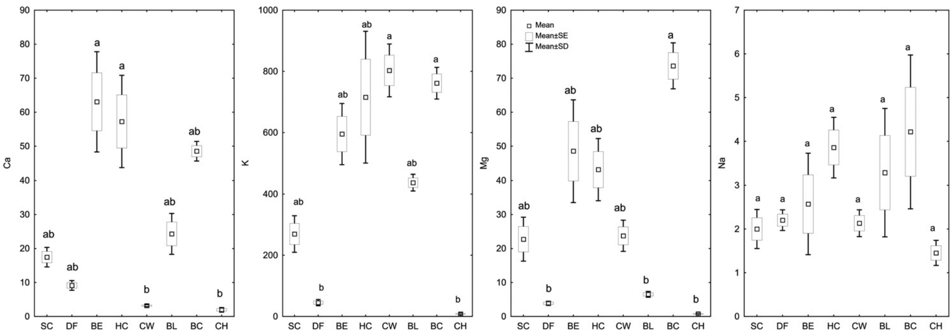

Fig. 3.

C:N:P stoichiometry in soil under the influence of different alien tree species

SC – sweet chestnut, DF – Douglas fir, BE – box elder, HC – horse chestnut, CW – common walnut, BL – black locust, BC – black cherry, CH – Canada hemlock, small letters mean significant differences between species

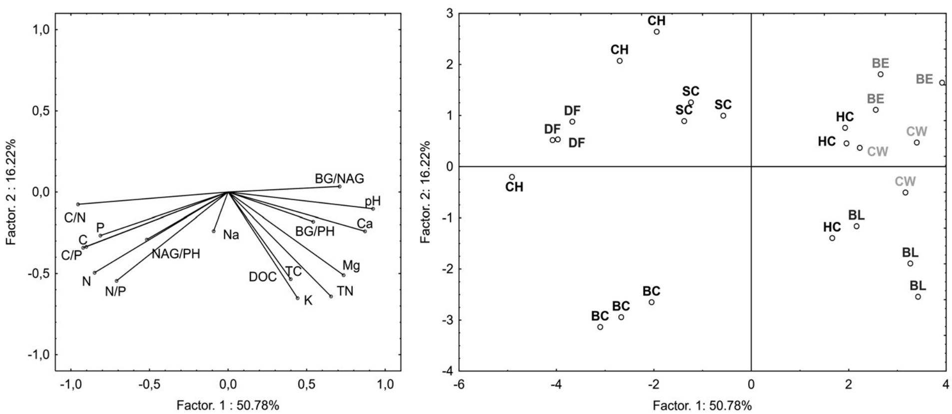

Fig. 4.

The projection of variables on a plane of the first and second PCA factors

BG – β-glucosidase, NAG – N-acetyl-β-D-glucosaminidase, PH – phosphatase, DOC – dissolved organic carbon, TC – total carbon, TN – total nitrogen, SC – sweet chestnut, DF – Douglas fir, BE – box elder, HC – horse chestnut, CW – common walnut, BL – black locust, BC – black cherry, CH – Canada hemlock of the organic substances coniferous and deciduous species supply. On average, the organic carbon content was twice as high in soils with Douglas fir and Canada hemlock trees. These soils have a high C/N ratio, which means they decompose at a slower rate. In the case of Douglas fir Cremer *et al*. (2016) recorded one of the highest C/N ratio which was approximately 25. A similar C/N ratio was determined in soils influenced by Scots pine (Błońska *et al.*, 2018). The litter deciduous and coniferous species supply differs in its C/N ratio and lignin/N ratio (Taylor *et al.*, 1989; Rahman and Tsukamoto, 2013). Valachovic *et al*. (2004) demonstrated a lower weight loss in the litter of coniferous species compared to deciduous species in an experiment with litter bags. The litter rotation rate of conifers is lower than that of deciduous trees (Vesterdal *et al.*, 2008; Rahman and Tsukamoto, 2013). The study found that the soils with coniferous species, such as Douglas fir and Canada hemlock, had a wider C/N/P stoichiometry (521/21/1 and 423/18/1, respectively).

On the other hand, the soils with box elder had a narrower C/N/P stoichiometry (92/8/1). Our results confirm a strong relationship between the C/N, C/P and N/P ratios, pH and the primary cation content. The properties of forest soils are shaped by the aboveground biomass, especially the litter, which is the source of essential nutrients. The TC, DOC and TN content of coniferous litter was 10 times lower than that of other species and characterised by the lowest base cation content, especially of Ca, K and Mg. The results confirm how strongly trees, through the biomass they provide, can modify the rate of decomposition of soil organic matter, which may be reflected in the C/N/P stoichiometry of the soil. The C/N ratio is an indicator of the degree of plant-available nitrogen contained in plant residues (Błońska, 2015). Tree species that produce higher quality litter (with a higher N concentration and lower C:N ratio) in greater quantity may facilitate the abundance and diversity of soil fauna (Peng *et al.*, 2022). The composition of the soil microbial community and enzyme activities are directly affected by the soil's N/P and C/P ratio, which is influenced by the soil's elemental stoichiometry (Shen *et al.*, 2019). The NAG, XYL and PH activity was strongly correlated with soils' stoichiometry. Our analysis of the BG, NAG and PH activity stoichiometry demonstrates that the investigated tree species affect the BG/NAG, BG/PH and NAG/PH ratios differently. Previous studies have verified that species play a vital role in determining stoichiometry, with the C/N ratio being the most significant factor, followed by the C/P and N/P ratios to a lesser extent (Lasota *et al.*, 2021). The amount and diversity of soil microorganisms are related to the amount of C, N and P in the soil; therefore, the stoichiometry of soil enzymes can be used to characterise microbial nutrient requirements and limits (Sterner and Elser, 2002).

As expected, soils with coniferous species like Douglas fir and Canada hemlock were characterised by the lowest pH. Coniferous stands have a more acidifying effect on the soil than deciduous and mixed stands (Błońska *et al.*, 2016). Augusto *et al.* (2002) compiled a ranking of species by acidifying ability: coniferous species > beech, oak and birch > maple, hornbeam, ash and linden. The experiments with the litter of the tested species showed which species' litter had the lowest pH. The litter of Douglas fir, showed a low pH and, among deciduous species, a low pH characterised the ash-leaf maple – a high pH characterised black locust litter. Qiu *et al.* (2010) reported high pH values (around 8.0) in soils affected by black locust. Previously conducted studies indicate that the C/N ratio can be used to assess the quality of organic remains delivered to the soil, which has a direct impact on the properties of surface soil horizons (Błońska *et al.*, 2017, 2021). In the conducted studies, we confirmed the diversity of C/N, which indicates the different qualities of detritus delivered to the soil by the studied tree species. The initial quality of the litter expressed by the C/N ratio is essential in the processes of litter decomposition and for the amount of released components (Li *et al.*, 2020). The statistical analysis of the obtained results shows a strong dependence of enzymatic activity with soil pH and the C, N and P content. Soil enzymes are affected by the pH of the soil, which affects their activity by controlling ionisation, enzyme conformation changes, and the availability of substrates and cofactors (Tabatabai, 1994). Soil pH significantly impacts microorganisms, as many enzymes are sensitive to it. NAG, XYL, SP, and PH activity are negatively affected by pH levels but strongly correlate with carbon and nitrogen content. Organic matter can be identified as the critical factor determining the activity of these enzymes. Organic matter, as the fundamental source of energy for soil organisms, stimulates microbial activity, which is reflected in the level of enzymatic activity (Błońska *et al.*, 2016). Soil fauna primarily relies on the forest floor and top mineral soil horizon for carbon and nutrients. The influence of tree species on these habitats and soil properties can significantly impact soil biological activity (Peng *et al.*, 2022). We also noted a relationship between the activity of the tested enzymes and the soil P content. According to Fatemi *et al.*(2016), litter is an essential source of organic P in forest ecosystems. We expect litter decomposition rates to result in P substrates becoming available for microbes to degrade. Microorganisms often cannot access phosphorus (P) due to its binding to iron minerals and organic matter, as noted by Liu *et al.* (2020). However, changes in soil stoichiometry can affect microbial interactions and community dynamics, potentially leading to feedback that impacts nutrient availability (Zechmeister-Boltenstern *et al.*, 2015).

The studied species of alien trees influenced the alkaline cation content in the surface soil horizons. Differences in the base cation content between alien tree species may result from the quality of litter along with the cation uptake and accumulation rates in biomass (Błońska *et al.*, 2021; Stefanowicz *et al.*, 2021). We noted significant differences in the Ca, Mg and K content in leachates from the litter of the studied species. Significantly higher Ca content was found in soils with box elder and horse chestnut, significantly higher Mg content in soils with black cherry and significantly higher K content in soils with common walnut and cherry trees. High Ca content in horse chestnut soils were recorded in previous studies (Karliński *et al.*, 2014). Leachates from the litter of the studied coniferous species were characterised by significantly lower Ca, Mg and K content compared with deciduous species. The low base saturation in Douglas fir soils was noted by Šrámek *et al.* (2019). Leaf litter Ca and Mg concentrations are critical factors for soil biological activity (Reich *et al.*, 2005).

Conclusions

Soils influenced by the studied alien tree species were characterized by diverse physicochemical and biochemical properties. Differences in the tested soil properties result from differences in the properties of the supplied organic matter. The results indicate significant differences in C, N, and P cycles among the soils altered by the study species of trees as confirmed by C/N/P stoichiometry in soils. The results of our research indicated the possibility of using the C/N/P stoichiometry in assessing the impact of various tree species on soil conditions in urban forests. The general conclusion from this research is that by diversifying the species composition of the forest stand with the use of alien tree species, we significantly influence the physicochemical and biochemical properties of urban forest soils. Understanding these effects is important for the sustainable management of forest ecosystems. The obtained results may have practical applications in shaping urban forests.

Authors' contributions

PK, JL and EB contributed to the conception, design, and with MK investigation of the study. PK and EB organized the database, and with MK performed the formal analysis. PK wrote the first draft of the manuscript. PK, JL, MK and EB wrote sections of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

Conflicts of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Adamczyk, B., Kilpeläinen, P., Kitunen, V.H., Smolander, A., 2014. Potential activities of enzymes involved in N, C, P and S cycling in boreal forest soil under different tree species. *Pedobiologia*, 57: 97-102. DOI: https://doi.org/10.1016/j.pedobi.2013.12.003.

Augusto, L., Ranger, J., Binkley, D., Rothe, A., 2002. Impact of several common tree species of European temperate forests on soil fertility. *Annals of Forest Science*, 59: 233-253. DOI: https://doi.org/10.1051/forest:2002020.

Baldrian, P., Šnajdr, J., 2011. Lignocellulose-degrading enzymes in soil. In: G. Shukla, A. Varma, eds. *Soil enzymology*. Berlin: Springer-Verlag, pp.167-186.

Beven, K., Germann, P., 2013. Macropores and water flow in soils revisited. *Water Resources Research*, 49: 3071-3092. DOI: https://doi.org/10.1002/wrcr.20156.

Błońska, E., 2015. Effect of stand species composition on the enzyme activity and organic matter stabilization in forest soil. *Zeszyty Naukowe Uniwersytetu Rolniczego im. Hugona Kołłątaja w Krakowie nr* 527. *Rozprawy*, 404: 1-85.

Błońska, E., Klamerus-Iwan, A., Lasota, J., Gruba, P., Pach, M., Pretzsch, H., 2018. What characteristics of soil fertility can improve in mixed stands of Scots pine and European Beech compared with monospecific stands? *Communication in Soil Science and Plant Analysis*, 49: 237-247. DOI: https://doi.org/10.1080/00103624.2017.1421658.

Błońska, E., Lasota, J., Gruba, P., 2016. Effect of temperate forest tree species on soil dehydrogenase and urease activities in relation to other properties of soil derived from loess and glaciofluvial sand. *Ecological Research*, 31 (5): 655-664. DOI: https://doi.org/10.1007/s11284-016-1375-6.

Błońska, E., Lasota, J., Gruba, P., 2017. Enzymatic activity and stabilization of organic matter in soil with different detritus inputs. *Journal of Soil Science and Plant Nutrition*, 63: 242-247. DOI: https://doi.org/10.1080/00380768.2017.1326281.

Błońska, E., Piaszczyk, W., Staszel, K., Lasota, J., 2021. Enzymatic activity of soils and soil organic matter stabilization as an effect of components released from the decomposition of litter. *Applied Soil Ecology*, 157: 103723. DOI: https://doi.org/10.1016/j.apsoil.2020.103723.

Cremer, M., Kern, N.V., Prietzel, J., 2016. Soil organic carbon and nitrogen stocks under pure and mixed stands of European beech, Douglas fir and Norway spruce. *Forest Ecology and Management*, 367: 30-40. DOI: https://doi.org/10.1016/j.foreco.2016.02.020.

Enescu, C.M., de Rigo, D., Caudullo, G., Durrant, T.H., 2016. *Pinus nigra* in Europe: distribution, habitat, usage and threats. In: J. San-Miguel-Ayanz, D. de Rigo, G. Caudullo, T.H. Durrant, A. Mauri, eds. *European atlas of forest tree species*. Luxembourg: Publication Office of the European Union.

Fatemi, F.R., Fernandez, I.J., Simon, K.S., Dail, D.B., 2016. Nitrogen and phosphorus regulation of soil enzyme activities in acid forest soils. *Soil Biology and Biochemistry*, 98: 171-179. DOI: https://doi.org/10.1016/j.soilbio.2016.02.017.

Gruba, P., Mulder, J., 2015. Tree species affect cation exchange capacity (CEC) and cation binding properties of organic matter in acid forest soils. *Science of the Total Environment*, 511: 655-662. DOI: https://doi.org/10.1016/j.scitotenv.2015.01.013.

Hobbie, S.E., Reich, P.B., Oleksyn, J., Ogdahl, M., Zytkowiak, R., Hale, C., Karolewski, P., 2006. Tree species effects on decomposition and forest floor dynamics in a common garden. *Ecology*, 87: 2288-2297. DOI: https://doi.org/10.1890/0012-9658(2006)87[2288:TSEODA]2.0.CO;2.

Karliński, L., Jagodziński, A.M., Leski, T., Butkiewicz, P., Brosz, M., Rudawska, M., 2014. Fine root parameters and mycorrhizal colonization of horse chestnut trees (*Aesculus hippocastanum* L.) in urban and rural environments. *Landscape and Urban Planning*, 127: 154-163. DOI: https://doi.org/10.1016/j.landurbplan.2014.04.014.

Landgraf, D., Klose, S., 2002. Mobile and readily available C and N fractions and their relationship to microbial biomass and selected enzyme activities in a sandy soil under different management systems. *Journal of Plant Nutrition and Soil Science*, 165: 9-16. DOI: https://doi.org/10.1002/1522-2624(200202)165:1%3C9::AID-JPLN9%3E3.0.CO;2-O.

Lasota, J., Małek, S., Jasik, M., Błońska, E., 2021. Effect of planting method on C:N:P stoichiometry in soils, young silver fir (*Abies alba* Mill.) and stone pine (*Pinus cembra* L.) in the upper mountain zone of Karpaty Mountains. *Ecological Indicators*, 129 (6): 107905. DOI: https://doi.org/10.1016/j.ecolind.2021.107905.

Li, Q., Zhang, M., Geng, Q., Jin, C., Zhu, J., Rian, H., Xu, X., 2020. The roles of initial litter traits in regulating litter decomposition: a 'common plot' experiment in a subtropical evergreen broadleaf forest. *Plant and Soil*, 452: 207-216. DOI: https://doi.org/10.1007/s11104-020-04563-8.

Liu, J, Chen, J, Chen, G, Guo, J, Li, Y., 2020. Enzyme stoichiometry indicates the variation of microbial nutrient requirements at different soil depths in subtropical forests. *PLoS ONE*, 15: e0220599. DOI: https://doi.org/10.1371/journal.pone.0220599.

Małek, S., Ważny, R., Błońska, E., Jasik, M., Lasota, J., 2021. Soil fungal diversity and biological activity as indicators of fertilization strategies in a forest ecosystem after spruce disintegration in the Karpaty Mountains. *Science of the Total Environment*, 751: 142335. DOI: https://doi.org/10.1016/j.scitotenv.2020.142335.

Mueller, K.E., Eissenstat, D.M., Hobbie, S.E., Oleksyn, J., Jagodziński, A.M., Reich, P.B., Chadwick, O.A., Chorover, J., 2012. Tree species effects on coupled cycles of carbon, nitrogen, and acidity in mineral soils at a common garden experiment. *Biogeochemistry*, 111: 601-614. DOI: https://doi.org/10.1007/s10533-011-9695-7.

Paluch, J., Gruba, P., 2012. Effect of local species composition on topsoil properties in mixed stands with silver fir (*Abies alba* Mill.). *Forestry*, 85: 413-426. DOI: https://doi.org/10.1093/forestry/cps040.

Peng, Y., Holmstrup, M., Schmidt, I.K., Schrijver, A.D., Schelfhout, S., Hedenec, P., Zheng, H., Bachega, L.R., Yue, K., Vesterdal, L., 2022. Litter quality, mycorrhizal association, and soil properties regulate effects of tree species on the soil fauna community. *Geoderma*, 407: 115570. DOI: https://doi.org/10.1016/j.geoderma.2021.115570.

Pritsch, K., Raidl, S., Marksteiner, E., Blaschke, H., Agerer, R., Schloter, M., Hartmann, A., 2004. A rapid and highly sensitive method for measuring enzyme activities in single mycorrhizal tips using 4-methylumbelliferone-labelled fluorogenic substrates in a microplate system. *Journal of Microbiological Methods*, 58: 233-241. DOI: https://doi.org/10.1016/j.mimet.2004.04.001.

Qiu, L., Zhang, X., Cheng, J., Yin, X., 2010. Effects of black locust (*Robinia pseudoacacia*) on soil properties in the loessial gully region of the loess Plateau China. *Plant and Soil*, 332: 207-217.

Rahman, M.M., Tsukamoto, J., 2013. Leaf traits, litter decomposability and forest floor dynamics in an evergreen – and deciduous-broadleaved forest in warm temperate Japan. *Forestry*, 86 (4): 441-451. DOI: https://doi.org/10.1093/forestry/cpt015.

Reich, P.B., Oleksyn, J., Modrzynski, J., Mrozinski, P., Hobbie, S.E., Eissenstat, D.M., Chorover, J., Chadwick, O.A., Hale, C.M., Tjoelker, M.G., 2005. Linking litter calcium, earthworms and soil properties: a common garden test with 14 tree species. *Ecology Letters*, 8 (8): 811-818. DOI: https://doi.org/10.1111/j.1461-0248.2005.00779.x.

Sanaullah, M., Razavi, B.S., Blagodatskaya, E., Kuzyakov, Y., 2016. Spatial distribution and catalytic mechanisms of β-glucosidase activity at the root-soil interface. *Biology and Fertility of Soils*, 52: 505-514. DOI: https://doi.org/10.1007/s00374-016-1094-8.

Santa-Regina, I., Tarazona, T., 2001. Nutrient cycling in a natural beech forest and adjacent planted pine in northern Spain. *Forestry*, 74: 11-28. DOI: https://doi.org/10.1093/forestry/74.1.11.

Scheu, S., Parkinson, D., 1995. Successional changes inmicrobial biomass, respiration and nutrient status duringlitter decomposition in an aspen and pine forest. *Biology and Fertility of Soils*, 19: 237-332. DOI: https://doi.org/10.1007/BF00336103.

Shen, F., Wu, J., Fan, H., Liu W., Guo, X., Duan, H., Hu, L., Lei, X., Wie, X., 2018. Soil N/P and C/P ratio regulate the responses of soil microbial community composition and enzyme activities in a long-term nitrogen loaded Chinese fir forest. *Plant and Soil*, 436: 91-107. DOI: https://doi.org/10.1007/s11104-018-03912-y.

Skiba, S., Drewnik, M., 2013. Directions of agricultural development. In: B. Degórska, M. Baścik, eds. *The natural environment of Krakow. Reosurces – Protection – Shaping.* Kraków: Publishing House of the Institute of Geography and Spatial Management UJ, pp. 225-229.

Šrámek, V., Fadrhonsová, V., Hellebrandová, K.N., 2019. Nutrition of Douglas-fir in four different regions of the Czech Republik. *Journal of Forest Science*, 65: 1-8. DOI: http://dx.doi.org/10.17221/130/2018-JFS.

StatSoft, 2012. Statistica (data analysis software system), version 10. Available from: www.statsoft.com.

Stefanowicz, A.M., Rożek, K., Stanek, M., Rola, K., Zubek, S., 2021. Moderate effects of tree species identity on soil microbial communities and soil chemical properties in a common garden experiment. *Forest Ecology and Management*, 482: 118799. DOI: https://doi.org/10.1016/j.foreco.2020.118799.

Sterner, R.W., Elser, J.J., 2002. Ecological stoichiometry: The biology of elements from molecules to the biosphere. Princeton: Princeton University Press.

Tabatabai, M.A., 1994. Soil enzymes. In: R.W. Weaver, S. Angle, P. Bottomley, D. Bezdicek, S. Smith, A. Tabatabai, A. Wollum, eds. *Methods of soil analysis. Part 2. Microbiological and biochmical properties soil science Society of America*. Madison: WI, pp. 775-833

Taylor, B.R., Parkinson, D., Parsosns, W.F.J., 1989. Nitrogen and lignin content as predictors of litter decay rates: a microcosm test. *Ecology*, 70: 97-104. DOI: https://doi.org/10.2307/1938416.

Turner, B.L., 2010. Variation in pH optima of hydrolytic enzyme activities in tropical rain forest soils. *Applied and Environmental Microbiology*, 76: 6485-6493. DOI: https://doi.org/10.1128/AEM.00560-10.

Uzarowicz, Ł., Wolińska, A., Błońska, E., Szafranek-Nakonieczna, A., Kuźniar, A., Słodczyk, Z., Kwasowski, W., 2020. Technogenic soils (*Technosols*) developed from mine spoils containing Fe sulphides: microbiological activity as an indicator of soil development following land reclamation. *Applied Soil Ecology*, 156: 103699. DOI: https://doi.org/10.1016/j.apsoil.2020.103699.

Valachovic, Y.S., Caldwell, B.A., Cromack, K., Griffiths, R.P., 2004. Leaf litter chemistry controls on decomposition of Pacific Northwest trees and woody shrubs. *Canadian Journal of Forest Research*, 34: 2131-2147. DOI: https://doi.org/10.1139/x04-089.

Vesterdal, L., Schmidt, I.K., Callesen, I., Nilsson, L.O., Gundersen, P., 2008. Carbon and nitrogen in forest floor and mineral soil under six common European tree species. *Forest Ecology and Management*, 255 (1): 35-48. DOI: https://doi.org/10.1016/j.foreco.2007.08.015.

Wardle, D.A., 1992. A comparative assessment of factors which influence microbial biomass carbon and nitrogen levels in soil. *Biological Reviews*, 67: 321-358. DOI: http://dx.doi.org/10.1111/j.1469-185X.1992.tb00728.x.

Zechmeister-Boltenstern, S., Keiblinger, K.M., Mooshammer, M., Penuelas, J., Richter, A., Sardans, J., 2015. The application of ecological stoichiometry to plant-microbial-soil organic matter transformations. *Ecological Monographs*, 85: 133-55. DOI: https://doi.org/10.1890/14-0777.1.

Zhong, Z., Makeschin, F., 2006. Differences of soil microbial biomass and nitrogen transformation under two forest types in central Germany. *Plant and Soil*, 283: 287-297. DOI: https://doi.org/10.1007/s11104-006-0018-z.

STRESZCZENIE

Właściwości gleb krakowskich lasów miejskich z wybranymi obcymi gatunkami drzew

Lasy miejskie odgrywają ogromną rolę społeczną, szczególnie w dynamicznie rozwijających się dużych aglomeracjach miejskich. Stabilność ekosystemów leśnych w miastach jest jednak silnie zagrożona. Z jednej strony znajdują się one pod dużą presją oddziaływania czynników antropogenicznych, z drugiej zaś cierpią wskutek obserwowanych zmian klimatu. Trwałość takich ekosystemów i możliwość pełnienia przez nie różnorodnych funkcji uzależniona jest od kondycji gleby. Skład gatunkowy drzewostanu silnie determinuje cechy glebowej materii organicznej, zakwaszenie gleb, pojemność sorpcyjną gleb oraz ich aktywność biochemiczną. Każdy gatunek może jednak wywierać specyficzny wpływ na cechy środowiska glebowego poprzez dostarczanie detrytusu o swoistym składzie chemicznym. Znajomość wpływu różnych obcych gatunków drzew na środowisko glebowe w warunkach lasów miejskich przyczynia się do pogłębienia wiedzy na temat wymagań ekologicznych takich gatunków, jak również oceny ich możliwości adaptacyjnych w specyficznych warunkach środowiska lasów miejskich.

Przeprowadzone badania dotyczyły określenia właściwości gleb w lasach miejskich Krakowa z wybranymi obcymi gatunkami drzew: daglezją zieloną, choiną kanadyjską, kasztanem jadalnym, czeremchą amerykańską, kasztanowcem zwyczajnym, orzechem włoskim, klonem jesionolistnym i robinią akacjową. Głównym celem badań było określenie ilości i jakości glebowej materii organicznej, właściwości fizykochemicznych gleb, stechiometrii C/N/P oraz aktywności enzymatycznej gleb.

Analizy potwierdziły zróżnicowanie właściwości fizykochemicznych i aktywności enzymatycznej gleb lasów miejskich w Krakowie pod wpływem obcych gatunków drzew liściastych i iglastych (tab. 1 i 2). Badane gleby charakteryzowały się pH w zakresie 3,99-6,90. Aktywność enzymatyczna N-acetyl-β-D-glukozaminidazy (NAG), β-ksylozydazy (XYL), arylosulfatazy (SP) i fosfatazy (PH) silnie korelowała z pH badanych gleb i zawartością P. Aktywność NAG, XYL i PH dodatnio korelowała z zawartością C i N (tab. 3). Stechiometria C/N/P gleb była zróżnicowana

(ryc. 1). Szerszą stechiometrię C/N/P odnotowano w glebach z gatunkami iglastymi (daglezją zieloną i choiną kanadyjską), natomiast węższą w glebach z klonem jesionolistnym. Gleby z klonem jesionolistnym cechował również najniższy stosunek C/N, C/P i N/P (ryc. 1). Analiza stechiometrii enzymatycznej wykazała, że badane próbki gleby różnią się statystycznie istotnie pod względem stosunku BG/NAG, BG/PH i NAG/PH (ryc. 2). Przeprowadzona analiza potwierdziła związek pomiędzy właściwościami fizykochemicznymi badanych gleb a stechiometrią C/N/P (tab. 4). Analizy ściółek badanych gatunków potwierdziły zróżnicowanie ich właściwości (tab. 5). Najwyższe pH stwierdzono w ściółce robinii akacjowej i kasztanowca zwyczajnego, natomiast istotnie niższe pH odnotowano w ściółce klonu jesionolistnego. Analiza przesączy ze ścioły badanych obcych gatunków drzew wykazała różnice w składzie chemicznym. Odmiennymi właściwościami charakteryzowały się gatunki iglaste (daglezja zielona i choina kanadyjska) w porównaniu do pozostałych badanych gatunków. Zawartość węgla całkowitego (TC), węgla rozpuszczalnego (DOC) i azotu (TN) w przesączach ze ścioły drzew iglastych była dziesięciokrotnie niższa niż w przypadku pozostałych gatunków (tab. 6). Jednocześnie gatunki iglaste charakteryzowały się najniższą zawartością kationów zasadowych, zwłaszcza Ca, K i Mg (ryc. 3). Analiza PCA wyróżniła dwie grupy gatunków: pierwszą zdominowaną przez gatunki iglaste, a drugą przez gatunki liściaste (ryc. 4). Korzystniejsze właściwości charakteryzują gleby i ściółkę drugiej grupy w porównaniu z grupą gatunków iglastych. Analiza PCA wskazała, że gleby z gatunkami iglastymi, kasztanowcem i czeremchą charakteryzowały się wyższymi stosunkami C/N, C/P i N/P (ryc. 4).

Gleby pozostające pod wpływem badanych obcych gatunków drzew charakteryzowały się zróżnicowanymi właściwościami fizykochemicznymi i biochemicznymi, co wynika z różnic we właściwościach dostarczanej materii organicznej. Uzyskane wyniki wskazują na istotne różnice w obiegu C, N i P pomiędzy glebami zmienionymi przez badane gatunki drzew, co potwierdza stechiometria C/N/P. Wyniki badań wskazały na możliwość wykorzystania stechiometrii C/N/P w ocenie wpływu różnych gatunków drzew na warunki glebowe w lasach miejskich. Badania wykazały, że różnicując skład gatunkowy drzewostanu z wykorzystaniem obcych gatunków drzew, znacząco wpływa się na właściwości fizykochemiczne i biochemiczne gleb lasów miejskich. Zrozumienie tych efektów jest ważne dla zrównoważonego zarządzania ekosystemami leśnymi. Uzyskane wyniki mogą mieć praktyczne zastosowanie w kształtowaniu lasów miejskich.