



Which Soil Properties Determine Tree Nutrient Supply in Extreme Technosol Conditions?

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Abstract

In recent years, there has been an increased interest in the selection of tree species for their adaptation to difficult habitat conditions in post-mining areas. As global climate change can cause changes in the circulation of elements, it is vital to understand how soil and habitat conditions affect the mineral nutritional status of trees.

The study compared the nitrogen (N) and phosphorus (P) content in the leaves of various tree species on different substrates created by mining activities. The research was carried out in stands growing on reclaimed post-mining soils composed of various parent materials, including sands, clays, and ashes. The factors influencing the N and P supply to trees in the designated parent material were investigated. The soil's physicochemical properties were determined, and biochemical analyses were conducted. The tests performed showed that there were no differences in the N and P content in the leaves of scots pine (*Pinus sylvestris*), black locust (*Robinia pseudoacacia*), black alder (*Alnus glutinosa*), and common birch (*Larix decidua*) growing on different substrates. The results confirmed a significant relationship between the mineral nutritional status of trees and the chemical (N, Mg^{2+} , and K^+) and biological (AcidPho_{SP}) properties of soils. The N supply was related to the contents of nitrogen total (N_{tot}) and exchangeable magnesium (Mg^{2+}) in soils and to the specific activity of acid phosphatase (AcidPho_{SP}). The level of phosphorus (P) supply to the studied tree species growing on technogenic soils was shown to be a factor related to the activity of acid phosphatase (AcidPho_{SP}).

Keywords Mineral nutrition · Scots pine · Black locust · Black alder · Common birch · Leaves

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1 Introduction

The availability of nutrients is one of the leading environmental factors that limit the productivity of terrestrial ecosystems (Lambers and Oliveira 2019). In recent decades, nitrogen oxide (Nox) emissions into the atmosphere have changed nitrogen (N) availability in many forest ecosystems in Europe and North America (Crowley et al. 2012; Jonard et al. 2015; Talkner et al. 2015). An increased N pool in forests affects the mineral nutrition status of trees (Driscoll et al. 2003). Increased N availability stimulates tree growth, leading to phosphorus (P) deficiency (Åkcelsson et al. 2008; Reich et al. 2006). Although total P resources in soils are relatively high, only a small proportion of this is available to plants (Hinsinger 2001). The content of N and P in leaves is perceived to be an indicator of the nutritional status of plants, and the N:P ratio can shed light on potential limitations—resulting from nutrient deficiencies—that affect the productivity of terrestrial ecosystems and plant growth (Reich and Oleksyn 2004). Numerous studies have shown

that the content of N and P in leaves reflects the content of these elements in the soil (Aerts and Chapin 2000). One of the main stages in the circulation of nutrients between the plant and soil is leaf decomposition. In addition, the nutrient contents of the litter, soil properties, and climatic conditions are the primary factors influencing the accumulation rate of dead organic matter (Manzoni et al. 2008; Parton et al. 2007).

The accumulation of dead organic matter is crucial for soil formation in soilless areas (Woś and Pietrzykowski 2015). In mining areas, soil reconstruction and afforestation are potentially the best strategies for restoring post-mining areas to their previous state (Dutta and Agrawal 2003; Pietrzykowski and Krzaklewski 2007). From an ecological point of view, the goal of restoring post-mining areas is the development of a stable forest ecosystem (Bradshaw and Hüttl 2001). In order to alleviate nutrient deficiencies in reconstructed soils, tree species capable of binding atmospheric N are introduced, and thanks to symbiosis with bacteria, these species enrich the soil with N (Pietrzykowski et al. 2015; Vlachodimos et al. 2013; Zipper et al. 2011). In recent years, there has been increased interest in the selection of tree species for this purpose and in their adaptation to difficult habitat conditions in post-mining areas (Baumann et al. 2006; Chodak and Niklińska 2010; Pietrzykowski and Socha 2011).

The role of N-fixing species in alleviating P deficiencies has not been investigated in depth (Hinsinger et al. 2011). Plants play a central role in the transformation and circulation of P in the soil. Moreover, plants can take up P only in mineral forms and deposit it in organic forms, which become substrates for organic forms of P in the soil (Hinsinger et al. 2011). Although organic P may constitute up to 50% of the total P in the topsoil, it is not directly available to plants (Sulieman and Mühling 2021). In nature, however, several mechanisms allow plants to access organic forms of P. By increasing phosphatase activity and increasing P absorption by microorganisms, some tree species have improved their ability to absorb P from the soil (Richardson et al. 2009).

As global climate change can cause changes in the circulation of elements, it is vital to understand how soil and habitat conditions affect the mineral nutritional status of trees (Schaaf 2001). Such knowledge is essential at sites restored after severe disturbance since conditions are often harsh and nutrient supply is insufficient for healthy plant growth. Of particular concern are the low concentrations and availability of essential nutrients in the parent materials of technosols. N and P are considered the primary limiting elements for the development of vegetation planted on post-industrial barrens (Zipper et al. 2011; Manimel Wadu et al. 2017; Cross et al. 2019). The current knowledge on the impact of chemical properties and microbiological activity on forest tree N and P supply is mainly based on research material

from intact areas. In contrast, reports from reclaimed sites are relatively scarce. Determining the factors influencing the supply of N and P to trees is crucial in monitoring stands mineral nutrition status. Therefore, this study aimed to determine the influence of microbiological and physicochemical properties of soils formed from different substrates on the mineral nutrition status of pioneer tree species (Scots pine and silver birch) and N-fixing tree species (black locust and black alder), expressed through the supply of nitrogen and phosphorus to their leaves. We hypothesized that the status of tree N and P supply in restored forest ecosystems depends on the chemical properties of parent materials and the microbial activity of developing soils.

2 Materials and Methods

2.1 Study Sites and Field Study

The research was carried out in stands growing on reclaimed post-mining soils (RMS) composed of various types of parent materials representing sands (sand quarry, Szczakowa; open-pit lignite mine, Bełchatów), clays (open-pit lignite mine, Turów; open-pit sulfur mine, Piaseczno), and ashes (combustion waste disposal site, Lubień). The age of forest stands growing on the ashes was 18–20 years, those growing on the sands 30–35 years, and those growing on clays 38–44 years. Detailed characteristics of the examined objects are presented in Table 1.

2.2 Soil Sampling

To determine the factors influencing the state of N and P supply to trees in the designated parent material variants, for stands of age classes I and II (class I, stands up to 20 years old; class II, 21–40 years), permanent research plots with an area of 100 m² have been created, within which there are single-species stands of black locust, black alder, common birch, and Scots pine. The experiment was fully randomized. At the turn of August and September, leaf samples were collected from the sunlit part of the crown. The samples were placed in PVC bags, transported to the laboratory, and dried. Five soil samples distributed in the envelope system were taken on the surface of each of the 0–5 cm and 5–20 cm layers, from which one composite soil sample was prepared. After collection, the samples were transported to a laboratory and separated into samples for physicochemical and biochemical analyses. The samples for physicochemical and chemical analysis were dried to constant weight and passed through a 2-mm mesh before analysis. The samples for biochemical analysis were stored in a refrigerator at 4 °C.

Table 1 Characteristics of the tested objects

	Sand quarry, Szczakowa	Open-pit lignite mine, Bełchatów	Open-Pit lignite mine, Turów	Open-pit sulfur mine, Piaseczno	Combustion waste disposal site, Lubień
Variants	Sands SS		Clayes CS		Ash AS
Number of sampling sites	17	7	12	12	24
Located	South Poland	Central Poland	South-Western Poland	South-Eastern Poland	Central Poland
Latitude	50° 16' N	51° 13' N	50° 52' N	50° 35' N	51° 27' N
Longitude	19° 26' E	19° 25' E	14° 52' E	21° 47' E	19° 27' E
Mean annual precipitation (mm)	700	580	706	697	576
Mean annual temperature (°C)	8.1	7.6	8.3	9.3	7.6
Area approx (ha)	3100	1480	2200	120	440
Relative height (m)	– 25	195	245	30	No data
Parent material (substrate variant)	Fluvioglacial Quaternary sediments	Quaternary loamy sands	Kaolinite clays	Clays or fine loams	Thermally processed silicates: Content of Al ₂ O ₃ and SiO ₂ 60–70% Content of CaO 20%
Reclamation treatments (only for mine lands)	Cultivation (<i>Lupinus polyphyllus</i> Lindl.) NPK fertilization (70 kg N ha ⁻¹ , 120 kg P ha ⁻¹ , 120 kg K ha ⁻¹)	NPK fertilization (60 kg N ha ⁻¹ , 70 kg P ha ⁻¹ , 60 kg K ha ⁻¹) Cultivation leguminous plant and grasses Planting of trees	NPK fertilization (50 kg ha ⁻¹ , 28 kg ha ⁻¹ , 16 kg ha ⁻¹) Cultivation of leguminous plant and grasses Planting of trees	Cultivation of leguminous plant and grasses NPK fertilization (80 kg N ha ⁻¹ , 50 kg P ha ⁻¹ , and 60 kg K ha ⁻¹) Planting of trees	Hydro-seeding with a sewage sludge and a mixture of grasses (<i>Dactylis glomerata</i> L., <i>Lolium multiflorum</i> Lam.) NPK fertilization (60 kg N ha ⁻¹ , 36 kg P ha ⁻¹ , 36 kg K ha ⁻¹) Planting of trees

2.3 Determination of Soil Physicochemical Properties and Biochemical Analyses

Soil texture was measured spectrally using the Fritsch GmbH Laser Particle Sizer ANALYSETTE 22. The pH was measured potentiometrically in H₂O and 1 M KCl. The contents of N and carbon (C) were measured using the dry combustion method with a TruMac® CNS analyzer. Exchangeable K⁺ and Mg²⁺ were extracted with 1 M CH₃COONH₄ and determined using an iCAP 6000 Series ICP OES spectrometer. The total Mg, K, and P were measured using the same instrument after extraction with a mixture of HNO₃ and HClO₄ at a ratio of 3:1.

Acid and alkaline phosphatase (phosphomonoesterase) activities (AcdPho_{SP} and AlkoPho_{SP}) and inorganic pyrophosphatase (PyroPho) were measured as described by Margesin (1996). Briefly, the soil samples (1 g d.w.) were mixed with disodium p-nitrophenyl phosphate solution (115 mM) and a buffer solution (pH = 6.5 for AcdPho_{SP}; pH = 11.0 for AlkoPho_{SP}) and incubated at 37 °C for 1 h. The p-nitrophenol released by phosphatase activity was extracted, reacted with NaOH, and determined photometrically at 400 nm. Activities of AcdPho_{SP} and AlkoPho_{SP} were expressed per dry soil

mass in units of µg p-NP·g⁻¹·h⁻¹. Total phosphatase activity (PhoSuma) was expressed as the sum of AcdPho_{SP} and AlkoPho_{SP}. For PyroPho measurement, the soil samples (1 g d.w.) were mixed with buffered pyrophosphate solution and incubated for 1 h at 37 °C. Orthophosphate released by inorganic pyrophosphatase activity was extracted with sulfuric acid, reacted with ammonium molybdate, and determined photometrically at 700 nm. PyroPho activity was expressed per dry soil mass in units of µg P-PO₄³⁻·g⁻¹·h⁻¹.

2.4 Statistical Procedures

Differences in the mean values of the basic soil properties, and results of biochemical analyses between different types of parent materials, were tested using one-way ANOVA followed by an RIR-Tukey multiple comparison procedure (at $p < 0.05$). Additionally, two-way ANOVA was used to test for differences in the N, P, K, and Mg contents, and N-to-P ratios, in the leaves of the studied tree species growing on different substrates. Before statistical analyses, test assumptions were checked using the Shapiro-Wilk test (for normal distribution) and the Brown-Forsyth test (for homogeneity of variances). Statistical analysis included the implementation

of generalized additive models (GAM). The relationships between N and P content in leaves and the predictor variables N_{tot} and Mg^{2+} and the activity of $\text{AcidPho}_{\text{SP}}$ were modeled using GAM models, a non-parametric extension of the generalized linear model (GLM). An identity join function was specified for normally distributed response data. Predictor variables were entered into the models one at a time. The selection of the best model (i.e., the model containing independent variables explaining the largest amount of observed variance) was made based on the adjusted model determination/efficiency coefficient (R^2_{adj}). Smoothing spline function plots of GAM models were used to illustrate the influence of individual predictor variables on dependent variables. The remaining analyzed variables (pH KCl, sand, silt, clay, C_{tot} , P_{tot} , K_{tot} , Mg_{tot} , $\text{AlkPho}_{\text{SP}}$, PhoSuma , and PyroPho) were not significant or showed collinearity. Statistical analysis was performed using Statistica 13.3 software (StatSoft Inc.) (Table 2).

3 Results

3.1 Basic Soil Properties

There were significant differences in texture between the tested substrates in the 0–5 cm soil layer. The tested substrates were characterized by their reactivity as very strongly acid (SS), moderately acid (CS), or slightly alkaline (AS). The sand content in the SS, AS, and CS substrates was 81%, 70%, and 29%, respectively. In addition, there were differences in the content of C_{tot} and N_{tot} between the tested

substrates. The highest content of C_{tot} and N_{tot} was found in the CS substrate and the lowest in the SS substrate.

The AS and CS substrates contained more P_{tot} and Mg_{tot} . The Mg_{tot} content in the SS variant was ten times lower than in the AS and CS variants. In addition, higher concentrations of K^+ $\text{cmol}\cdot\text{kg}^{-1}$ and Mg^{2+} $\text{cmol}\cdot\text{kg}^{-1}$ were found in AS and CS soils than in SS soils. $\text{AcidPho}_{\text{SP}}$ and PyroPho activities were higher in the CS substrate than in the AS and SS substrates. The activity of $\text{AlkPho}_{\text{SP}}$ was lower in the SS substrate than in the AS and CS substrates.

There were also significant differences in texture between the substrates in the 5–20 cm layer. The sand content in the SS substrate was 80%, in the AS substrate 85%, and in the CS substrate only 21%. There were differences in the content of C_{tot} and N_{tot} between the tested substrates. The highest content of C_{tot} and N_{tot} was found in the CS substrate and the lowest in the SS substrate. The CS substrate contained more P_{tot} and Mg_{tot} . The Mg_{tot} content in the SS variant was ten times lower than in the CS variants. In addition, CS soils contained higher concentrations of K^+ $\text{cmol}\cdot\text{kg}^{-1}$ and Mg^{2+} $\text{cmol}\cdot\text{kg}^{-1}$ than SS soils. $\text{AcidPho}_{\text{SP}}$, PyroPho , and $\text{AlkPho}_{\text{SP}}$ activities were higher in the CS substrate than in the AS and SS substrates (Table 3).

3.2 Mineral Nutritional Status and Quantification in Leaves

In substrate variants AS and CS, the N content in alder and black locust leaves was higher than in birch and pine leaves. In the SS substrate variant, the highest content of N was found in black locust leaves and the lowest in pine leaves. The type of substrate did not affect the N content in the leaves of birch, pine, and alder. A higher N content was found in the black locust leaves in the SS substrate variant than in the AS and CS substrate variants. Furthermore, no differences in P content were found in the birch, alder, pine, and black locust leaves in the AS and CS variants. In the SS substrate variant, pine leaves contained less P than alder and black locust leaves. The substrate type also affected the K and Mg content in the leaves of alder, birch, and black locust. K in birch and black locust leaves was higher in variants CS and SS than in variant AS. A higher content of Mg was found in pine, black locust, and birch leaves in the AS and SS substrate variants compared with the CS substrate. The lowest N:P ratio was found in pine leaves and the highest in black locust leaves (Table 4).

Analysis of individual soil properties showed that N content was strongly influenced by the contents of N_{tot} and Mg^{2+} and by the activity of $\text{AcidPho}_{\text{SP}}$ in the soil (Fig. 1). Increasing N_{tot} in the topsoil layer (0–5 cm) caused a substantial increase in the N content of the leaves. However, further growth was much slower above $2.5 \text{ mg}\cdot\text{g}^{-1} N_{\text{tot}}$ (Fig. 1a). A relatively steep decrease in the N content of

Table 2 Approximate significance of seven predictor variables on the periodic annual volume increment described using the GAM (generalized additive model)

	GAM factor	Standard error	Non-linear <i>p</i> value
pH KCl	– 2.17904	1.289608	0.084961
Sand	0.30873	0.060010	0.901118
Silt	0.39734	0.145045	0.955695
Clay	0.59922	0.124427	0.777815
C_{tot}	– 0.14055	0.073868	0.087360
N_{tot}	8.81605	1.344303	0.000000
P_{tot}	– 0.01838	0.012691	0.841251
K_{tot}	– 0.00287	0.000958	0.088825
Mg_{tot}	0.00218	0.001306	0.141299
Mg^{2+}	– 0.08252	0.025548	0.002664
$\text{AcidPho}_{\text{SP}}$	0.03474	0.0083	0.034208
$\text{AlkPho}_{\text{SP}}$	– 0.00776	0.0026	0.362674
Pho Suma	0.00000	226.4715	0.206881
Pyro Pho	– 0.02227	0.0107	0.107060

Significant analyzed variables are the bold printed ($p < 0.05$)

Table 3 One-way ANOVA for the basic soil properties (mean $\pm$ standard errors) in two soil layers (0–5 cm and 5–20 cm)

Soils properties		Soil layer of 0–5 cm			Soil layer of 5–20 cm		
Units		Types of parent materials					
		Ash AS	Sands SS	Clays CS	Ash AS	Sands SS	Clays CS
pH KCl		7.6 $\pm$ 0.0 ^a	4.8 $\pm$ 0.2 ^b	5.7 $\pm$ 0.4 ^c	7.8 $\pm$ 0.0 ^a	5.2 $\pm$ 0.2 ^b	5.8 $\pm$ 0.4 ^b
Sand	%	70 $\pm$ 2 ^a	81 $\pm$ 2 ^b	29 $\pm$ 3 ^c	85 $\pm$ 2 ^a	80 $\pm$ 1 ^a	21 $\pm$ 3 ^b
Silt	%	23 $\pm$ 2 ^a	10 $\pm$ 1 ^b	16 $\pm$ 1 ^c	9 $\pm$ 2 ^a	9 $\pm$ 1 ^a	15 $\pm$ 2 ^b
Clay	%	7 $\pm$ 1 ^a	9 $\pm$ 1 ^a	55 $\pm$ 3 ^b	6 $\pm$ 1 ^a	11 $\pm$ 1 ^a	64 $\pm$ 3 ^b
C _{tot}	mg $\cdot$ g ⁻¹	46.3 $\pm$ 3.2 ^a	18.8 $\pm$ 2.8 ^b	72.9 $\pm$ 4.5 ^c	24.9 $\pm$ 3.1 ^a	5.4 $\pm$ 1.2 ^b	43.9 $\pm$ 2.2 ^c
N _{tot}	mg $\cdot$ g ⁻¹	1.9 $\pm$ 0.2 ^a	1.2 $\pm$ 0.2 ^b	3.1 $\pm$ 0.2 ^c	0.6 $\pm$ 0.0 ^a	0.4 $\pm$ 0.1 ^a	1.4 $\pm$ 0.1 ^b
P _{tot}	μ g $\cdot$ g ⁻¹	400.4 $\pm$ 18.0 ^a	151.4 $\pm$ 15.3 ^b	411.8 $\pm$ 20.7 ^a	195.3 $\pm$ 9.2 ^a	121.8 $\pm$ 14.1 ^b	334.8 $\pm$ 14.7 ^c
K _{tot}	μ g $\cdot$ g ⁻¹	866.4 $\pm$ 27.8 ^a	623.8 $\pm$ 74.8 ^a	8226.1 $\pm$ 629.1 ^b	645.8 $\pm$ 37.5 ^a	589.8 $\pm$ 80.2 ^a	8385.2 $\pm$ 681.0 ^b
Mg _{tot}	μ g $\cdot$ g ⁻¹	3636 $\pm$ 122.7 ^a	436.8 $\pm$ 65.0 ^b	4320.6 $\pm$ 614.0 ^a	2293.2 $\pm$ 112.7 ^a	447.4 $\pm$ 83.1 ^b	4527.9 $\pm$ 673.9 ^c
K ⁺	cmol $\cdot$ kg ⁻¹	178 $\pm$ 19.4 ^a	39.4 $\pm$ 7.6 ^b	187.6 $\pm$ 18.8 ^a	84.7 $\pm$ 10.3 ^a	18.5 $\pm$ 2.9 ^b	185.7 $\pm$ 24.3 ^c
Mg ²⁺	cmol $\cdot$ kg ⁻¹	106.6 $\pm$ 7.4 ^a	53.5 $\pm$ 11.5 ^b	130.9 $\pm$ 12.1 ^a	69.8 $\pm$ 7.3 ^a	25.3 $\pm$ 5.9 ^b	104.9 $\pm$ 11.4 ^c
AcidPho _{SP}	[ug NP $\cdot$ g ⁻¹ $\cdot$ dm $\cdot$ h ⁻¹]	272.9 $\pm$ 15.9 ^a	273.5 $\pm$ 35.8 ^a	600.7 $\pm$ 35.2 ^b	72.9 $\pm$ 7.3 ^a	55.1 $\pm$ 11.0 ^a	303.6 $\pm$ 27.9 ^b
AlkPho _{SP}	[ug NP $\cdot$ g ⁻¹ $\cdot$ dm $\cdot$ h ⁻¹]	660.4 $\pm$ 35.6 ^a	161.6 $\pm$ 55.3 ^b	748 $\pm$ 120.4 ^a	219.5 $\pm$ 20.2 ^a	73.6 $\pm$ 28.7 ^a	438.6 $\pm$ 79.8 ^b
Pho Suma	[ug NP $\cdot$ g ⁻¹ $\cdot$ dm $\cdot$ h ⁻¹]	933.4 $\pm$ 49.8 ^a	435.1 $\pm$ 76.2 ^b	1348.6 $\pm$ 128.2 ^c	292.4 $\pm$ 27.1 ^a	128.7 $\pm$ 39.2 ^a	742.1 $\pm$ 96.5 ^b
PyroPho	[ug PO ₄ ³⁻ $\cdot$ P $\cdot$ g ⁻¹ $\cdot$ dm $\cdot$ h ⁻¹]	106.0 $\pm$ 7.0 ^a	133.4 $\pm$ 12.9 ^a	311.6 $\pm$ 41.9 ^b	52.0 $\pm$ 6.0 ^a	63.0 $\pm$ 4.6 ^a	126.9 $\pm$ 17.1 ^b

Different letters indicate significant differences between the ash (AS), sands (SS), and clays (CS) within one layer

C_{tot}, contents of carbon; N_{tot}, contents of nitrogen; P_{tot}, contents of phosphorus; K_{tot}, contents of potassium; Mg_{tot}, contents of magnesium; K⁺, exchangeable potassium; Mg²⁺, exchangeable magnesium; AcidPho_{SP}, acid phosphatase activities; AlkPho_{SP}, alkaline phosphatase activities; Pho Suma, sum acid and alkaline phosphatase activities; PyroPho, inorganic pyrophosphatase

Table 4 Two-way ANOVA for the N, P, K, and Mg contents and N-to-P ratios (mean values $\pm$ standard errors) in leaves studied tree species growing on different substrates (N, contents of nitrogen; P, contents of phosphorus; K, contents of potassium; Mg, contents of magnesium)

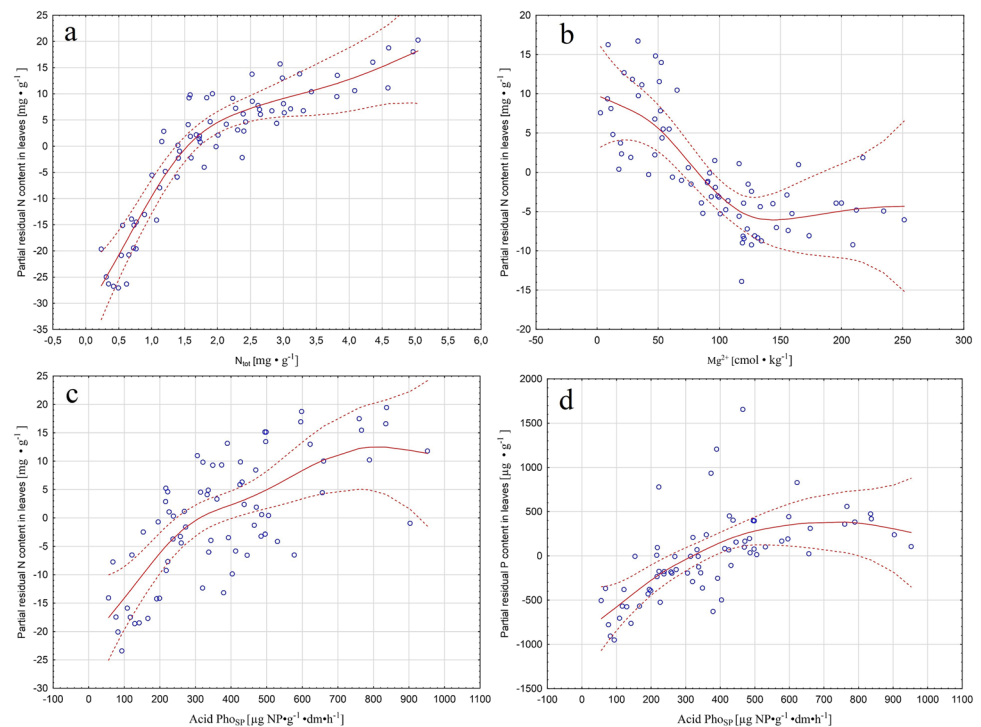
Types of parent materials			Species			
Units			Alder	Birch	Pine	Robinia
Ash AS	N	mg $\cdot$ g ⁻¹	26 $\pm$ 0.7 ^{Aa}	19.9 $\pm$ 0.8 ^{Ab}	13.2 $\pm$ 0.4 ^{Ac}	31.4 $\pm$ 1.2 ^{Aa}
Clayes CS			29.8 $\pm$ 1.3 ^{Aa}	17.6 $\pm$ 1.2 ^{Ab}	11.2 $\pm$ 0.4 ^{Ac}	32 $\pm$ 1.7 ^{ABa}
Sands SS			28.6 $\pm$ 1.8 ^{Aa}	18.4 $\pm$ 0.9 ^{Ab}	11.8 $\pm$ 0.9 ^{Ac}	37.6 $\pm$ 2.2 ^{Bd}
Ash AS	P	μ g $\cdot$ g ⁻¹	1198.2 $\pm$ 31.1 ^{Aa}	1083.2 $\pm$ 35.7 ^{Aa}	1023.6 $\pm$ 18.8 ^{Aa}	1188.9 $\pm$ 77.5 ^{Aa}
Clays CS			1466.4 $\pm$ 99.4 ^{Aa}	1158.2 $\pm$ 104.9 ^{Aa}	965.4 $\pm$ 52.2 ^{Aa}	1206.4 $\pm$ 80.2 ^{Aa}
Sands SS			1812.4 $\pm$ 193.5 ^{Aa}	1587.9 $\pm$ 308.4 ^{Aab}	1037.1 $\pm$ 94.5 ^{Ab}	1808.9 $\pm$ 246.9 ^{Aa}
Ash AS	K	μ g $\cdot$ g ⁻¹	5501.2 $\pm$ 726.1 ^{Aa}	7619.7 $\pm$ 864.8 ^{Aa}	5354.4 $\pm$ 264.5 ^{Aa}	14279 $\pm$ 652.3 ^{Ab}
Clays CS			11004.9 $\pm$ 1105.0 ^{Ba}	10474.7 $\pm$ 2151.5 ^{Aab}	4822.7 $\pm$ 426.4 ^{Ab}	20380.6 $\pm$ 1620.5 ^{Bc}
Sands SS			10141.6 $\pm$ 1906.6 ^{Ba}	10317.3 $\pm$ 1095.2 ^{Aa}	11692.6 $\pm$ 680.4 ^{Aab}	16112.2 $\pm$ 1364.0 ^{ABb}
Ash AS	Mg	μ g $\cdot$ g ⁻¹	4621.8 $\pm$ 231.0 ^{Aa}	3581.2 $\pm$ 201.3 ^{ABd}	1230.4 $\pm$ 60.5 ^{Ac}	3135.8 $\pm$ 121.2 ^{Ad}
Clays CS			3068.8 $\pm$ 310.3 ^{Ba}	2393.5 $\pm$ 195.7 ^{Ba}	771.9 $\pm$ 65.6 ^{Ab}	1267.4 $\pm$ 305.2 ^{Bbc}
Sands SS			3042.8 $\pm$ 198.8 ^{Ba}	3277.7 $\pm$ 304.5 ^{ABa}	935.4 $\pm$ 76.8 ^{Ab}	3094.1 $\pm$ 226.9 ^{Aa}
Ash AS	N:P		21.7 $\pm$ 0.4 ^{Ac}	18.4 $\pm$ 0.4 ^{Ab}	12.8 $\pm$ 0.2 ^{Ab}	26.8 $\pm$ 1.6 ^{Ac}
Clays CS			20.7 $\pm$ 1.4 ^{Aa}	15.9 $\pm$ 2.1 ^{Aa}	11.7 $\pm$ 0.3 ^{Ab}	26.7 $\pm$ 1.1 ^{Ac}
Sands SS			16.2 $\pm$ 0.8 ^{ABb}	12.9 $\pm$ 1.4 ^{Aa}	11.6 $\pm$ 0.8 ^{Aa}	22.1 $\pm$ 2.1 ^{Ab}

Different letters (a, b, c, d) indicate significant differences between the studied species (for the same substrate). Different capital letters (A, B) indicate significant differences between the studied types of parent materials (on the same trees species)

leaves was observed with the increase of Mg²⁺ from 2 to 110 cmol $\cdot$ kg⁻¹. Furthermore, the same change in Mg²⁺ caused a decrease of the N supply to trees by 20 mg $\cdot$ g⁻¹ (Fig. 1b).

The increase in the activity of AcidPho_{SP} in the range 55 to 500 ug NP $\cdot$ g⁻¹ $\cdot$ dm $\cdot$ h⁻¹ also contributed to the improvement of the N supply in trees (Fig. 1c). However, a further increase

Fig. 1 **a** Varied nitrogen (N) content in leaves depending on nitrogen (N) content in the soil, **b** varied nitrogen (N) content in leaves depending on exchangeable magnesium (Mg^{2+}) concentration in the soil, **c** Varied nitrogen (N) content in leaves depending on acid phosphatase ($\text{AcidPho}_{\text{SP}}$) activity in the soil, **d** varied phosphorus (P) content in leaves depending on acid phosphatase ($\text{AcidPho}_{\text{SP}}$) activity in the soil (shown using generalized additive models). An identity join function was specified for normally distributed response data. R^2_{adj} models = 80%



in the activity of $\text{AcidPho}_{\text{SP}}$ did not significantly increase the content of N in the leaves. The analysis also revealed the influence of soil properties on the P content in leaves. A positive effect of the $\text{AcidPho}_{\text{SP}}$ activity on P content in the leaves was apparent up to $500 \mu\text{g NP}\cdot\text{g}^{-1}\cdot\text{dm}\cdot\text{h}^{-1}$; further increase in $\text{AcidPho}_{\text{SP}}$ activity did not affect P content in leaves (Fig. 1d).

4 Discussion

As expected, the leaves of alder and black locust contained more N than those of birch and pine, on each tested substrate. Compared to the available literature, the concentration of N in the leaves of the examined tree species was similar or high in relation to the values obtained on natural and reclaimed post-mining areas. In the forests of Europe, the concentration of N in alder leaves varies from 20 to $40 \text{ mg}\cdot\text{g}^{-1}$ (Kuznetsova et al. 2010; Lorenc-Plucińska et al. 2013; Uri et al. 2002). The N content in the leaves of black alder found in the combustion waste dump of the Bełchatów power plant was $24 \text{ mg}\cdot\text{g}^{-1}$, and the N content in the leaves of alder found on extremely sterile sands was $29 \text{ mg}\cdot\text{g}^{-1}$. The N content of the birch leaves was high compared to data in previous studies (Hytonen et al. 1995; Saarsalmi 1995). Studies in Estonia show that, with high N soil concentration, the N concentration in birch leaves can be similar to or even higher than in alder leaves. In the forests of the temperate climate zone, the N content in pine needles ranges from 11.7

to $29.1 \text{ mg}\cdot\text{g}^{-1}$ (Fober 1993). Similar results were obtained for Scots pine stands on extremely poor sands reclaimed for forestry, where the N concentration was $12.1 \text{ mg}\cdot\text{g}^{-1}$ (Pietrzykowski et al. 2013). N content in black locust leaves under natural conditions is about $32 \text{ mg}\cdot\text{g}^{-1}$, compared with $30 \text{ mg}\cdot\text{g}^{-1}$ in the Bełchatów furnace waste landfill (Woś et al. 2020). However, the 25-year-old black locust stands found in unpolluted areas of eastern Bulgaria were characterized by lower N leaf content, amounting to $21 \text{ mg}\cdot\text{g}^{-1}$ (Tzvetkova and Petkova 2015). Furthermore, a similar N content in black locust leaves was obtained in a reclaimed opencast lignite mine in Appalachia (Brinks et al. 2011).

As the deficient component, the content of P was lower than the adopted limit numbers for the supply of this element for the tested tree species. The optimal P content for pine, black locust, alder, and birch is 1.8, 2.0, 3.6, and $3.7 \text{ mg}\cdot\text{g}^{-1}$, respectively. The P content in the leaves of alder found in the furnace waste landfill was $1.1 \text{ mg}\cdot\text{g}^{-1}$ and in the oil shale extraction area in northeastern Estonia, $1.9 \text{ mg}\cdot\text{g}^{-1}$ (Kuznetsova et al. 2010). P content in birch leaves was lower than on post-agricultural lands in Estonia ($3890 \text{ mg}\cdot\text{g}^{-1}$) (Uri et al. 2007). Furthermore, the P content in birch leaves in the oil shale mining area was $3.2 \text{ mg}\cdot\text{g}^{-1}$ (Kuznetsova et al. 2010). The P content in black locust leaves was similar to that determined in the USA waste landfill (Sopper 1992). Moreover, the concentration of P in the leaves of black locust growing in areas affected by industrial emissions ranged from 1680 to $2530 \text{ mg}\cdot\text{g}^{-1}$ (Tzvetkova and Petkova 2015). A much higher P content ($3.8 \text{ mg}\cdot\text{g}^{-1}$) in black locust leaves was found in

the areas of a reclaimed coal mine in the USA (Marschner 2012). The P content of pine needles found in natural forests of Europe ranges from $1.52 \text{ mg}\cdot\text{g}^{-1}$ for the central population to $1.56 \text{ mg}\cdot\text{g}^{-1}$ for the northern population (Oleksyn et al. 2002). A similarly low P content has been found in pine needles on Poland's reclaimed land, ranging from $1.03 \text{ mg}\cdot\text{g}^{-1}$ on coal-bearing shales to $1.12 \text{ mg}\cdot\text{g}^{-1}$ on neogene sands with loam and clay, both carbonated and carbonated sulfurized (Pietrzykowski et al. 2013).

The content of individual elements in the assimilation apparatus and the mutual proportions between them are important in assessing the mineral nutrition status of trees (Baule and Fricker 1971; Pietrzykowski et al. 2013). A N:P ratio above 14 was determined to limit plant growth due to P deficiency, while a value below 14 limited growth due to N deficiency. Atmospheric N-fixing trees (alder and black locust) contained a much higher N:P ratio in leaves than birch and pine. Low concentrations of P in leaves, and high N:P ratios, indicate an insufficient supply of P for all species except pine and birch in the SS substrate. A decrease in the P concentration in leaves may cause health problems for trees: a N:P ratio above 14.8 for deciduous trees and above 7.3 for conifers can cause an increase in defoliation (Verosoglou et al. 2014). Many studies show that an unbalanced increase in the concentration of C and N in relation to P significantly impacts ecosystem functioning (Sardans et al. 2012).

The content of N in the soil affected the content of N in the leaves of the examined tree species across the entire range of analyzed concentrations. Studies conducted on a global scale have also shown that soil N content is a good predictor of phosphatase activity (Margalef et al. 2017). Therefore, acid phosphatase concentration can be a good predictor of N and P concentration in leaves. An increase in $\text{AcdPho}_{\text{SP}}$ activity in the soil to about $500 \text{ ug NP}\cdot\text{g}^{-1}\cdot\text{dm}\cdot\text{h}^{-1}$ favors an increase in the concentration of N and P in leaves (see Fig. 1c, d). The stimulating effect of N on the $\text{AcdPho}_{\text{SP}}$ content is particularly visible in soils poor in this element (Olander and Vitousek 2000). The relationship between $\text{AcdPho}_{\text{SP}}$ activity and N and P concentrations in leaves may also be due to intensive accumulation of N in soils forested with N-fixing trees increasing acid phosphatase activity, which results from the greater availability of N necessary for the synthesis of this enzyme (Olander and Vitousek 2000).

5 Conclusions

Our research showed differences in the content of nitrogen in the leaves of black locust, black alder, common birch, and Scots pine occurring on the same substrate. As expected, the

alder and black locust leaves contained more nitrogen than the leaves of birch and pine on each tested substrate. However, there were no differences in the phosphorus content in the leaves of these tree species. The results confirm that nitrogen content was strongly influenced by the content of nitrogen total and exchangeable magnesium and the activity of acid phosphatase in the soil. Moreover, acid phosphatase activity can be a good predictor of nitrogen and phosphorus concentration in leaves. An increase in the activity of acid phosphatase in the soil to about $500 \text{ ug NP}\cdot\text{g}^{-1}\cdot\text{dm}\cdot\text{h}^{-1}$ favors an increase of nitrogen and phosphorus concentrations in the leaves.

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Data Availability All data used during the study appear in the submitted article and are available.

Declarations

Ethics Approval All authors have read, understood, and have complied, as applicable, with the statement on “Ethical responsibilities of Authors” found in the Instructions for Authors.

Competing Interests The authors declare no competing interests.

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