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Assessment of multivariate associations and spatial variability of forest soil properties and their stand factors in the Czech Republic

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Abstract: Knowing the relationship between forest soil properties and their stand conditions is relevant for the sustainable exploitation and management of forest soils. This study examines the influence of stand environmental factors on soil properties within forest environments. We further assessed the spatial variability of these soil properties and their controlling factors. A harmonised soil database on the entire forest areas of the Czech Republic was considered; however, only 851 sampling points with complete data on soil properties was used out of the more than 8 thousand sampling points in the database. The topsoil mineral layer of 0–30 cm was analysed. Principal component analysis was used to determine the relationships between the forest soil properties and their stand controlling factors. The nugget ratios for the semivariograms and cross-variograms were used to evaluate the spatial dependence of soil properties, and their relevant controlling factors. Forest types influence soil reaction and the availability of cations within the topsoils. Phosphorus is influenced by aluminium and cation exchange capacity. There are higher concentrations of total phosphorus and aluminium under broadleaved forest.

Keywords: environmental factors; forest soils; geostatistics; principal component analysis; spatial variability

Forest soils play an important role in global climate change mitigation efforts with their carbon sequestration (Gorte 2009; Baritz et al. 2010; Burke et al. 2016). Temperate forests are degraded by anthropogenic activities such as acid deposition, fires, and organic matter removal (Page-Dumroese et al. 2021). The sustainable exploitation and management of forest soils will support the global climate change efforts and contribute to supporting forests to achieve their ecosystem functions such as providing timber. The conditions and nature of the forest environment impact soils and their properties (Binkley & Fisher 2013). Several studies have found environmental conditions of forests to influence their soils. Zhang et al. (2016) found that stand characteristics impacted the forest floor and root biomass. An established relationship between carbon stocks and site conditions, including climate and soil type, was observed for European forest soils (Baritz et al. 2010).

Forest soils of Czechia have undergone atmospheric acid pollution from sulphur and nitrogen compounds discharged from anthropogenic activities before

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the end of the 20th century (Krupová et al. 2018; Borůvka et al. 2020). The soils in these forests have experienced nutrient imbalance (Berger et al. 2016; Novotný et al. 2018). To better manage forest soils, it will be important to have an understanding of the relationships between these forest soils and their effects on environmental factors (Zhang et al. 2016).

Gruba and Mulder (2015) for example observed an influence of forest trees on the cation exchange capacity of forest soils. Soil depth and soil class were observed to have affected the soil organic carbon stability of French soils (Soucémarianadin et al., 2018). High contents of soil organic carbon stocks in organic and mineral layers were found to be spatially concentrated in high-altitude Czech forests (Oppong Sarkodie et al. 2023). Weathering of parent minerals influences the base cation contents of soils (Nieman & Johnson 2021).

We hypothesise in this study that there exists a relationship between forest soil properties and their environmental covariates. The objective of this study is to determine the influence of stand environmental factors on soil properties within forest environments. We further assessed the spatial variability of the soil properties, and their controlling factors within the study area.

MATERIAL AND METHODS

Area description. The study area (Figure 1) includes all the forest areas of the Czech Republic, which lies within the temperate broad-leaved deciduous forest zone of central Europe. The altitudinal range for the study area is from 115 to 1 602 m a.s.l. The area has a temperate oceanic through temperate continental climate (Rivas-Martínez et al. 2004). The continental character of climate increases from the west to the east, and while moving from the high mountain altitudes downwards to lowland areas. Mean annual temperatures range from 1 °C to 10 °C, with annual precipitation ranging between 400 and 1 400 mm (https://www.chmi.cz; Tolasz et al. 2007). The forests cover an area of 2 923.2 thousand hectares, which constitutes 37.1% of the entire land area of the Czech Republic (ÚHÚL 2024). Cambisols (IUSS Working Group WRB 2014) constitute almost 60% of the soils within the forest areas. This is followed by Podzols (approximately 25%), and much smaller portions of the forest soils in Czech forests are Fluvisols, Gleysols, Histosols, Leptosols, Luvisols, Retisols, Stagnosols etc. (Němeček & Kozák 2005; Borůvka et al. 2022).

Soil properties and stand factors. In this study, we focus our assessment on pH_{H_2O} and pH_{KCl}, cat-

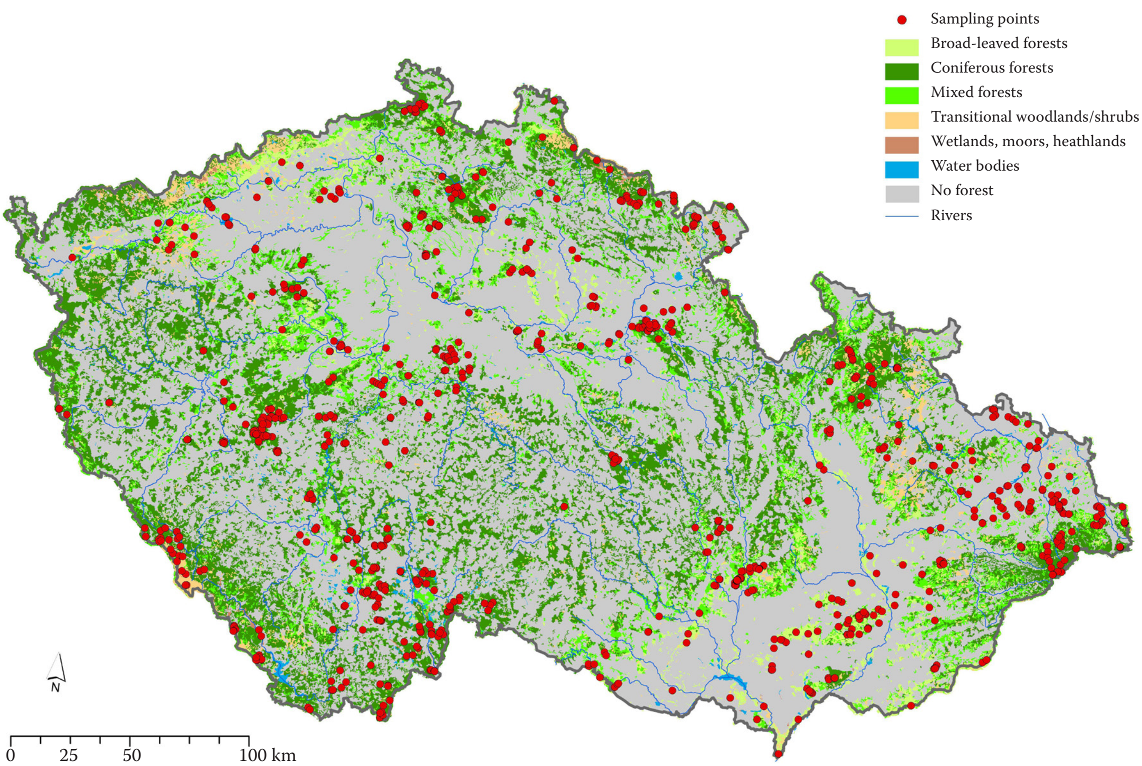

Figure 1. Study area with sampling points

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ion exchange capacity (CEC), base saturation (BS), total phosphorus (P), total carbon (C), and total aluminium (Al). The pH_{H_2O} and pH_{KCl} were determined potentiometrically using a glass electrode from soil reaction in water and KCl suspension, respectively. CEC was calculated as the sum of exchangeable elements (H^{+}, Al, Ca, Fe, K, Mg, Mn and Na) determined by the atomic absorption spectrometry method, and BS was calculated as the ratio of base elements content and CEC. The contents of P and Al were analysed by the aqua regia extract using atomic absorption spectrometry , carbon was determined by CNS analyser, combustion, or NIRS method (Neudertová Hellebrandová et al. 2024).

The considered stand controlling factors are properties of the parent rocks (acidity and structure), thirteen soil classes, forest types (coniferous, mixed and deciduous), altitude, slope, average annual temperature and mean annual precipitation.

Data sources. The data for this study include forest soil properties, collected by several Czech institutions in different surveys. These institutions are the Forest Management Institute, Central Institute for Supervising and Testing in Agriculture, Forestry and Game Management Research Institute, and the Czech University of Life Sciences Prague. The data collection was carried out between the years 2000 and 2021 across the entire forest areas of the Czech Republic (Neudertová Hellebrandová et al. 2024). The soil properties were recalculated to a uniform depth of the mineral topsoil (0–30 cm). The database provided 8 051 sampling points, however, only 851 points were used for this study, i.e. those sampling points where data on all assessed soil properties were available.

The climate data (mean annual precipitation and average annual temperature) on the forest areas were extracted from the WorldClim.org database at a resolution of 1 km (Fick & Hijmans 2017). Altitude, forest type, and soil classification for the stands were extracted from the digital elevation model (DEM) ArcČR® 500 with resolution of 200 m (ARCDATA PRAHA 2016), CORINE Land Cover 2018 (EEA 2018), and Soil Information System PUGIS at the resolution 1 : 250.000 (Kozák et al. 1996), respectively. Rock structure and acidity classification for the stands were derived from the geological maps of the Czech Republic (Chuman et al. 2014; Tóth et al. 2016; Matys Grygar et al. 2023). For purposes of easy analysis, the parent rocks acidity was given numeric ratings as follows; acid – 1, acid-neutral – 2, neutral – 3, neutral (loess-basic) – 4, neutral-basic – 5, basic – 6, and various – 7. The parent rock structure was also given the ratings for as follows; fine – 1, fine (tuff-coarse) – 2, fine/coarse – 3, medium to coarse – 4, coarse – 5, various – 6. Qualitative variables (forest types, soil classes) were transformed into bivariate variables: for each category (each forest type, each soil class), a new variable was created with a value of 1 if the category was true for the sampling point, and with a value of 0 if it was not.

Statistical analysis and software. First, summary statistics were calculated on the data. Principal component analysis (PCA) was used for the evaluation of associations within the soil properties and the stand controlling factors. Spatial variability of the soil properties was assessed by semivariograms and cross-variograms. The principal component analysis and the spatial variability seek to show the influence the environmental factors and their variability in space have on the soil properties within the forest areas (Borůvka et al. 2007). Three parameters define the semivariograms and cross-variograms. These are the nugget value, the sill and the range. The nugget value reflects possible errors in sampling and/or variation in distances shorter than the minimum sampling distance. The sill reveals variability within data, thus comparing to the variance. The range for the variogram suggests the distance at which spatial dependence of the soil property ceases (Oliver & Webster 2015; Gringarten & Deutsch 2001).

The semivariogram and cross-variogram model fit is evaluated with the sum of squared error (SSErr). This is the difference between the observed and predicted values. Lower SSErr indicates better model fit (Oliver & Webster 2015; Belkhiri et al. 2020). This evaluation is not possible for comparison between properties of different units. Thus, we used the ratio of the nugget to the sill to evaluate the extent of spatial dependence in both the semivariograms and cross-variograms (Cambardella et al. 1994). The strongest spatial dependences are those with a nugget ratio of less than 25%. Nugget ratios between 25 and 75% indicate moderate spatial dependence, and nugget ratios higher than 75% mean weak spatial dependence (Cambardella et al. 1994).

The descriptive statistics, principal component analysis and variograms were done in R Studio (R Core Team 2022), whilst the cross-variograms were done in the GS+ software (Gamma Design Software 2001).

RESULTS

Descriptive statistics. The average pH_{H_2O} and pH_{KCl} levels were 4.76 and 3.92, respectively. The mean

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Table 1. Descriptive statistics for selected forest soil properties

	pH		P	Al	C	CEC	BS
	H_2O	KCl	(mg/kg)		(%)	(mmol$_{(+)}$/kg)	(%)
Mean	4.76	3.92	330.55	1 5367.0	3.46	126.76	40.13
SD	0.81	0.76	306.02	9 019.4	5.24	112.79	32.29
Min	2.97	2.32	25.21	85.38	0.09	0.27	2.87
Max	7.89	7.37	3604.8	56 292.1	42.81	1 056.2	99.91
Range	4.92	5.05	3579.5	56 206.7	42.72	1 055.9	97.05
Skewness	1.50	2.17	3.77	0.82	4.17	3.36	0.74
Kurtosis	2.33	5.48	25.22	1.12	20.84	17.90	–0.92
1^{s}t Qu.	4.26	3.54	153.33	9 385.0	1.04	61.23	13.37
3rd Qu.	5.02	4.02	409.06	20 535.8	3.45	156.35	65.21

SD – standard deviation; Qu. – quartile; CEC – cation exchange capacity; BS – base saturation

values for the total concentrations of phosphurus, aluminium and carbon were 330 mg/kg, 15 367 mg/kg and 3.46 g/kg, respectively. Cation exchange capacity had an observed mean value of 127 mmol$_{(+)}$/kg. The mean base saturation value was 40.13% (Table 1).

Principal component analysis. The PCA shows a strong relationship between altitude and precipitation. Altitude and precipitation both have an inverse relationship with temperature. Deciduous forests are in a direct opposite direction to the coniferous forest axis on the PCA plot (Figure 2). The axis of arenic Cambisols (KAR) points in the second upper positive direction of the second dimension of the PCA plot. Arenic Cambisols are inversely positioned to alu-

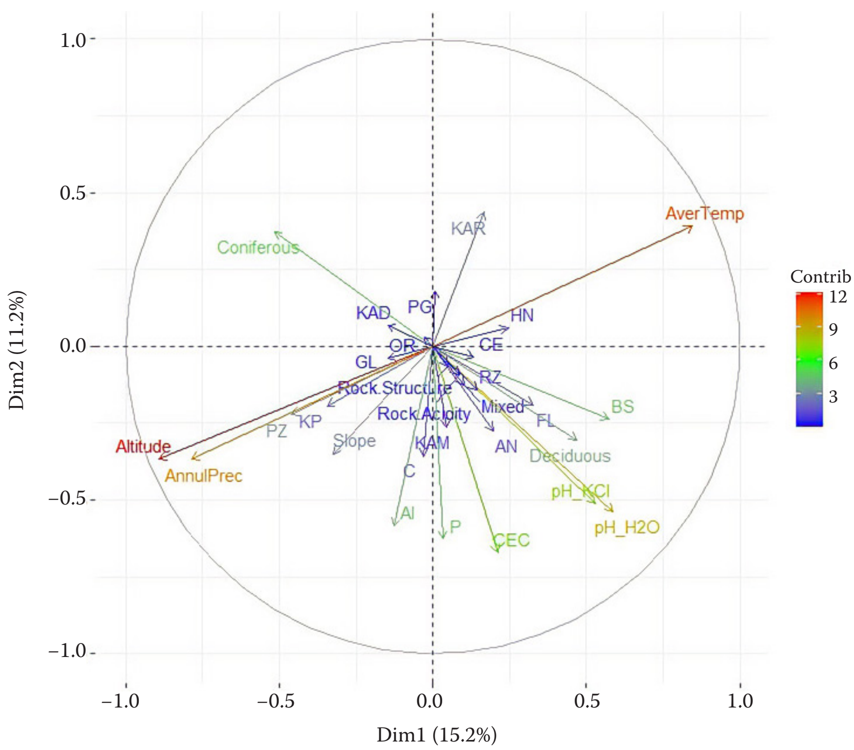

Figure 2. Highlight of principal component anaysis (PCA) for forest soil properties and their stand characteristics
AN – Technosols; CE – Phaeozem; Chernozem; Vertisols; FL – Fluvisols; GL – Gleysols; HN –Luvisols; Retisols; KAD – dystric Cambisols; KAM – eutric Cambisols; KAR – arenic Cambisols; KP – entic Podzols; OR – Histosols (peat soils); PG - Stagnosols; PZ – haplic Podzols; RZ – rendzic/calcaric Leptosols (Zádorová & Penížek 2011; Borůvka et al. 2022)

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Table 2. Semivariogram model parameters for soil properties

	pH_{H_2O}	pH_{KCl}	P	Al	C	CEC	BS
Model	exp	exp	exp	exp	sph	exp	sph
Nugget	0.3578	0.2774	77 413.4	46 323 788	19.98	6894.5	579.62
Sill	0.62	0.55	376 804.8	89 098 493	28.44	13617.5	968.99
Nugget ratio (%)	57.65	50.43	20.54	51.99	70.24	50.63	59.81
Range (m)	10 562.3	7 947.5	1 803 677	46 569.5	83 325.4	43 555.6	32 672.6
SSErr	1.02E-07	8.21E-08	14 177.05	4.37E+08	0.0003	33.63	0.14

SSErr – sum of squared error; exp – exponential; sph – spherical; CEC – cation exchange capacity; BS – base saturation

minium, carbon and phosphorus contents, whereas eutric Cambisols (KAM), which are among the most productive soils globally (ISRIC 2024), have a strong direct relationship with these soil properties. The soil classes Phaeozem; Chernozem and Vertisols (CE), rendzic/calcaric Leptosols (RZ), Technosols (AN) and Fluvisols (FL) were in direct relationship with BS and pH (both exchangeable and active). There is a relationship observed between the soil type FL and the soil properties. The position of rock structure and rock acidity (parent material) are hardly visible in the PCA plot. However, these two controlling factors are weakly related to deciduous and mixed forests, pH (exchangeable and active), base saturation, Fluvisols and Technosols. The PCA plot shows a relationship between soil pH (both exchangeable and active), deciduous forests, and BS. Coniferous forests are positioned in an opposite position to pH, deciduous forests, and BS. The content of phosphorus, aluminium, carbon, CEC and eutric Cambisols are closely related. Strong among them is the relationship between aluminium, phosphorus and CEC. The

Table 3. Cross-variogram model parameters for soil properties vs. forest types

	pH_{H_2O}	pH_{KCl}	P	Al	C	CEC	BS
Model	exp	exp	pure nugget	pure nugget	sph	sph	sph
Coniferous forests							
Nugget	–0.04	–0.04	–21.26	–201.85	–0.13	–2.9	–1.48
Sill	–0.14	–0.10	–21.26	–201.85	–0.28	–9.85	–5.43
Nugget ratio (%)	26.05	35.77	100.00	100.00	45.25	29.44	27.26
Range (m)	55 200	163 100	343 663.35	343 663.4	780 300	86 700	197 300
SSErr	6.61E-04	5.21E-04	522	838557	0.06	84.9	1.21
Deciduous forests							
Model	exp	exp	pure nugget	pure nugget	sph	sph	exp
Nugget	0.03	0.02	17.88	0.00	0.14	2.64	1.51
Sill	0.10	0.07	17.88	0.00	0.35	7.78	4.88
Nugget ratio (%)	26.34	28.12	100.00	100	38.48	33.93	30.96
Range (m)	42 200	46 500	343 663.35	811 000	811 000	51 800	128 400
SSErr	1.02E-03	5.22E-04	398	1.59E+06	0.04	39.1	1.01
Mixed forests							
Model	exp	exp	sph	pure nugget	pure nugget	sph	sph
Nugget	0.02	0.01	0.01	0.1	0.00	0.00	0.00
Sill	0.09	0.07	4.18	0.1	0.00	1.94	1.16
Nugget ratio (%)	16.06	8.17	0.24	100	100	0.05	0.09
Range (m)	75 810	800 800	68 800	730 000	728 900	110 000	170 500
SSErr	8.21E-04	5.87E-04	46	88583	8.50E-03	12.1	1.38

SSErr – sum of squared error; exp – exponential; sph – spherical; CEC – cation exchange capacity; BS – base saturation

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direct relationship of slope with carbon, aluminium, phosphorus and KAM is stronger compared to the weak or no relationship of these soil properties with forest types (Figure 2).

Semivariograms. The nugget ratio for the content of phosphorus is less than 25%. All the remaining soil properties have nugget ratio between 25 and and 75%. The content of phosphorus is strongly spatially dependent, whereas all the other soil properties are moderately spatially dependent

Cross-variograms for the forest soil properties and their controlling stand factors. A strong spatial dependence is seen between all the soil properties and the mixed forests. Phosphorus content shows no spatial dependence with coniferous and deciduous forests. The content of aluminium shows no spatial dependence with coniferous forests, however, with deciduous forests, aluminium shows a strong spatial dependence. Moderate spatial dependence is observed for pH(active and exchangeable), carbon content, CEC and BS with coniferous and deciduous forests (Table 3). The properties of pH_{H_2O}, P, Al, CEC and BS show strong spatial dependence with altitude. The strongest spatial dependence of altitude is with Al which recorded a nugget ratio of 0.15%. Moderate spatial dependence is observed for exchangeable reaction and carbon in their relationship with altitude. The P and Al contents show moderate spatial dependence with slope. However, pH (active and exchangeable), carbon, cation exchange capacity, and base saturation are strongly spatially dependent with less than a 25% nugget ratio (Table 4).

The cross-variograms show inverse relationships between coniferous forests and pH (active and exchangeable), as well as aluminium, carbon, CEC, and BS. Altitude and slope are inversely related to pH (active and exchangeable) and BS. Deciduous forests are inversely related to aluminium. An inverse spatial relationship is found between mixed forests and carbon.

DISCUSSION

These pH levels compare to observed pH of 4 and 3.62 for active and exchangeable reactions, respectively, for studies conducted within the acidic forest soils in the Jizera Mountains region of Czechia (Borůvka et al. 2005). A comparison of total P content in five sites in the frame of Pan-European International Co-operative Program on assessment and monitoring of air pollution effects on forests (ICP Forests) in Central Europe showed mean contents of 2 966, 1 375, 1 017, 929 and 195 mg/kg for Bad Brückenau, Mitterfels, Vessertal, Conventwald and Lüss sites in central, southern and north Germany (Lang et al. 2017). The observed mean for P in our study was only higher than the P poor Lüss site amongst the ICP forest sites. An average total Al content of 1 487 mg/kg was observed for a reclaimed mining site in Lítov, north -west of the Bohemia region of Czechia

Table 4. Cross-variogram model parameters for soil properties terrain factors

	pH_{H_2O}	pH_{KCl}	P	Al	C	CEC	BS
Model	exp	exp	sph	sph	sph	pure nugget	exp
Altitude							
Nugget	–29.1	–25.3	4970	1000	88.7	10	–810
Sill	–119.2	–100.87	23740	651200	303.9	10	–3958
Nugget ratio (%)	24.41	25.08	20.94	0.15	29.19	100	20.46
Range (m)	496 800	615 700	790 200	157 800	811 000	730 200	147 900
SSErr	357	456	7.29E+07	2.17E+11	26882	1.68E+07	1.04E+06
Slope							
Model	sph	sph	exp	sph	sph	exp	exp
Nugget	0.00	0.00	3.32	15.44	0.01	0.00	–0.20
Sill	–0.03	–0.02	8.05	38.38	0.14	1.26	–0.89
Nugget ratio (%)	1.90	7.83	41.27	40.23	6.92	0.08	23.05
Range (m)	811 000	811 000	811 000	56 300	782 400	34 300	811 000
SSErr	8.44E-04	5.14E-04	4.84	25168	1.92E-03	0.72	0.79

SSErr – sum of squared error; exp – exponential; sph – spherical; CEC – cation exchange capacity; BS – base saturation

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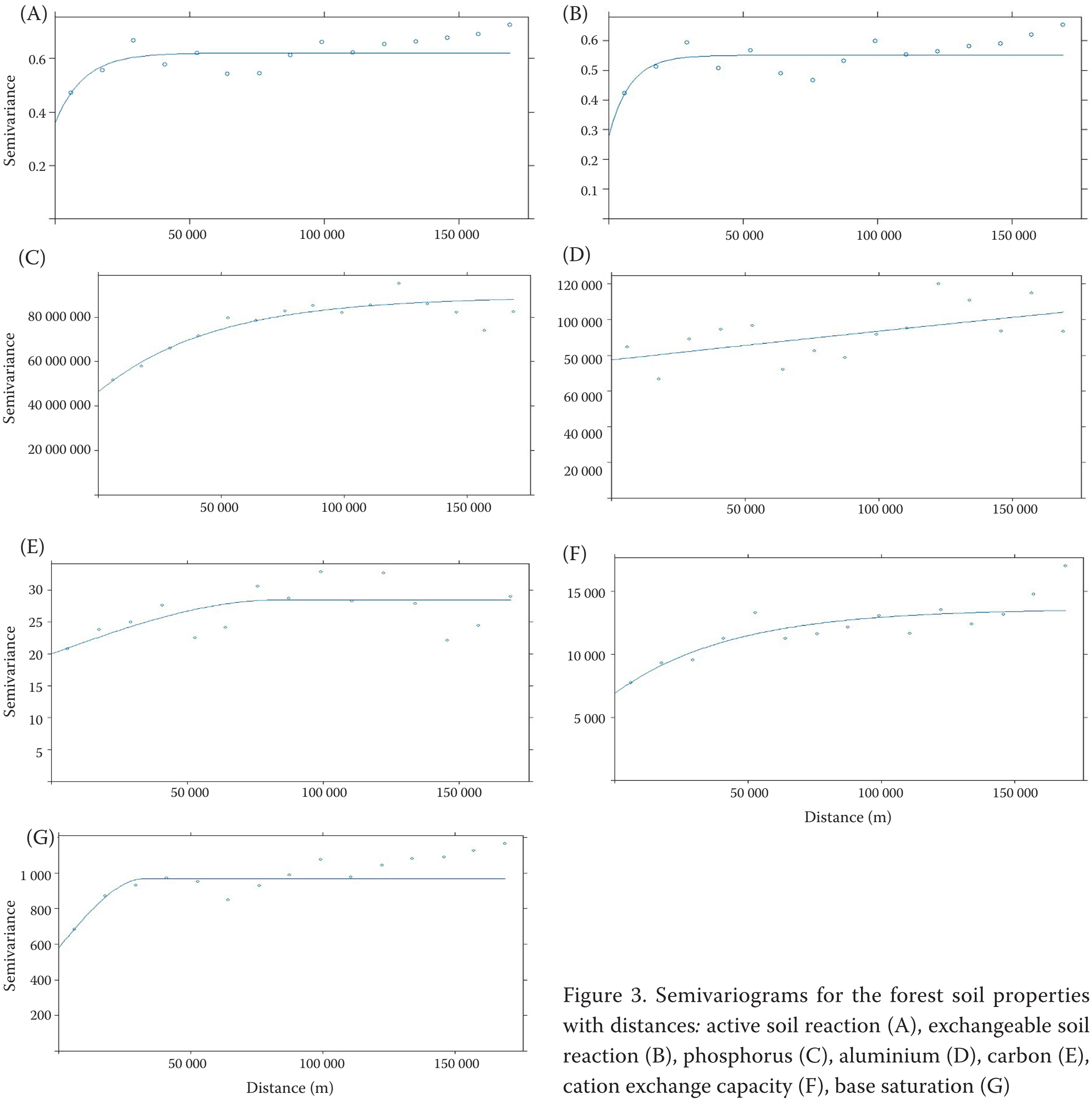

Figure 3. Semivariograms for the forest soil properties with distances: active soil reaction (A), exchangeable soil reaction (B), phosphorus (C), aluminium (D), carbon (E), cation exchange capacity (F), base saturation (G)

(Borůvka & Kozák 2001). The mean percentage carbon concentration observed in this study compares to 4.5% total carbon found by Mládková et al. (2005) in the Jizera Mountain region of Czechia. This low mean percentage of carbon within the mineral 0–30 cm of forest soil could result from Mor or Moder humus forms, which, although they have bigger organic carbon accumulated in their forest floor, the mineral topsoil is rather poor in organic matter (Weston & Whittaker 2004). The observed mean CEC value, which is higher than 40 $mmol_{(+)}/kg$, suggests that the forest soils in the Czech Republic have higher resistance to chemical changes that may be occasioned by land use. The mean BS value suggests moderately leached base cations and or moderately rich parent material (Hazelton & Murphy 2007).

The relationship between altitude and precipitation comes from the use of the digital elevation model as a covariate for interpolating the climatic data (Fick & Hijmans 2017). Cambisols are the dominating soil type within the study area, among the 13 soil types considered for this study (Němeček & Kozák 2005; Borůvka et al. 2022). Cambisols were therefore further categorized into arenic, dystric and eutric (Zádorová & Penížek 2011; Borůvka et al. 2022). The dystric Cambisols (KAD) are generally acidic,

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and have low base saturation (Zádorová & Penížek 2011; Preusser et al. 2021; Beck-Broichsitter et al. 2022). These characteristics of dystric Cambisols correlate with coniferous forests, where mineral topsoils are also known to be acidic and have low base saturation (Šantrůčková et al. 2019). Deciduous forest soils are not strongly acidic, and have higher base saturation (Šantrůčková et al. 2019). Cambisols properties generally depend more on parent material rather than forest types (Petrášová et al. 2009), arenic Cambisols are characterised by their sand, loamy sand, or sandy loam textural classification (Zádorová & Penížek 2011). Arenic Cambisols have dominance of sand, therefore lower content of aluminosilicates as a potential source of Al. Moreover, their coarser texture means that they have a smaller ability to retain nutrients and other elements (lower sorption capacity and stronger leaching due to high permeability). Eutric Cambisols are often formed on silicate rocks, which means a much stronger source of Al and other elements (Krasilnikov et al. 2013; Grčman et al. 2023). Fluvisols are characterised by neutral or near neutral reaction, with good base saturation in their exchange complex (ISRIC 2024). The soil pH (exchangeable and active), deciduous forests, and BS relationship suggests greater influence of forest types (coniferous and deciduous) on the pH and availability of cations within the topsoils for the forest areas, compared to the geological properties of parent materials from which these soils are formed (Augusto et al. 2015). This is further supported by the observed weak relationship between parent material and the controlling factors of deciduous and mixed forests, pH, and base saturation. We explain this to mean that the deciduous and mixed forests are more often on coarser and less acidic rocks and have higher pH and BS. Nevertheless, the contribution of the rock characteristics is quite low, which means that the effect of the rock is low or, more probably, it is hidden by other factors like forest type or soil class. Gruba & Mulder (2015) argued that tree species composition may influence changes in organic carbon, soil reaction, cation exchange capacity, exchangeable cations, base saturation and aluminium bonding in forest soils. The accumulation, movement and availability of phosphorus within forest soils is influenced by aluminium dynamics (SanClements et al. 2010). The availability of phosphorus to forest trees is influenced by their sorption mechanism, and this mechanism is influenced by soil organic carbon content, soil reaction and clay minerals (Duputel et al. 2013). The comparatively stronger relationship of the slope with carbon, aluminium, phosphorus and KAM is an indication of how the slope has a stronger influence on carbon, aluminium, and phosphorus, compared to its influence on pH (active and exchangeable) and base saturation, which is more influenced by forest types (Gruba & Mulder 2015). This also indicates that carbon accumulation in either the forest floor or topsoil can be influenced by the slope in the forest landscape. Slope gradient influence the distribution and storage of soil organic carbon through erosion and sedimentation (Chaplot et al. 2009). Slope shape (uniform, concave, and convex slopes) influences the variation in the amount and distribution of organic matter and sediments along hillslope during or between series of flow events (Sensoy & Kara 2014).

Strong spatial dependence is controlled by intrinsic factors, whereas external factors control weakly spatially dependent soil properties (Cambardella et al. 1994). The soil properties have shown an influence of internal factors on their spatial dependence, with phosphorus having the strongest influence. Phosphorus, which is influenced by aluminium, sorption mechanism, carbon and soil reaction (SanClements et al. 2010; Duputel et al. 2013) is seen in a relationship with aluminium, and cation exchange capacity in the PCA. The absence of spatial dependence from the cross-variograms with forest types means that phosphorus and aluminium are not spatially related to coniferous forests. However, aluminium is strongly spatially related to deciduous forests. We see from their relationship with the environmental factors in the PCA, an influence of deciduous forests, indicating higher total concentrations of both elements under broadleaved trees than under conifers.

CONCLUSION

Spatial analysis of data from Czech forests imply that forest types have a greater influence on soil pH and BS compared to the geological properties of parent materials, whose influence is low or dominated by other controlling factors like forest type or soil class. Deciduous forest soils are not strongly acidic and have higher base saturation. This attribute of deciduous forest soils is also apparent in mixed forests, where deciduous trees co-exist with coniferous trees. The deciduous and mixed forests are more often on soils developed from coarser and less acidic rocks which results in higher pH and BS.

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Phosphorus is influenced by aluminium and cation exchange capacity. The accumulation, movement and availability of phosphorus within forest soils is influenced by aluminium abundance and dynamics.

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