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Research article

Relationship of selected properties of Cambisols to altitude and forest ecosystems of four vegetation grades

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ABSTRACT

Currently, little is known about the spatial variability of significant soil properties and their relationships to forest ecosystems of different vegetation grades. This work evaluates the variability of the properties of the upper layer of Cambisol taxa and their relationship to altitude and forest ecosystems of 2nd to 5th forest vegetation grades selected in the Western Carpathians using PCA and regression analysis. The content of clay, total carbon and total nitrogen, humus, energy, and ash in the soils varied between 5.43 and 11.53 %, 21–65 mg g^{-1}, 1.9–4.7 mg g^{-1}, 36–112 mg g^{-1}, 438.4–5845.7 J g^{-1} and 852.9–946.3 mg g^{-1}, and C/N, pH_{H2O}, and pH_{KCl} values ranged between 11.2 and 16.7, 4.0–5.8 and 3.1–4.6. PCA showed that EAC in the 3rd oak-beech vegetation grade had significantly higher pH values and significantly lower energy content, ESC in the 4th beech vegetation grade had a significantly higher ash content and a significantly lower energy content, and DC in the 5th fir-beech vegetation grade had a significantly higher content of Ct, Nt, and humus. Linear regression revealed a strong negative correlation between the energy content and soil reaction (R^2 for $pH_{H2O} = 0.48$; R^2 for $pH_{KCl} = 0.38$) for all Cambisol taxa. Ct content and ash show a strong negative correlation ($R^2 = 0.78$). The positive relationship between altitude and FVGs was found only for the soil C_t ($R^2 = 0.87$), N_t ($R^2 = 0.81$), and humus content ($R^2 = 0.87$). A strong negative linear relationship between altitude and FVGs showed the ash content ($R2 = 0.77$). In turn, the oscillatory, polynomial course had a relationship between the clay content ($R2 = 0.65$) and energy ($R2 = 0.75$) to altitude and FVGs. Recognizing significant soil variables and better understanding their impact on the development of forest ecosystems is a prerequisite for distinguishing areas with the highest risk of their damage under conditions of various anthropogenic interventions and climate change. Therefore, this topic continues to require increased research efforts. For this reason, a better understanding of the relationships between soil properties and ecologically differentiated communities of forest ecosystems will allow us to identify areas with the highest risk of ecological changes that could lead to the degradation of European forests in the future.

AbbreviationsAbbreviations: FVG, Forest vegetation grade; GFT, Group of forest type; PCA, Principal component analysis; DC, Dystric cambisol; ESC, Eutric stagnic cambisol; EAC, Eutric andic cambisol; EC, Eutric cambisol; SOC, Soil organic carbon.

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1. Introduction

Various aspects of global climate change, such as higher CO2 levels, elevated temperatures, modified nutrient cycles, and altered disturbance regimes, can have either negative or positive effects on soil properties and carbon pools in forest ecosystems. The sequestration rate of soil organic carbon (SOC) is dependent on land use/land cover and is influenced by climate factors interacting with land use/land cover [1]. Inputs to the soil mainly come in the form of above-ground and underground plant litter originating from photosynthesis. Carbon outputs primarily result from the respiratory activity of soil decomposers [2]. Clay and silt soils have higher carbon stocks than sandy soils and show a greater response to carbon sequestration [3].

Significant differences in carbon sequestration potential exist among different stand types due to variations in stand structural attributes, plant species, age, climate, topography, and edaphic factors [4,5]. Disturbance events in forests have various impacts on the soil properties [6]. Ecosystem responses affect the exchange of carbon (C) with the atmosphere, providing feedback for future climate responses [7]. More serious threats to ecosystems are desertification and erosion associated with drought, strong winds and intense rains. The above threats can cause significant losses of the soil carbon and long-term carbon storage capacity [8].

Increased above-ground carbon stocks tend to exceed below-ground carbon stocks [9]. While above-ground carbon is concentrated in living plants, below-ground carbon is dispersed in a complex mixture of plant parts, soil animals, fungi and bacteria, mostly in various stages of decomposition. Well-developed forest soils typically exhibit a vertical succession of layers and a progressive decrease in carbon concentration with soil depth [3]. The formation and stabilization of the soil organic carbon are controlled by the amount of litter and its interaction with the soil conditions, rather than the quality of the litter [10]. Wiesmeier et al. [11] propose a set of indicators that allow for time- and cost-efficient estimates of actual and potential SOC storage from the local to the regional and subcontinental scale. As a key element, the fine mineral fraction was identified to determine SOC stabilization in most soils. The quantification of SOC can be further refined by including climatic proxies, particularly elevation, as well as information on land use, soil management and vegetation characteristics.

In the present scenario of climate change, progressive destruction of natural ecosystems, desertification, increasing food demand, and social and economic uncertainties, soil conservation is a fundamental pillar for attaining the sustainability of our life on Earth [12]. The view of soil as a mere physicochemical system serving as a substrate to sustain vegetation and crop production has been replaced by the recognition of the multifunctionality of soils and their biodiversity [13,14]. An area of interest that is experiencing a rapid growth is the subject of global change [15] the ramifications related to the carbon cycle [16–18].

Given the importance of soil C storage, several studies have been conducted to assess SOC in natural ecosystems [19]. Post et al. [20] provided a review of perspectives on monitoring and verifying changes in soil carbon. Weissert et al. [21] investigated differences in SOC stocks and soil CO_2 efflux between grass- and tree-dominated urban systems. The authors found that mean soil organic C stocks (0–10 cm) were significantly higher in the park soils compared to the urban forest soils, which was largely due to the higher bulk densities in the park soils.

The ability of plants to fix solar radiation is an important indicator of primary production. Although there is some controversy about the calorific value, it is considered to be a useful tool for studying energy transfer and flow efficiency [22]. However, changes in soil energy content have been less studied. Salmi [23] found that the calorific value of peat depends on the type of peat and the degree of its humification. Ovington and Heitkamp [24] and Ovington [25] analyzed the surface organic matter of a varying large number of different forest soils and found that the material in the F + H layers had a lower calorific value (3.317–4.562 kcal/g) than freshly fallen litter (3.781–5.187 kcal/g). This was partly a reflection of a higher mineral content of the F + H layers.

Future climate could negatively impact forest recovery, thus potentially amplifying climate change through carbon loss from ecosystems [26]. Energy from solar radiation and precipitation represents the dominant source of energy input into most soil systems [27]. Zhou et al. [28] found that the soils in the 20 cm soil layer of preserved old-growth forests in southern China accumulated atmospheric carbon at an unexpectedly high rate, pointing to the need to study complex reactions and adaptation of underground processes to global environmental changes.

As forests and forest soils play a key role in carbon sequestration, more and more attention is being paid to the systematic detection and assessment of carbon and energy stocks in forest soils [10]. The results of Baritz et al. [29] support relationships between carbon stocks and site factors such as climate zones and soil type. From an ecosystem perspective, the highest concentration of organic carbon is in the surface layer of the forest, decreasing in the order forest > pasture > arable land [30]. Gonet and Dębska [31] compared the total organic carbon content in different layers of agricultural and forest soils, and find 12 g kg^{-1} and 38.4 g kg^{-1}, respectively. Compared to much lower carbon concentrations in agricultural soils, these results underscore the importance of forest soils for the terrestrial carbon cycle in Europe.

Although an extensive inventory of carbon stocks in European forest soils has been published [32,33], detailed site-specific studies are still needed because C content is highly variable spatially and depends on specific soil, ecological and management factors. However, little is known about the spatial variability of significant soil variables within forest vegetation grades. Forest vegetation grades characterize the climatic conditions of mountainous regions based on the presence or absence of plant indicators of vegetation grades. Mindáš and Škvarenina [34] believe that global climate changes can also affect plant communities of forest vegetation grades.

Land use, intricately tied to planning and policies, undergoes continuous evolution, necessitating an increasing emphasis on soil quality [35,36] and sustainable development natural soil functions. Recognizing the factors of the spatial distribution of soil characteristics will allow distinguishing areas with the highest risk of forest damage, as well as subsurface and surface water pollution [37]. How these new threats affect soil multifunctionality is a topic that deserves new research efforts, especially considering real field situations.

Currently, little is known about the spatial variability of important soil properties and their relationships to forest ecosystems occurring in different forest vegetation grades. More often, the properties of the soil refer only to the altitude, which does not sufficiently reflect the climate and vegetation characteristics of the ecosystems. We assume that the properties of the top layer of forest soils occurring along the vertical gradient depend on the soil type, altitude, group of forest types, and forest vegetation grade, which reflects the changing intensity of climatic factors such as precipitation, evaporation, temperature of air and soil, and others. The aim of the work is therefore to evaluate the relationships of selected properties of the upper layer of Cambisol taxa to altitude and ecologically different forest ecosystems of four forest vegetation grades. A better understanding of the relationships between soil properties and forest communities is a prerequisite for distinguishing areas with the highest risk of ecological changes arising as a result of forestry practices, and especially global climate change.

2. Material and methods

2.1. Study site and sampling

The research was carried out in nine forest ecosystems selected in the orographic units the Podunajská pahorkatina Mts, the Kremnické vrchy Mts, the Štiavnické vrchy Mts and the NP Slovenský raj Mts (the Western Carpathians, Slovakia) during the growing season of 2016 (Fig. 1). The research sites were chosen regarding the presence of the same soil type (Cambisol), the properties of which should change in connection with changes in climatic elements along the height transect of mature forest stands of four forest vegetation grades. The Cambisols are the most widespread soil type in Slovakia, with 33 % representation.

The basic characteristics of the examined forest ecosystems are listed in Table 1. The soils of forest ecosystems are medium-deep to deep, loamy-sandy to clay-loamy, crumbly to cloddy with a content of rock fragments in ranging from 10 to 40 % in the upper part to 30–70 % in the lower part of the profile. Soil samples were taken from the 0–10 cm layer of probes dug in each studied forest ecosystem at 3 randomly selected locations, in triplicate (3x9 = 27 sampling points). Approximately 1–2 kg of soil was collected from each sampling point. Approximately 1–2 kg of soil was collected from each sampling point. Soil classification was performed according to the principles of the World Reference Base for Soil Resources [38].

The geobiocoenological classification of forest ecosystems into groups of forest types (GFT) and forest vegetation grades (FVG) was carried out based on the floristic composition of communities and the presence/absence of plant indicators of edaphic-hydric orders, edaphic-trophic orders and forest vegetation grades in the sense of Zlatník [39]. Geobiocoenology deals with the reconstruction and classification of changed geobiocoenoses through plant indicators of ecological factors (trophic, hydric, thermic) and floristic characteristics of natural (nature close) plant communities.

2.2. Laboratory analyses

The soil samples freed from necrotized organic residues were air-dried and passed through a sieve with a 2 × 2 mm mesh size. The granulometric composition of the fine earth fraction of soils dispersed with sodium hexametaphosphate and ultrasound was determined using a laser particle size measuring device, Analysette 22 (Fritsch, Germany).

The active and exchange reactions were determined using a digital pH meter Inolab pH 720 (Weilheim, Germany), when the ratio of fine soil to water or 1 M KCl solution was 1:2.5. The total content of C and N was determined using CNS Flash EA 1112 from Thermo Finnigan in triplicate (STN EN ISO 16948). The amount of humus was calculated by multiplying the carbon content by a factor of 1.724. The energy content (Joul g^{-1} d.m.) of an average soil sample weighing 0.7–1 g obtained by quartering and placed in a combustion bag with a known calorific value (46,367 J g) was determined using an IKA C-4000 adiabatic calorimeter (software C-402, DIN 51900). The relative deviation between measurements of each sample was limited to less than 1 %. The ash content was determined

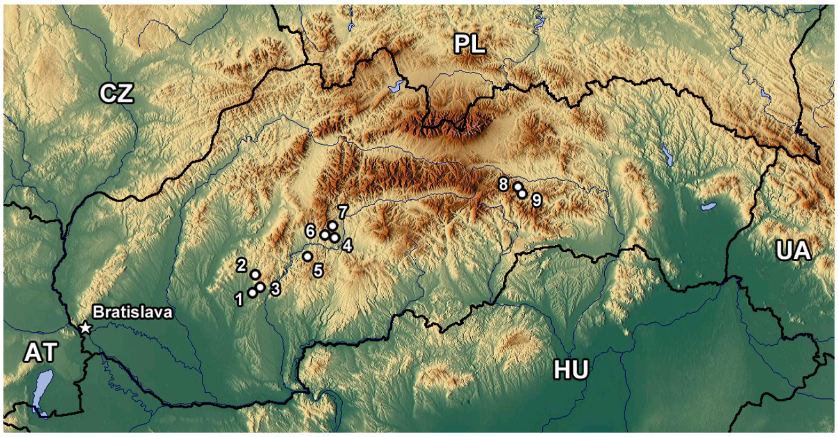

Fig. 1. Locations of the studied forest ecosystems in the Western Carpathians (1–3: the Podunajská pahorkatina Mts.; 4, 6, 7: the Kremnické vrchy Mts.; 5: the Štiavnické vrchy Mts.; 8, 9: the Slovenský raj Mts.).

Table 1
Basic characteristics of the studied forest ecosystems.

Orographic unit	Geographic coordinates	Altitude (m)	Exposure	Parent rock	Soil subtype	Stand age (years)	Group of forest type (GFT)	Forest vegetation grade (FVG)
1. Podunajská pahorkatina	18°28′47″E 48°26′35″N	265	NNW	andesitic tuff	Dystric Cambisol (Siltic)	70–90	*Fagi-Querceta typica*	2nd Beech-Oak
2. Podunajská pahorkatina	18°30′42″E 48°22′20″N	257	NW	pleistocene clay-gravel sediments		70–90		
3. Podunajská pahorkatina	18°28′39″E 48°21′05″N	294	SSE	loess loam/slope clays (rarely quartz)	Eutric Stagnic Cambisol (Siltic)	70–90	*Querci-Fageta typica*	3rd Oak-Beech
4. Kremnické vrchy Mts.	19°04′18″E 48°38′08″N	500	WSW	andesitic tuffaceous agglomerates	Eutric Andic Cambisol (Silitic)	110	*Fagetum paupe inferiora*	
5. Štiavnické vrchy Mts.	18°51′53″E 48°32′01″N	450	NNW	rhyolitic tuff, tuffit	Eutric Stagnic Cambisol (Siltic)	100	*Fagetum pauper superiora*	4th Beech
6. Kremnické vrchy Mts.	19°02′14″E 48°38′44″N	690	WSW	andesitic tuffaceous agglomerates	Dystric Cambisol (Siltic)	90		
7. Kremnické vrchy Mts.	19°03′38″E 48°41′36″N	795	N	andesitic tuffaceous agglomerates	Eutric Cambisol (Siltic)	200		
8. Slovenský raj Mts. (Hliníky)	20°30′42″E 48°53′17″N	760	ENE	variegated sandstones and slates	Dystric Cambisol (Siltic)	80–100	*Abieti-Fageta inferiora*	5th Fir-Beech
9. Slovenský raj Mts. (Stolíky)	20°32′12″E 48°51′49″N	950	SW	violet-gray polymict conglomerates		80–100		

gravimetrically by burning the samples in an electric muffle furnace at 500 °C in triplicate.

2.3. Data analysis

Statistical evaluation of the data was performed using the STATISTICA program (version 9). PCA analysis was carried out in the PAST program (version 4.03). The results were expressed as mean ± standard deviation (SD). For normally distributed data, a one-way ANOVA followed by a Tukey's post hoc test was used to find significant differences in the average clay, carbon, nitrogen, energy and ash content of the soils in the studied ecosystems. Principal component analysis (PCA) was conducted using nine selected Cambisol variables (clay, carbon, nitrogen, humus, energy and ash content; pH_{H2O}, pH_{KCl} and C/N values) to identify their relationships with elevation and forest vegetation grades. Linear regression analysis was applied to evaluate the relationships between soil properties. All tests were performed with a significance level (α) set at 0.05.

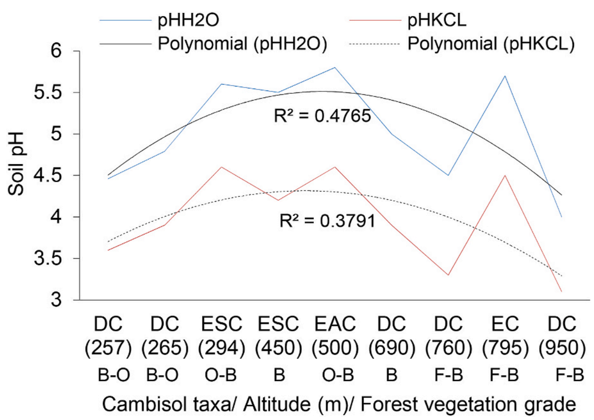

Fig. 2. Relationship of the pH values of soils to altitude and forest vegetation grades (DC– Dystric Cambisol, ESC – Eutric Stagnic Cambisol, EAC – Eutric Andic Cambisol, EC – Eutric Cambisol; B–O: Beech-Oak, O–B: Oak-Beech, B: Beech, F–B: Firch-Beech).

3. Results

3.1. Variability of soil properties and their relationship to altitude and forest vegetation grades

The values of the active and exchange reactions of Cambisols in forest ecosystems of the 2nd to 5th FVGs vary from pH_{H2O}/pH_{KCl} 5.81/4.55 to pH_{H2O}/pH_{KCl} 4.0/3.1. The development of the reaction values has an oscillatory, polynomial course, with the highest values at medium altitudes (Fig. 2). The highest pH values were found in the EAC of the GFT *Fagetum pauper inferiora* of the 3rd oak-beech FVG (pH_{H2O}/pH_{KCl} 5.81/4.55), in the EC of the GFT *Fagetum pauper superiora* of the 4th beech FVG (pH_{H2O}/pH_{KCl} 5.67/4.49) and in of the ESC of the GFT *Querci-Fageta typica* of the 3rd oak-beech FVG (pH_{H2O}/pH_{KCl} 5.58/4.62) located at altitudes of 500, 795 and 294 m.

The trend of acidification can be observed in the upper layer of DC of oak stands located at altitudes of 257 and 265 m in the GFT *Fagi-Querceta typica* of the 2_{nd} beech-oak FVG (pH_{H2O}/pH_{KCl} 4.5–4.8/3.6–3.9) and especially DC in the GFT *Abieti-Fageta inferiora* of the 5th fir-beech FVG (pH_{H2O}/pH_{KCl} 4.0–4.5/3.1–3.3), which are affected by acidic litter of secondary spruce stands and acidic atmospheric emissions. The DC of the beech stand located at an altitude of 690 m in the GFT *Fagetum pauper superiora* of the 4th FVG is only weakly acidified (pH_{H2O}/pH_{KCl} 5.0/3.9).

A very important soil component is clay, which is involved in forming clay-humus complexes. Together with other soil components, such as microorganisms, and dusty and sandy fractions, it significantly contributes to the formation of a stable soil structure. In the soils of the studied forest ecosystems, the content of physical clay (<0.002 mm) fluctuated in the range of 6.19–13.69 % (Table 2). The highest clay contents were found in the soils of the 3rd and 4th FVG ecosystems located at medium altitudes, similar to the soil reaction values. The lowest clay content was found in the DC at an altitude of 950 m in the GFT *Abieti-Fageta inferiora* of the 5th beech-fir FVG. Compared to the stated value, only the clay content is significantly higher in the ESC located at an altitude of 294 m in the GFT *Querci-Fageta typica* 3rd oak-beech FVG and in the DC located at an altitude of 690 m in the GFT *Fagetum pauper superiora* of the 4th beech FVG. The differences between the other soils are not significant.

Carbon is an important component of soil that affects its properties and is an important part of the global carbon cycle. The C_t content detected in the soils of the investigated forest ecosystems fluctuated in the range of 21.1 and 65.0 mg g^{-1} and generally increased with altitude and FVGs (Table 2). Compared to the other soils, the C_t contents are significantly lower in the DCs located at altitudes of 257 and 265 m in the GFT *Fagi-Querceta typica* of the 2nd beech-oak FVG and in the ESC located at an altitude of 450 m in the GFT *Fagetum pauper superiora* of the 4th beech FVG. On the other hand, the highest C_t contents compared to the other soils are in the EC and DCs located at altitudes of 760–950 m in the GFT *Fagetum pauper superiora* of the 4th beech FVG and in the GFT *Abieti-Fageta superiora* of the 5th fir-beech FVG.

The N_t content detected in the soils fluctuated in the range of 1.78 and 4.7 mg g^{-1} and generally increased with altitude and FVGs (Table 2). Compared to the others, the N_t contents are significantly lower in the DCs located at altitudes of 257 and 265 m in the GFT *Fagi-Querceta typica* of the 2nd beech-oak FVG. On the other hand, a significantly higher N_t content compared to the others is in the DC, located at an altitude of 760 m in the GFT *Abieti-Fageta inferiora* of the 5th fir-beech FVG.

The quality of humus depends on the carbon-to-nitrogen ratio. In very fertile soils, the C/N ratio is lower than 10. In the soils of the investigated forest ecosystems, the C/N values fluctuate in the interval 9.64−16.67. Compared to the others, the C/N value is significantly lower in the ESC located at an altitude of 450 m in the GFT *Fagetum pauper superiora* of the 4th beech FVG. The only exception is the DC located at an altitude of 257 m in the GFT Fagi-Querceta typica of the 2nd beech-oak FVG, whose C/N value does

Table 2
Significance of differences in the values of selected soil variables depending on altitude and forest vegetation grade (Tukey HSD test). Significantly different values (p<0.05) are indicated by different letters ([a,b,c,d]).

Forest vegetation grade/ altitude (m)	Soil unit	Clay	C_t	N_t	C/N	Humus	Ash	Energy
		(%±SD)	(mg g^{-1}±SD)			(mg g^{-1}±SD)		(J g^{-1}±SD)
2nd beech-oak/265	Dystric Cambisol	9.49 ± 1.9[ab]	25.9 ± 1.2[a]	1.78 ± 0.13[a]	14.55 ± 1.17[a]	45 ± 2.1[a]	927 ± 12[a]	2,613.5 ± 303[a]
2nd beech-oak/257		8.55 ± 1.7[ab]	21.1 ± 1.1[a]	1.89 ± 0.14[a]	11.16 ± 0.90[bc]	36 ± 1.9[a]	939 ± 14[a]	3,157.3 ± 96[ab]
3rd oak-beech/294	Eutric Stagnic Cambisol	13.19 ± 4.7[b]	34.8 ± 1.7[b]	2.46 ± 0.20[ab]	14.15 ± 1.08[ab]	60 ± 2.9[b]	909 ± 13[ab]	3,847.8 ± 108[b]
3rd oak-beech/500	Eutric Andic Cambisol	12.67 ± 2.8[ab]	48.0 ± 2.3[c]	3.30 ± 0.26[b]	14.55 ± 1.16[a]	83 ± 4.0[c]	913 ± 2.0[ab]	999.1 ± 157[c]
4th beech/450	Eutric Stagnic Cambisol	11.18 ± 1.3[ab]	27.0 ± 1.3[a]	2.80 ± 0.22[b]	9.64 ± 0.77[c]	47 ± 2.2[a]	946 ± 0.6[a]	438.1 ± 14[c]
4th beech/690	Dystric Cambisol	13.69 ± 1.9[b]	49.0 ± 2.4[c]	3.40 ± 0.27[b]	14.41 ± 1.15[a]	84 ± 4.2[c]	893 ± 3.0[bd]	656.0 ± 15[c]
4th beech/795	Eutric Cambisol	10.87 ± 2.3[ab]	64.0 ± 3.1[d]	4.00 ± 0.32[bc]	16.00 ± 1.28[a]	110 ± 5.2[d]	874 ± 2.0[d]	1,303.1 ± 229[c]
5th fir-beech/760	Dystric Cambisol	9.40 ± 2.1[ab]	63.0 ± 4.0[d]	4.70 ± 0.37[c]	13.40 ± 1.07[ab]	109 ± 5.2[d]	858 ± 8.0[d]	3,645.6 ± 494[b]
5th fir-beech/950		6.19 ± 0.8[a]	65.0 ± 3.0[d]	3.90 ± 0.31[b]	16.67 ± 1.33[a]	112 ± 5.6[d]	853 ± 2.0[d]	5,845.9 ± 415[d]

not differ significantly.

Humus is a very important part of soils because it improves soil structure, permeability, cation exchange capacity, storage of water and nutrients, and so on. In the soils of the investigated forest ecosystems, the humus content fluctuated in the range of 36 and 112 mg g^{-1} and generally increased with altitude and FVGs, similar to the carbon content (Table 2). Compared to the others, the humus contents are significantly lower in the DCs located at altitudes of 265 and 257 m in the GFT *Fagi-Querceta typica* of the 2nd beech-oak FVG and in the ESC located at an altitude of 450 m in the GFT *Fagetum pauper superiora* of the 4th beech FVG. On the other hand, significantly higher humus contents compared to the others are in the EC and DCs located at an altitude of 760–950 m in the GFT *Fagetum pauper superiora* of the 4th beech FVG and the GFT *Abieti-Fageta inferiora* of the 5th fir-beech FVG.

The ash content found in the soils varies between 853 and 946 mg g^{-1} and generally decreases with altitude and FVGs (Table 2). Compared to the others, the ash contents are significantly higher in DCs located at altitudes of 257 and 265 m in GFT *Fagi-Querceta typica* of the 2nd beech-oak FVG and ESC located at an altitude of 450 m in GFT *Fagetum pauper superiora* of the 4th beech FVG. On the other hand, significantly lower ash contents compared to the others are found in EC and DC, located at an altitude of 760–950 m in GFT *Abieti-Fageta inferiora* of the 5th fir-beech FVG.

The energy content of soils depends on the amount and quality of organic matter. In the soils of the studied forest ecosystems, it fluctuates between 438.1 and, 5845.9 J g^{-1} (Table 2). Compared to others, the energy content is significantly higher in the DC, located at an altitude of 950 m in the GFT *Abieti-Fageta inferiora* of the 5th FVG. On the other hand, significantly lower energy content is found in the EAC located at an altitude of 500 m in the GFT *Fagetum pauper inferiora* of the 3rd oak-beech FVG and in the ESC, EC and DC located at altitudes of 450, 690 and 795 m in the GFT *Fagetum pauper superiora* of the 4th beech FVG. The cause of the decrease in the energy content in the middle of the height range of soils is unknown. We can only conclude that the lowest energy contents are correlated with the highest pH values and clay contents in the middle part of the height range of the studied soils, and the highest ash content (946 mg g^{-1}) is in the ESC with the lowest energy content. But there is also the possibility that the firm binding of humic substances with clay prevents the complete burning of humus. According to Barré et al. [40], the low energy content of persistent OM may be attributed to a combination of reduced content of energetic C–H bonds or stronger interactions between OM and the mineral matrix.

3.2. Principal component analysis

The results of principal component analysis (PCA) were used to identify the relationships between key soil characteristics (variables) of Cambisol taxa, altitude, and FVGs. In Table 3, nine soil variables (soil clay, nitrogen, carbon, humus, ash and energy; values of pH_{H2O}, pH_{KCl} and C/N) were reduced to a set of new variables called principal components (PCs). PCA shows that the first principal component (PC1) describes 50.71 % of the total variability and the second (PC2) 29.31 %. Eigenvalues for the first two PCA axes greater than 1 indicate that these axes describe 80.02 % of the total variability. PC1 is negatively correlated with ash content (−0.904) and positively correlated with soil carbon (0.884), nitrogen (0.804), humus (0.906) and energy (0.569) content. The contents of ash and carbon, as well as ash and humus, are inversely correlated, which means that as the amount of ash increases, the amount of carbon and humus decreases significantly.

Active and exchange reactions of soils and clay content are positively correlated with PC2 (0.837, 0.735, and 0.646, respectively). On the other hand, the energy content is inversely correlated with PC2 (−0.595), meaning that as soil reaction increases, energy content decreases and vice versa. The C/N vector is the shortest, indicating that the first two principal components do not describe it well.

The PCA biplot (Fig. 3) shows that the ash content is a dominant factor contributing significantly to the distinguishing of ESC located at an altitude of 450 m in the *Fagetum pauper superiora* of the 4th beech FVG from the other soils. The ash and energy contents are inversely correlated, meaning that as the ash content increases, the energy content decreases, and vice versa. The amount of C, N and humus significantly distinguishes DC's located at altitudes of 760 and 950 m in the GFT *Fagetum pauper superiora* of the 4th beech FVG and GFT *Abieti-Fageta inferiora* of the 5th fir-beech FVG from other soils. This means that the content of carbon, nitrogen and humus increases significantly at higher altitudes and is inversely correlated with ash. On the other hand, the DC located at an altitude of 257 m in the GFT *Fagi-Querceta typica* of the 2nd beech-oak FVG is characterized by a significantly higher content of ash and a

Table 3
Soil variables of Cambisol taxa shown based on correlation with principal components.

Parameter	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9
Clay	0.416	0.646	−0.103	0.624	−0.061	0.070	0.008	0.001	0.0002
Nitrogen	0.804	0.412	−0.349	−0.100	0.057	0.193	−0.098	−0.022	0.004
Carbon	0.884	0.438	−0.035	−0.070	0.021	0.040	0.126	−0.049	0.005
Humus	0.906	0.405	−0.060	−0.040	−0.006	0.008	0.029	0.092	0.002
Ash	−0.904	−0.167	0.092	−0.176	−0.144	0.302	0.039	0.018	0.003
Energy	0.569	−0.595	0.377	0.216	0.337	0.136	0.009	0.002	−0.001
pH_{H2O}	−0.470	0.837	0.115	−0.165	0.189	0.017	0.005	−0.0001	−0.029
pHKCl	−0.565	0.735	0.313	−0.113	0.162	−0.044	−0.016	−0.0003	0.029
C/N	0.678	0.263	0.625	0.022	−0.279	0.015	−0.048	−0.010	−0.006
Eigenvalue	4.56	2.64	0.79	0.52	0.28	0.16	0.03	0.01	0.002
Variability (%)	50.71	29.31	8.78	5.83	3.14	1.74	0.35	0.12	0.02

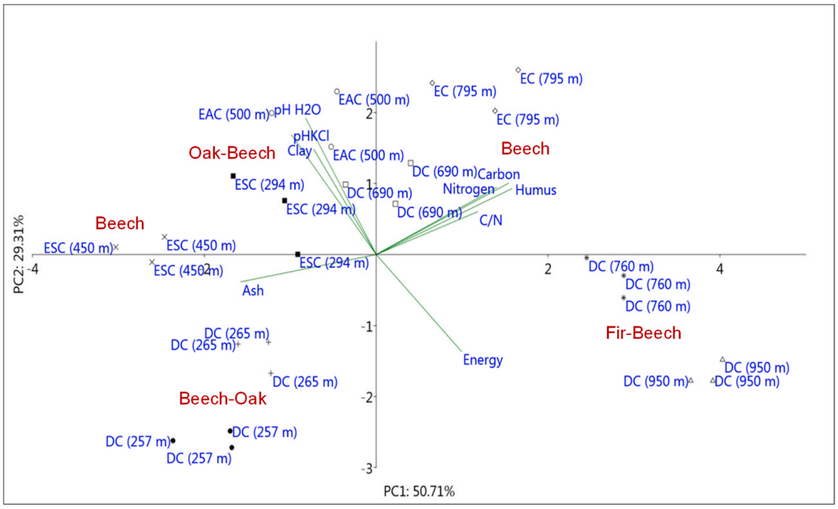

Fig. 3. PCA biplot showing correlation of the first two principal component axes to the soil variables (content of clay, carbon, nitrogen, humus, energy, ash, values of pH_{H2O}, pH_{KCl}, and C/N) of Cambisol taxa (DC, ESC, EAC, EC) in relation to altitude and FVGs (Beech-Oak, Oak-Beech, Beech, Fir-Beech).

significantly lower content of carbon, humus and N. The active and exchange reaction of the EAC located at an altitude of 500 m in the GFT *Fagetum pauper* of the 3rd oak-beech in turn significantly distinguishes these soils from other soils. Soil reaction is inversely correlated with energy content and positively correlated with clay.

3.3. Regression analysis

Linear regressions show the closest positive linear relationships only for soil C_t, N_t and humus content to altitude and FVGs. On the other hand, the ash content showed a strong negative relationship with altitude and FVGs. The development trend of clay content with altitude and FVG, in turn, has an oscillatory, negative polynomial course. There is also a positive polynomial trend in the development of the soil energy content to altitude and FVGs. The tightness of the dependence of the linear regression of clay and energy on elevation and FVG is low (R2 < 10 %), (Table 4).

Linear regression revealed a relatively strong negative relationship between energy content and soil pH_{H2O} (R^2 = 48 %), as well as energy content and soil pH_{KCl} (R^2 = 38 %). The coefficient of determination showed a strong relationship between carbon and ash content (R^2 = 78 %) and a moderate relationship between energy and ash content (R^2 = 18 %), (Fig. 4). The relationships between other soil parameters are not significant, representing only 0.2 %–7 % according to *R2*.

4. Discussion

The soil pH reaction, as an indicator of soil acidity, is the primary factor controlling nutrient availability and microbial processes [41]. The soils under coniferous trees show lower pH values than those under deciduous trees [42]. This finding is consistent with our pH values that are the lowest in Dystric Cambisols of the 5th fir-beech FVG. The development of the soil reaction values with altitude has an oscillatory, polynomial course, with the highest values at medium altitudes. Badia et al. [43], who investigated the forest soil catena in the Moncayo massif (Iberian Range, SW Europe), found that with increasing altitude, the pH value, the degree of base saturation, and the content of exchangeable potassium and fine dust particles decrease significantly, while the content of organic

Table 4
Relationships of the soil variables to altitude and FVGs. Correlations are significant at the 0.05 level (n = 27, *R2* = coefficient of determination).

Soil variable	Regression equation	*R2*
clay	linear: $y = -0.0027x + 12.066$	0.0812
	polynomial: $y = -4E\text{-}05x^2 + 0.042x + 1.5801$	0.6534
C_t	linear: $y = 0.0637x + 9.0608$	0.8706
N_t	linear: $y = 0.0035x + 1.2264$	0.8107
C/N	linear: $y = 0.0048x + 11.193$	0.3110
humus	linear: $y = 0.1096x + 15.788$	0.8694
ash	linear: $y = -0.1166x + 965.61$	0.7732
energy	linear: $y = 1.397x + 1730.6$	0.0395
	polynomial: $y = 0.0323x^2 - 35.619x + 10413$	0.7500

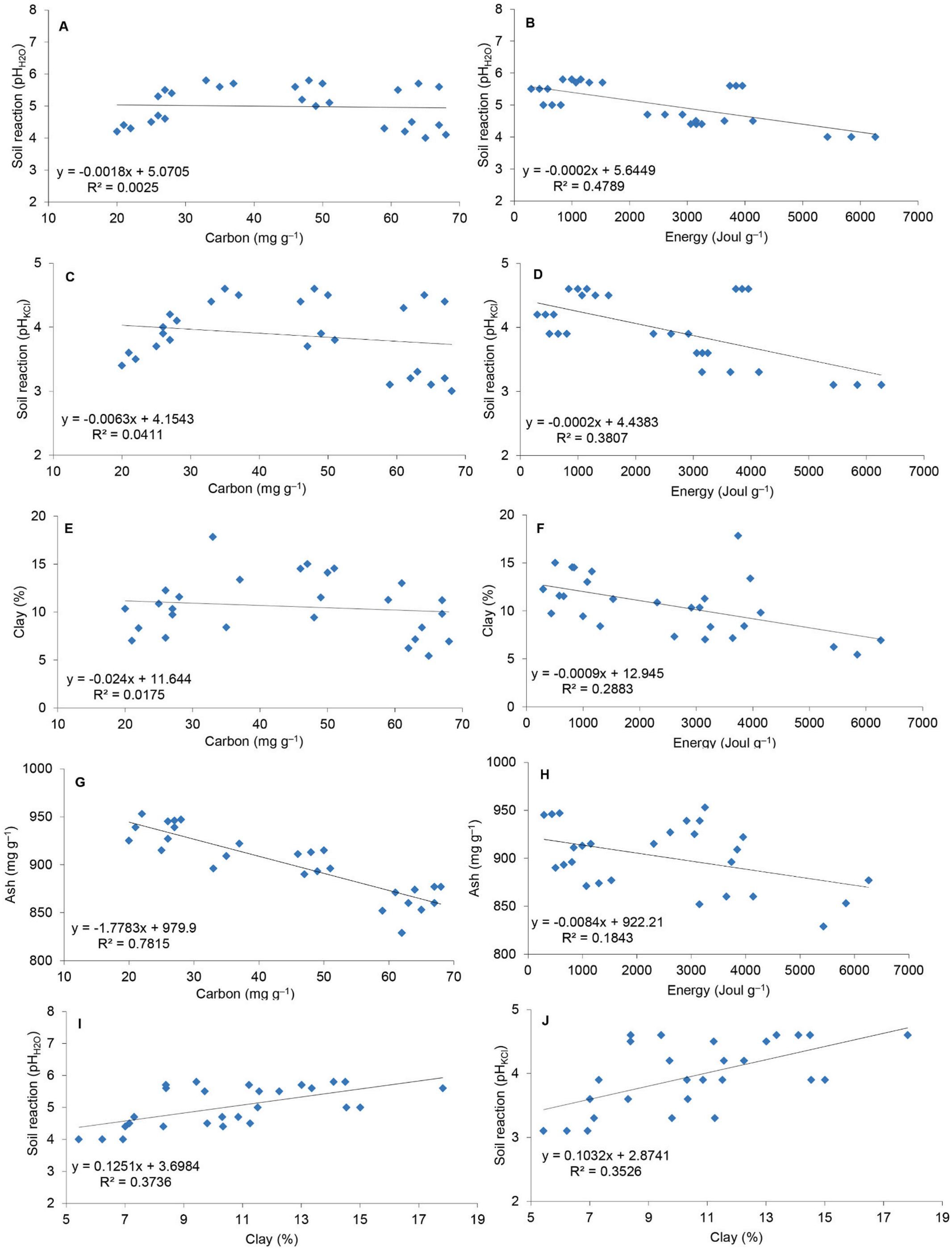

Fig. 4. Linear regressions of the soil variables (n = 27, $p < 0.05$, R^2 = determination coefficient): A (carbon – pH_{H2O}), B (energy – pH_{H2O}), C (carbon – pH_{KCl}), D (energy – pH_{KCl}), E (carbon – clay), F (energy – clay), G (carbon – ash), H (energy – ash), I (clay – pH_{H2O}), J (clay - pH_{KCl}).

matter, the ratio C/N, stability of soil aggregates, water repellence of soil, and the content of coarse sand particles increase significantly. On the other hand, in the dry deciduous forest of the Western Ghats of Tamil Nadu, Kanagaraj et al. [44] found that organic carbon, water-soluble carbon, and even soil pH were positively correlated with an altitude, with a rate of correlation coefficient of 0.92, 0.87, and 0.75, respectively. Zhang et al. [45], who studied the spatial distribution of SOC and N stocks in soils of nine vegetation types along an altitude gradient (600–4500 m) in southwestern China, report that total organic carbon and nitrogen also increased with elevation and were positively correlated with mean annual temperature and precipitation. Simon et al. [46] in Eastern Himalayan mountain forests revealed a linear correlation between soil organic carbon stock and pH with an altitude. The soil pH-values in the

Eastern Himalaya showed a linear correlation with elevation in the topsoil, with higher values at lower elevations. However, the soil reaction values determined by us in the Western Carpathians had an oscillatory, polynomial course, with the highest values at medium altitudes. The tightness of the dependence of the linear regression of C:N values on elevation and FVG was low (30 %). This fact is not consistent with the results of Hamid et al. [47], who report that soil temperature, pH, electrical conductivity, and C:N ratio showed an increased trend towards the altitudinal gradient.

In the soils of forest ecosystems studied by us, the highest clay contents were found in the soils located at medium altitudes, similar to the soil reaction values. The clay content and the soil reaction were negatively correlated with altitude and FVG. The tightness of the dependence of the linear regression of clay on altitude and FVGs was low ($R2 < 10$ %). On the other hand, in the less accessible Sida forest of southern Ethiopia, Hailemariam et al. [48] found a significant positive correlation of clay with altitude ($r = 0.40$; $p < 0.001$). Sims and Nielsen [49] reported that clay content apparently has much less effect on organic C accumulation in cool Montana soils than in warmer soils of the southern Great Plains. The mentioned authors did not find significant correlations between the clay content and organic C for any group of pedons. The contribution of silt and clay content to C stock changes in Poland was 15 %. It is most evident in the O-horizons and the 0–10 cm mineral soil layer at altitudes from 300 to 1000 m [50].

Forest soils are one of the major carbon sinks on Earth because of their high organic matter content [51,52]. However, carbon stocks can potentially be influenced by soil disturbance events [53], forest type [37], or topographic parameters [54]. Petrášová et al. [55] state that in the top layer of Cambisols managed in different ways in the Czech Republic, the content of total organic carbon ranges from 2.7 % (Přemyslov–Tři Kameny, 803 m a.s.l.) to 1.3 % (Náměšť n/Oslavou, 430 m a.s.l.). A higher content of humus of lower quality was found in the soils under grasslands. A higher C content, from 9.1 to 12.2 %, was found by Barančíková et al. [56] in the Dystric Cambisols of the Tatra National Park in Slovakia, while the highest values were found in the soils of reference intact spruce forests and in the clearings damaged by a surface fire. Even slightly higher values (13.3 mg g^{-1} C) are reported by Wordell-Dietrichet et al. [57] for Dystric Cambisol at the beech-dominated Grinderwald site, 35 km northwest of Hannover, Germany. However, the highest C content (up to 15.4 %) is reported by Kabała and Szerszeń [58] in the A-horizons of the Dystric Cambizems developed from granite and gneiss in the Sudeten Hills. On the other hand, the average amount of Ct stored in the Cambisols of the forest ecosystems studied by us is considerably lower and varies between 21.1 mg g^{-1} (2.1 %) and 65 mg g^{-1} (6.5 %).

The soil C concentrations in mountainous terrain increase with elevation [59,60]. A positive correlation between soil organic carbon and elevation in Montana, probably due to the influence of elevation on precipitation, was also found by Sims and Nielsen [49]. In the forest ecosystems studied by us, the content of C increases with altitude and FVG due to a decrease in the intensity of mineralization processes. The C_t content increased from 21.1 to 25.9 mg g^{-1} in the Dystric Cambisols of the 2nd beech-oak FVG up to 63−65 mg g^{-1} in the Dystric Cambisols of the 5th fir-beech FVG. According to Baritz et al. [29] and Zhu et al. [61], soil C concentration increases with increasing elevation (decreasing temperature) and decreases with decreasing latitude. Dieleman et al. [62] found a clear linear relationship between the soil organic carbon stocks and altitude along the vertical transect in Papua New Guinea. The soil organic carbon stocks increased with altitude for the top 30 cm of soil and the total 1 m soil profile.

The variability of C stocks in soil can be primarily influenced by soil factors (soil type, texture, pH), [63]. Sims and Nielsen [49] state that in Montana, organic C content is better predicted by elevation and mean annual precipitation. The R-value for the multiple linear regression equation using these variables was 0.88. Gruba and Socha [50] report that the positive effect of altitude on higher C stocks is most evident in the O-horizons and the 0–10 cm mineral soil layer at altitudes from 300 to 1000 m. Still, it was not observed in the lowlands. The contribution of significant variables to C stock changes in Poland was 13 % for pH_{H2O} values, 8 % for elevation, and 3 % for dominant tree species. In the forest ecosystems studied by us, the share of altitude and FVG in the variability of carbon and humus in the soils reaches 78 %. The degree of dependence between the soil reaction and C_t content for all the soils is weaker (4 %, according to $R2$). Linear regression revealed a moderate relationship (19 %) between carbon and ash content.

The N_t content detected in the soils of the forest ecosystems studied by us indicates a positive relationship with altitude, or FVG ($R2 = 0.811$). A significant correlation ($p \leq 0.05$) of total topsoil nitrogen with altitude was also found by Kidanemariam et al. [64] in the Tsegede highlands of the Tigray region of northern Ethiopia and Hailemariam et al. [48] in a less accessible Sida Forest, southern Ethiopia ($r = 0.44$; $p < 0.001$). Malik and Haq [65] report that at altitudes of 900–2600 m in a part of the western Himalayas, only the N content showed a significant positive correlation with altitude ($r = 0.924$, $p<0.05$), while all the other soil nutrients showed a non-significant negative correlation with it. Tashi et al. [66], who investigated the effect of altitude and forest composition on C and N stocks in the soils of a transect extending from 317 m to 3300 m a.s.l. in the eastern Himalayas, found that carbon and nitrogen were correlated with altitude and temperature. Slower rates of organic matter decomposition at higher altitudes were accompanied by increasing soil acidity, and increased stocks of C and N. The soil C/N ratio also increased with altitude.

The C:N ratio generally gives us information about the mineralization of organic matter [67]. A C:N ratio >35 leads to microbial immobilization, a ratio of 20–30 leads to an equilibrium state between mineralization and immobilization, and soil microorganisms have a C:N ratio of around 8 [68]. In the forest ecosystems studied by us, the C:N values of the Cambisols, except for those located at altitudes of 795 and 950 m with C:N 16–16.7, ranged from 11 to 14, which represents a medium to low nitrogen supply in the soil organic matter. Yin et al. [69], who synthesized 62 altitudinal transects, found that altitudinal trends in soil C and N stocks were essentially inconsistent, with mean annual temperature being the most important predictor of these variations. Specifically, low latitudes with warm climates showed an increase in the soil C and N storage along increasing elevation, while high latitudes with cold climate showed a decreased or unchanged C and N storage along increasing elevation. The altitudinal trend in the soil C:N ratio was relatively stable and independent of all the candidate predictors. He et al. [70] report that in subtropical China, concentrations of total soil N, microbial biomass N, and C:N increased linearly with increasing altitude (from 50 m to 950 m a.s.l.), while nitrogen concentrations in litter decreased linearly with altitude.

Organic matter is the most mobile and active component of soil and serves as a readily available source of nutrients and energy for microbes and other living organisms [71]. The soil organic matter (SOM) mineralization is faster in warmer and drier conditions than in cooler and wetter areas with low soil pH [72]. The final product of the decomposition of SOM, or plant and animal matter, is humus. In

the soils of the forest ecosystems studied by us, the content of carbon and humus increased linearly with increasing altitude and FVG (R2 = 0.871 and R2 = 0.869, respectively). The Cambisols located at altitudes of 257 and 265 m in the 2nd beech-oak FVG had significantly lower humus contents (36–45 mg g^{-1}), while the extremely acidic Dystric Cambisols located at altitudes 760 and 950 m in the 5th fir-beech FVG had significantly higher humus contents (109–112 mg g^{-1}). Hailemariam et al. [48] in a less accessible Sida Forest, southern Ethiopia also found significant positive correlations between the soil organic carbon ($r = 0.42$; $p < 0.001$) and organic matter ($r = 0.41$; $p < 0.001$) with altitude. Based on the characteristics of 12,742 soil samples taken over from forest management plans from 1982 to 2014, Enescu et al. [73] report that the organic matter content in the Eutric and Dystric Cambisols of Romania is affected by altitude and tree age, especially on shaded and partially shaded slope aspects. Matus et al. [74] state, that stabilization and destabilization of the organic matter in Andic soils is mainly controlled by the soil pH. The most important stabilization processes are related to the incorporation and decomposition of microbial derived C, along with the changing C storage capacity with increasing soil development.

The soil's energy storage can be affected by excess or deficit water, acidic pH, and nutrient deficiency, as they affect the microbial degradation of plant residues [2]. In the forest ecosystems studied by us, the development of the soil energy content with altitude and FVGs has a positive polynomial trend. We can conclude that the lowest energy contents are correlated with the highest pH values, and the clay contents are in the middle part of the height range of the studied soils. Gunina and Kuzyakov [75] state, that soil energy fluxes and storage are not the same as organic C fluxes and storage. Based on the annual C sequestration from litter to SOM of 0.4–5% of the total SOM pool, the energy input is equal to 1–10 % of the total SOM energy.

5. Conclusions

Currently, little is known about the spatial variability of significant soil properties and their relationships to forest ecosystems of different vegetation grades. More often, the properties of the soil refer only to the altitude, which, however, does not sufficiently reflect the climate characteristics of the ecosystems. The emergence of the vegetation grade is, namely, not only conditioned by the altitude, but also by the exposure of the slope, the action of winds, the intensity of evaporation, the calorific value of rocks, etc. Therefore, the vegetation grade is a better indicator of the climatic conditions at the site.

The Cambisols are the most widespread soil type in Slovakia, with 33 % representation. PCA of the relationships of their properties to forest ecosystems of the 2nd to 5th forest vegetation grade showed that EAC in the 3rd oak-beech vegetation grade had significantly higher pH values and significantly lower energy content; ESC in the 4th beech vegetation grade had a significantly higher ash content and a significantly lower energy content, and DC in the 5th fir-beech vegetation grade had a significantly higher content of Ct, Nt, and humus. There is also a strong negative linear relationship between an altitude and ash content. The oscillating polynomial curve, in turn, shows the relationship of clay content and energy to altitude and FVG.

As a result of forest management, there is a greater or lesser change in the soil properties and the woody composition of the forest ecosystems. In addition, climate change can potentially lead to a shift in forest vegetation grades to higher altitudes. For this reason, a better understanding of the relationships of soil properties and ecologically differentiated communities of forest ecosystems will allow us to identify areas with the highest risk of ecological changes that could lead to the degradation of European forests in the future.

Data availability statement

The data are in the repository at the Institute of Forest Ecology in Zvolen and are accessible upon request (E-mail: kuklova@ife.sk).

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Ivica Pivková: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ján Kukla:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **František Hnilička:** Writing – review & editing, Validation, Software, Resources, Project administration, Funding acquisition. **Helena Hniličková:** Validation, Software, Data curation. **Danica Krupová:** Methodology, Formal analysis. **Margita Kuklová:** Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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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