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Slope aspect and altitude effect on selected soil organic matter characteristics in Beskid Mountains forest soils

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Abstract

In the era of dynamic climate change, it is important to have knowledge on the interactions between climatic factors and processes occurring in the soil environment. The present study aimed to determine how slope aspect and altitude above sea level influence carbon and nitrogen accumulation and dehydrogenases activity of forest soils. The study was conducted in the Beskid Żywiecki in the south-facing part of Poland. Soils of the same texture, with similar vegetation species composition, in different altitude variants (600, 800, 1000 and 1200 m above sea level) and different north-facing and south-facing slope aspect were selected for the study. For each height and slope aspect variant, samples were collected from the surface horizons of soils for further analyses. The basic chemical properties and dehydrogenases activity of the soil samples were determined. Carbon and nitrogen stocks in the surface horizons of the soils were calculated. The analyses confirmed the influence of location conditions on the carbon and nitrogen stocks in mountain forest soils. The stock of carbon and nitrogen increased with the height up to 1000 m a.s.l. In the soils at the highest altitude, the reserve of carbon and nitrogen decreased regardless of the slope aspect variant. There were no statistically significant differences in carbon and nitrogen stocks between slope aspect variant. The highest dehydrogenases activity was associated with the organic horizons of the soils at the lowest altitude in height gradient. In our study, higher dehydrogenases activity was observed in the north-facing slope soils, and this finding can be explained by more stable thermal conditions.

Key words

carbon stock, climatic factors, dehydrogenases activity, forest ecosystem, nitrogen stock

Introduction

Soil plays a key role in carbon storage (Degórski 2005; Nabuurs et al. 2007; Tolunay 2011). It is estimated that the amount of carbon in the soil is 2–3 times higher than that in the aboveground parts of plants (Post et al. 1990; Fornara et al. 2011). The carbon stock in the topsoil is 11.3–126.3 tonnes C/ha (Dixon et al. 1994; Baritz et al. 2010). In forest ecosystems, woody vegetation together with the shrubbery layer contributes to a better maintenance of soil moisture (Wang et al. 2012); moreover, it provides organic matter in the form of organic remains from the aboveground parts of plants and root systems, which enrich the surface horizonof soil through humification and mineralisation processes (Bardgett and Wardle 2010). Accumulation volumes in the soil depend on

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the type of plant cover and organic matter supplied and on the rate of decomposition processes (Błońska et al. 2021). Natural or human-induced disturbances are associated with the loss of soil carbon (Degórski 2005; Shiels et al. 2006). Soil carbon and nitrogen accumulation outside the vegetation species composition is influenced by pH and soil texture (Fotyma et al. 1998). Additionally, the level of carbon and nitrogen contentsin the soil is influenced by factors such as slope aspect, climate and altitude above sea level (Crowther et al. 2016).

Mountain areas are characterised by a variety of climatic factors, which results in diverse vegetation. Temperature decreases with altitude, which reduces the efficiency of ecosystems (Zhu et al. 2018) and slows down the rate of organic matter decomposition (Parras-Alcántara et al. 2015; Egli and Poulenard 2016; Bardelli et al. 2017). According to Egli and Poulenard (2016), mountain soils are highly dynamic systems that may react sensitively to environmental changes. It is known that slope aspect influences the local microclimate, especially solar radiation intercepted by the slope orientation, there by affecting the biochemical processes in the soil (Barbosa et al. 2015). Research shows that north-facing slopes capture less radiation from the sun and therefore have lower temperatures and higher humidity compared to south-facing slopes (Sewerniak et al. 2017). Slope aspect can affect species composition of ground flora, and thus indirectly involves alimentation of different types of litterfall to topsoils of contrasting exposures (Jasińska et al.2019). Climate in general affects the activity and composition of microbiota and mesobiota involved in organic matter decomposition (Ascher et al. 2012). According to Makoi and Ndakidemi (2008), climate impacts on the microbial biomass and abundance in the soil as well as on most of the enzymatic activities are dependent on the altitude. Enzymatic activity is used to assess the quality and fertility of soils and also to determine the nutrient cycling (Błońska et al. 2021). It correlates closely with soil condition so that changes occurring in the ecosystem can be captured. Carbon substrates and nitrogen are essential in enzymatic reactions (Piaszczyk et al. 2019; Lasota et al. 2020). Dehydrogenases are an integral part of intact cells and provide information about the biologically active microbial population in the soil. A decrease in bacterial and fungal biomass with increasing altitude was observed in a previous study (Margesin et al. 2009). Humus morphology strongly depends on the slope, altitude, climate, biological factors and species composition of forest stands (Zanella et al. 2011; Bayranvand et al. 2017). Łabaz et al. (2014) showed that the humus types were distinctly correlated to specific sets of environmental factors. In addition, the use of chemical properties such as alkaline cations is helpful in assessing soil quality (Brożek et al. 2011).

We hope that a better understanding of the mechanisms and factors influencing the dynamics of carbon and nitrogen in mountain forest soils will enable to predict these phenomena in the future. The present study aimed to determine how slope aspect and altitude above sea level influence carbon and nitrogen accumulation and dehydrogenases activity of forest soils. Forest soils with the same texture and vegetation along altitudinal climosequence were selected for the research. In the present study, we hypothesise that slope aspect and altitude influence the carbon and nitrogen accumulation in forest soils and dehydrogenases activity.

Material and methods

Study area and experimental design

The study was conducted in a managed forest located in Węgierska Górka (49°36'N, 19°07'E), Wisła (49°38'N, 18°51'E), Jeleśnia (49°38'N, 19°20'E) and Ujsoły Forest Districts (49°28'N, 19°08'E). The forest district covered by the research is located in the Western Beskid (south-facing Poland).The growing season in the lowest part of the Western Beskid (600 m a.s.l.) is 200 days, and it is shorter in the subsequent zones (1200 m a.s.l. –140 days) (Obrębska-Starkel 2004). The mean annual temperature at an altitude of 600 m is approximately 6°C, and the annual sum of precipitation is 1000 mm. At an altitude of 1200 m a.s.l., the temperature decreases to 2°C, and the annual sum of precipitation is 1400 mm.

The research plots of size 0.2 ha were located on similar parent material and soil type with old-growth forest (Tab. 1). The average contents of sand, silt and clay in soils were 45%, 41% and 14% respectively. The experimental plots were set up in areas that are dominated by the flysch sandstones. Tree stands with similar structure, canopy density and age (80–90 years) were selected for research. The most prevalent tree species in the study plots was spruce (*Picea abies*) with an admixture of fir (*Abies alba*). The research plots were dominated by habitats such as *Galio-Piceetum carpaticum* and in the highest variant of altitude slightly poorer *Plagiothecio-Piceetum* (Tab. 1). Study plots with a similar history of forest stands were selected for analysis. North- and south-facing plots located at different altitudes were selected for the study. The study plots were located between 600 and 1200 m a.s.l. (every 200 m). Four variants of altitude (600, 800, 1000 and 1200 m a.s.l.) were located at north- and south-facing slopes with a similar slope inclination (15–20°). Every variant of the study plot was in five repetitions. In total, 40 research plots were selected for the analysis. Soil samples were collected from each plot. The samples from Ofh horizon and from the highest mineral horizon (A or AE horizon) according to the observed depths were collected for analysis.

Table 1. Characteristics of study plots located in altitude gradient

Altitude (m.a.s.l.)	Slope	Plant community	Soil type	Parent material	Species composition
600	15–20°	*Galio-Piceetum-carpaticum*	Cambisols	Flysch sandstone	90% spruce 10% fir
800	15–20°	*Galio-Piceetum-carpaticum*			90% spruce 10% fir
1000	15–20°	*Galio-Piceetum-carpaticum*			90% spruce 10% fir
1200	15–20°	*Plagiothecio--Piceetum*			100% spruce

Laboratory analysis

After drying to an air-dried state, all soil samples were sieved through a 2-mm mesh. Physicochemical properties were determined in these prepared samples (Ostrowska et al. 1991). Soil pH was determined by the potentiometric method in water and 1M KCl. Hydrolytic acidity was determined by the Kappen method, and exchangeable acidity and content were estimated by the Sokołow method. Total nitrogen and carbon content was determined using a LECO CNS True Mac Analyser (Leco, St. Joseph, MI, USA).To determine the amount of alkaline cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}), 1M ammonium acetate (ICP-OES) was used (iCAP 6500 DUO, Thermo Fisher Scientific, Cambridge, UK). In samples with natural moisture, the dehydrogenases activity was determined by the Lenhard method according to the Casida procedure and expressed as milligrammes of triphenyl formazan (TFF) per 100g of soil within 24 h. This method is known as the 'TTC test' and uses a 3% solution of triphenyl tetrazolium chloride (TTC). To extract the resulting soil formazan, methanol-denatured ethyl alcohol was used (Alef and Nannipieri 1995).

Soil nitrogen and organic carbon stocks (Ns, Cs) were calculated as the sum of its total content from individual soil horizons. Carbon and nitrogen stocks were calculated to the depth of 20 cm (the mineral horizon was always considered up to a depth of 20 cm):

$$Ns = N \cdot D \cdot m \; [Mg \cdot ha^{-1}]$$

$$Cs = C \cdot D \cdot m \; [Mg \cdot ha^{-1}]$$

where:

Ns – the nitrogen stock [$Mg \cdot ha^{-1}$],
N – the nitrogen content in the next horizon [%],
Cs – the carbon stock [$Mg \cdot ha^{-1}$],
C – the carbon content in the next horizon [%],
D – the soil bulk density at the appropriate horizon [$g \cdot cm^{-3}$],
m – the thickness of the next horizon [cm].

In addition, the carbon distribution index (CDI $Mg \cdot ha^{-1}$) and nitrogen distribution index (NDI $Mg \cdot ha^{-1}$) were given, which were calculated from the ratio of carbon accumulated in organic horizons to the amount of organic carbon accumulated in mineral horizons up to 20 cm according to the formula proposed by Błońska and Lasota (2017).

Statistical analysis

Differences between the mean values in soil of the investigated plots were evaluated with Tukey's test ($p < 0.05$). Spearman correlation coefficients between the properties of soil were calculated. Principal component analysis (PCA) was used to evaluate the relationships between soil properties in altitude gradient. On the basis of Ward's method (Everrit 1980), agglomeration of the soil in the altitude gradient with differences in the selected physicochemical properties was conducted. The carbon and nitrogen stocks were used in the agglomeration procedure. A general linear model (GLM) was used to investigate the effect of slope aspect and altitude on carbon and nitrogen stock. The results were considered to be statistically significant at α = 0.05. All statistical analyses were performed with Statistica 12 software (2012).

Results

Chemical analyses of the investigated soils

Analyses of the data showed differences in soil properties between the tested variants. pH in H_2O and KCl ranged from 3.26 to 4.02 and from 2.60 to 3.14 respectively. Statistically significant differences in pH in H_2O were noted in soils with north-facing slope aspect between 1000 and 1200 m a.s.l. pH in KCl was significantly differed in soils situated between north-facing and south-facing slope aspect at organic and mineral horizons (Tab. 2). Carbon and nitrogen contents in the soil samples collected from the north-facing slope aspect were not differed significantly at the organic horizon from the samples collected from the south-facing slope aspect. However, significant differences were noted in the C and N contents of soil samples at 600 m height compared to those collected at 1000 and 1200 m a.s.l. C and N contents ranged from 26.71% to 38.27% and from 1.25% to 1.61%, respectively. The C/N ratio showed no significant differences in soils of different test variants. The content of the cations Mg and Na showed significant differences in the organic horizon altitude gradient. Samples from the mineral horizon at an altitude of 1200 m a.s.l. differed significantly in Ca content compared to those collected from the lowest altitude. The soils of the north-facing and south-facing exhibition showed differences in the K content. The contents of alkaline cations increased with the height a.s.l. from the value of 2.51 cmol(+)·kg^{-1} to 4.78 cmol(+)·kg^{-1} for Ca up to 800 m, and then the value decreases. For K, Mg and Na, the highest values were recorded in the soils at the highest altitude, i.e. 1.15 cmol(+)·kg^{-1}, 1.42 cmol(+)·$kg^{-1}$and 0.15 cmol(+)·kg^{-1}respectively.The exchangeable acidity of organic horizons varied significantly between variants in the height gradient and mineral horizons according to different slope aspects. Hydrolytic acidity increased with height, from 86.46cmol(+)·kg^{-1} to 111.38 cmol(+)·kg^{-1} (Tab. 2). Additionally, differences in hydrolytic acidity were noted between the north-facing and south-facing slope aspect.

Dehydrogenases activity of the investigated soils

The dehydrogenases activity varied from 2.38 to 14.14 μmol TPF·kg^{-1}·h^{-1}. Significantly higher activity of this enzyme was recorded in soils at 600 m a.s.l., while the lowest enzymatic activity was observed in soils at 1200 m a.s.l. Carbon and nitrogen stocks up to a depth of 20 cm differed significantly in soils of particular height variants at the north-facing slope aspect (Tab. 3). The lowest C stock (61.40 Mg · ha^{-1}) was recorded in soils at the height of 1200 m a.s.l. for the north-facing slope aspect. The highest stock of C (118.49 Mg · ha^{-1}) was recorded in the soils of the north-facing slope aspect at 1000 m a.s.l. The nitrogen stock showed similar results, depending on the altitude and the slope aspect. The analysis of the Carbon Distribution Index (CDI) and the Nitrogen Distribution Index (NDI) showed significantly higher values in soils at the south-facing slope aspect, and the highest values were recorded in soils at 1200 m a.s.l. The significant differences between the exposures were shown there. To examine the relationships between the properties of the soils studied, an analysis of PCA was performed; the results are shown in Figure 1. Factors 1 and 2 explained a total of 48.75% of the variance of the analysed properties of the soils studied. Factor 1 explained 31.65% of the variance, while Factor 2 explained 17.10% of the variance in the tested

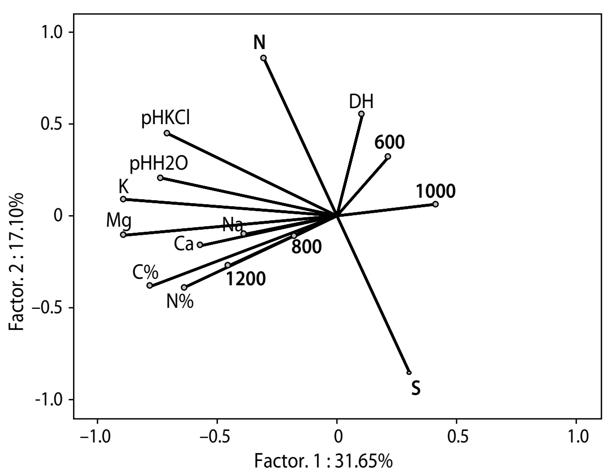

Figure 1. Diagram of principal component analysis (PCA) with projection of organic horizon properties on a plane of the first and second factors (S, N – slope aspect; 600, 800, 1000, 1200 altitude a.s.l.)

Table 2. Chemical properties and dehydrogenases activity of study soils in altitude gradient and taking into account slope aspect

Altitude (m a.s.l.)	Slope aspect	Horizon	pH H_2O	pH KCl	C	N	C/N	Ca	K	Mg	Na	Hex	Y	DH
600	N	Ofh	3.56±0.13^{bx}	2.76±0.09^{ax}	28.05±1.43^{cx}	1.32±0.06^{abx}	21.28±0.97^{ax}	2.51±0.39^{ax}	0.65±0.13^{ax}	0.61±0.07^{cx}	0.11±0.03^{abx}	13.56±2.14^{ax}	87.80±3.52^{ax}	14.14±8.44^{ax}
		Mineral horizon	3.74±0.13^{abx}	2.84±0.13^{abx}	3.63±1.25^{ax}	0.20±0.06^{ax}	18.31±1.72^{ax}	0.45±0.14^{bx}	0.14±0.04^{ax}	0.13±0.04^{ax}	0.05±0.01^{ax}	12.01±4.20^{ax}	25.62±7.54^{ax}	4.12±1.53^{abx}
	S	Ofh	3.50±0.01^{ax}	2.62±0.04^{ay}	29.91±3.39^{ax}	1.42±0.16^{ax}	21.12±0.59^{ax}	2.76±0.35^{ax}	0.62±0.19^{ax}	0.60±0.08^{ax}	0.12±0.02^{ax}	12.04±2.19^{abx}	96.60±26.97^{ay}	8.59±0.35^{ax}
		Mineral horizon	3.52±0.04^{ay}	2.72±0.11^{ay}	3.17±0.44^{ax}	0.15±0.04^{ax}	21.57±4.52^{ax}	0.35±0.06^{ax}	0.08±0.01^{ay}	0.09±0.01^{ax}	0.04±0.00^{ax}	7.09±1.22^{ay}	20.08±4.37^{ax}	7.14±0.92^{ax}
800	N	Ofh	3.52±0.36^{abcx}	2.84±0.30^{ax}	32.01±4.63^{abcx}	1.36±0.25^{abx}	23.74±2.31^{ax}	4.78±4.10^{bx}	0.69±0.27^{ax}	0.77±0.26^{abcx}	0.09±0.03^{abx}	9.45±3.28^{ax}	91.92±20.08^{ax}	5.85±4.78^{ax}
		Mineral horizon	3.70±0.12^{abx}	3.04±0.17^{abx}	4.92±2.13^{ax}	0.31±0.12^{ax}	15.46±1.85^{ax}	0.48±0.33^{abx}	0.15±0.05^{ax}	0.17±0.06^{ax}	0.04±0.02^{ax}	9.43±1.90^{ax}	27.92±7.95^{ax}	10.68±4.14^{abx}
	S	Ofh	3.48±0.08^{ax}	2.72±0.08^{ay}	33.58±5.85^{ax}	1.42±0.17^{ax}	23.53±2.08^{ax}	4.74±1.89^{ax}	0.64±0.11^{ax}	0.90±0.25^{ax}	0.10±0.04^{ax}	10.71±1.75^{bx}	102.20±13.72^{ay}	5.24±1.87^{abx}
		Mineral horizon	3.54±0.11^{ay}	2.86±0.15^{ay}	5.50±1.04^{ax}	0.27±0.08^{ax}	21.25±3.66^{ax}	0.39±0.18^{ax}	0.12±0.03^{ay}	0.15±0.05^{ax}	0.04±0.02^{ax}	10.84±3.84^{ay}	31.42±8.15^{ax}	9.36±4.18^{ax}
1000	N	Ofh	3.26±0.17^{cx}	2.68±0.08^{ax}	26.71±2.58^{bx}	1.25±0.10^{bx}	21.45±2.07^{ax}	2.02±0.87^{bx}	0.61±0.09^{ax}	0.59±0.13^{bx}	0.07±0.02^{bx}	13.48±2.81^{ax}	86.46±7.15^{ax}	9.98±7.32^{ax}
		Mineral horizon	3.56±0.09^{bx}	2.76±0.05^{bx}	5.83±0.81^{ax}	0.38±0.05^{ax}	15.27±1.06^{ax}	0.35±0.11^{abx}	0.16±0.02^{ax}	0.17±0.04^{ax}	0.03±0.01^{ax}	11.51±2.51^{ax}	30.84±4.12^{ax}	6.70±2.29^{abx}
	S	Ofh	3.38±0.13^{ax}	2.60±0.07^{ay}	32.57±5.05^{ax}	1.45±0.09^{ax}	22.50±2.81^{ax}	2.81±0.77^{ax}	0.65±0.12^{ax}	0.65±0.15^{ax}	0.12±0.07^{ax}	12.38±1.19^{abx}	102.76±10.46^{ay}	7.83±3.51^{abx}
		mineral horizon	3.52±0.15^{ay}	2.70±0.12^{ay}	3.96±2.60^{ax}	0.22±0.09^{ax}	17.35±7.80^{ax}	0.31±0.04^{ax}	0.12±0.05^{ay}	0.12±0.05^{ax}	0.04±0.02^{ax}	9.35±4.96^{ay}	26.20±12.21^{ax}	4.63±2.65^{ax}
1200	N	Ofh	3.72±0.04^{ax}	2.88±0.13^{ax}	38.27±2.28^{ax}	1.61±0.12^{ax}	23.85±1.57^{ax}	2.91±1.16^{ax}	1.15±0.17^{ax}	1.42±0.49^{ax}	0.15±0.05^{ax}	13.20±0.74^{ax}	101.86±9.95^{ax}	7.13±5.36^{ax}
		Mineral horizon	4.02±0.38^{ax}	3.14±0.32^{ax}	3.24±1.60^{ax}	0.24±0.16^{ax}	15.65±3.96^{ax}	0.15±0.07^{ax}	0.09±0.05^{ax}	0.10±0.07^{ax}	0.03±0.01^{ax}	7.48±3.26^{ax}	20.12±10.29^{ax}	2.40±1.56^{ax}
	S	Ofh	3.40±0.12^{ax}	2.60±0.12^{ay}	30.41±2.03^{ax}	1.38±0.20^{ax}	22.33±2.24^{ax}	2.14±1.03^{ax}	0.57±0.09^{ax}	0.70±0.15^{ax}	0.09±0.02^{ax}	15.39±0.83^{ax}	111.38±15.07^{ay}	2.38±3.56^{bx}
		Mineral horizon	3.68±0.29^{ay}	2.96±0.17^{ay}	3.03±1.52^{ax}	0.18±0.18^{ax}	15.68±3.22^{ax}	0.27±0.14^{ax}	0.07±0.02^{ay}	0.11±0.03^{ax}	0.04±0.01^{ax}	5.55±1.95^{ay}	18.60±7.83^{ax}	4.13±2.43^{ax}

Mean ± standard deviation, different lowercase alphabets in the upper index (a,b,c) mean significant differences of parameters between different altitudes; alphabets (x,y) mean significant differences of parameters between different slope aspect; C, N (%); Ca, K, Mg and Na (cmol(+)·kg^{-1}); Y, hydrolytic acidity (cmol(+)·kg^{-1}), Hex, exchangeable acidity (cmol(+)·kg^{-1}); dehydrogenases activity (µmol TPF·kg^{-1}·h^{-1}).

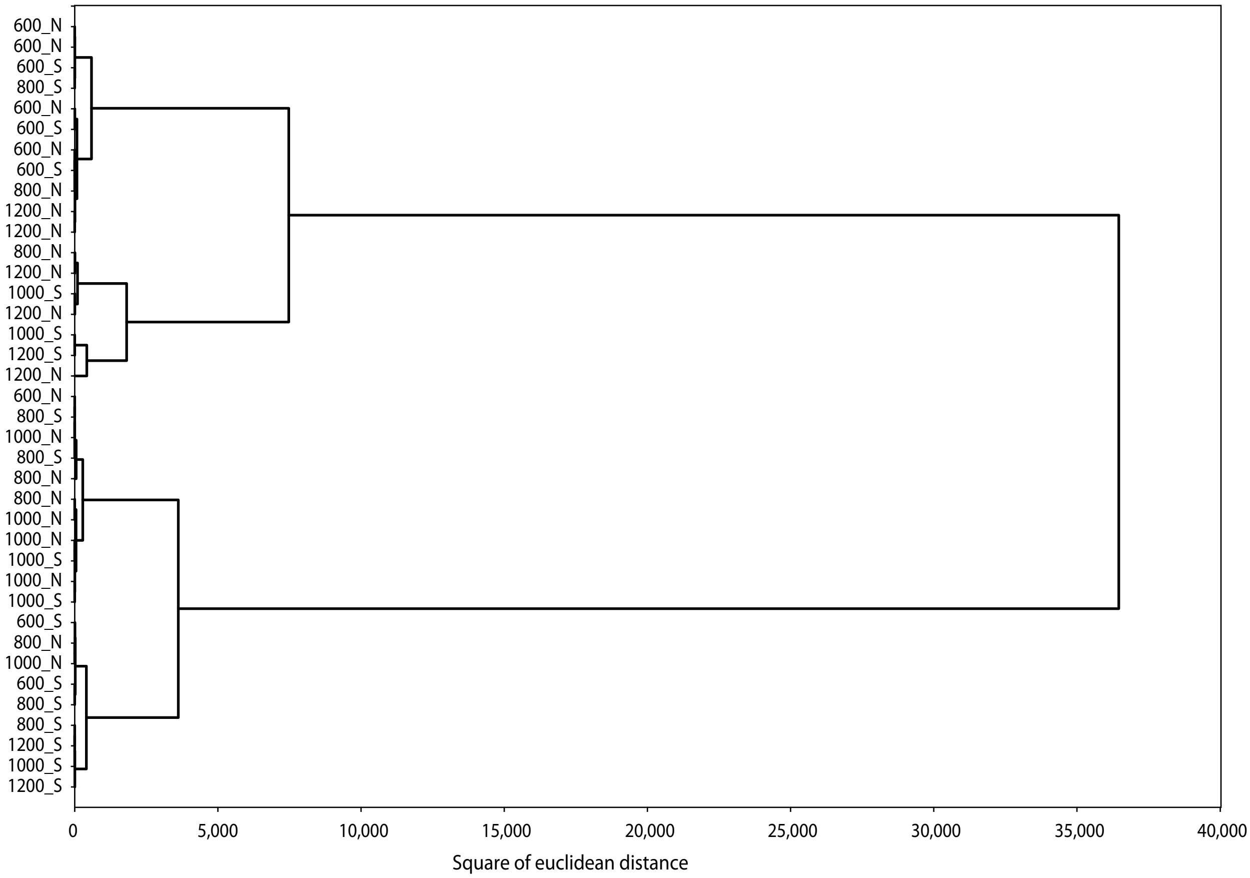

Figure 2. Cluster analysis grouping the soils in altitude gradient (a.s.l.); carbon and nitrogen stocks (Cs and Ns) in soil were used in the design of the diagram

data. Factor 1 was associated mainly with the chemical properties of the tested soils and the position in the altitude gradient. Factor 2, on the other hand, was related to the biochemical activity of soils expressed by the activity of dehydrogenases and the slope aspect of research plots. The PCA analysis confirmed the relationship between dehydrogenases activity and the soils of the lowest positions (600 m a.s.l.). Cluster analysis confirmed the distinctiveness of the soils according to the altitude gradient in terms of carbon and nitrogen stocks. One cluster consisted of soils with the lowest C and N stocks located at the lowest (600 m a.s.l.) and highest (1200 m a.s.l.) altitudes in the altitude gradient (Fig. 2). The C and N contents positively correlated with the content of alkaline cations and hydrolytic acidity (Tab. 4). The GLM analysis also confirmed the relevance of altitude in shaping the carbon and nitrogen stocks of the studied soils (Tab. 5). The

Table 3. Organic carbon and nitrogen stocks in soil of altitude gradient

Altitude (m a.s.l.)	Slope aspect	Cs	CDI	Ns	NDI
600	N	85.48±18.81^{abx}	0.56±0.30^{ax}	4.47±0.96^{ax}	0.48 ±0.26^{ax}
	S	89.80±15.56^{ax}	0.84±0.40^{ax}	4.31±0.51^{ax}	0.91 ±0.60^{ax}
800	N	97.37±26.74^{abx}	0.44±0.36^{ax}	5.78±1.45^{ax}	0.31±0.28^{ax}
	S	100.88±18.82^{ax}	0.48±0.27^{ax}	4.72±1.21^{ax}	0.44±0.26^{ax}
1000	N	118.49±7.49^{ax}	0.55±0.33^{ax}	6.93±0.37^{ax}	0.39±0.17^{ax}
	S	89.35±34.93^{ax}	0.71±0.39^{ax}	4.72±1.59^{ax}	0.71±0.28^{ax}
1200	N	61.40±24.32^{cx}	0.51±0.36^{ax}	3.98±2.29^{ax}	0.37 ±0.36^{ax}
	S	87.02±28.89^{ax}	2.01 ±1.53^{by}	4.45±1.51^{ax}	1.22±0.57^{by}

Mean ± standard deviation, different lowercase alphabets in the upper index (a,b,c) mean significant differences of parameters between different altitudes; alphabets (x,y) mean significant differences of parameters between different slope aspect; S, N – slope aspect; 600, 800, 1000, 1200 – altitude gradient; Cs – carbon stock; Ns – nitrogen stock (Mg·ha^{-1}); CDI – carbon distribution index (Mg·ha^{-1}); NDI – nitrogen distribution index (Mg·ha^{-1}).

GLM analysis, however, did not confirm the effect of the slope aspect on the amount of the accumulated C and N in the studied soils.

Table 4. Correlations between C, N and DH activity and testing variants of averages from both levels

	C%	N%	DH
pH H_2O	–0.3674	–0.3592	–0.1612
pH KCl	–0.3717	–0.3914	–0.0779
Ca	0.8547	0.8368	0.0968
K	0.9175	0.9267	0.1653
Mg	0.9370	0.9326	0.1599
Na	0.7004	0.7365	0.1566
Y	0.9388	0.9415	0.1518
Hex	0.5506	0.5676	0.0910

Correlations between variants are in gray; DH – dehydrogenases activity; Y – hydrolytic acidity; Hex – exchangeable acidity.

Table 5. Summary of GLM analysis for the carbon stock (Cs) and nitrogen stock (Ns) in soil of altitude gradient

	Cs		Ns	
	F	*p*	F	*p*
Slope aspect	0.1407	0.7098	2.8117	0.0776
Altitude	4.0444	0.0152	2.9473	0.0462
Slope aspect*Altitude	1.8341	0.1466	2.1649	0.0955

Significant effects ($p < 0.05$) are in gray; Cs – carbon stock, Ns – nitrogen stock.

Discussion

The analyses confirmed the importance of the location conditions, especially the altitude, and to a lesser extent, the slope aspect on the formation of C and N stocks in the surface horizons of mountain forest soils. The GLM analysis confirmed the importance of location in altitude gradient for C and N accumulation in forest soils. In the lowest positions at an altitude of 600 m a.s.l., the lowest C and N stocks were recorded, which increased at an altitude of 1000 m a.s.l. At the highest positions, i.e. at an altitude of 1200 m a.s.l., the stock of carbon and nitrogen decreased due to worsening thermal conditions and lower productivity of vegetation. Previous studies (Yang et al. 2008; Meier and Leuschner 2010; Wiesmeier et al. 2013; Wang et al. 2014).) have proved that the variation in the content of soil organic carbon is associated with a change in temperature and the occurrence of precipitation, which is due to the location in the height gradient. Due to a longer growing season, increase in production of biomass and soil respiration can be expected with decreasing forest altitude (Swetnam et al. 2017).In addition to climatic conditions, vegetation through supplied organic matter is important in shaping C stock in forest soils (Baldrian and Šnajdr 2011; Błońska et al. 2016). Trees provide carbon substrates and nutrients to the soil through the fall of litter and root systems (Błońska et al. 2016, 2021). Lower altitudes have more favourable thermal conditions, which result in a faster rate of decomposition of soil organic matter supplied in greater quantities by trees due to higher productivity. In the height gradient, differences in the amount of organic matter supplied may result from the intensity and differentiation of the development of lower vegetation layers. Altitudinal gradient is well known to be one of the decisive factors shaping the spatial patterns of species diversity (Lomolino 2001). Availability of light, humidity, soil depth and soil properties change in the altitudinal gradient, leading to local variations in the composition of vegetation species (Cirimwami et al. 2019).

The processes of decomposition of soil organic matter involve microorganisms, whose amount and diversity depend on the properties of soils, vegetation and, above all, thermal and moisture conditions (Bardelli et al. 2017). In our present study, we considered the activity of dehydrogenases as an indicator of the number and activity of microorganisms in soils. Higher dehydrogenases activity was recorded in soils at 600 m a.s.l. The higher activity of dehydrogenases in the lowest positions was due to the faster rate of decomposition of soil organic matter as an effect of higher temperature. Previous studies have indicated that the quantity and quality of soil organic matter are quite important in shaping the biochemical activity of soils (Kucharski and Niewolak 1997; Bielińska 2001; Mocek-Płóciniak 2006). The change in altitude leads to a change in temperature, thereby causing a decrease in ecosystem productivity (Zhu et al. 2018). At the higher altitudes of the mountains, as a result of lowering the average air temperature and increasing humidity, the decomposition of plant residues is difficult, which favours the accumulation of carbon in forest litter (Bojko and Kabala 2017). In our study, we noted a significantly lower reserve of C in the soils at the highest altitude, with a simultaneous reduction of enzymatic activity. The low activity of dehydrogenases confirmed the reduction of the decomposition rate of detritus delivered to the soil, which is directly related to thermal conditions. The soils tested in the present study were accompanied by stands with spruce dominance, whose litter often leads to acidification and organic matter accumulation (Paluch and Gruba 2012; Elbe 2014; Gałka et al. 2014). Spruce litter, which contains more difficult to decompose lignin, and the worsening thermal conditions lead to an increase in carbon stock in forest soils. An additional factor influencing the amount of accumulated C and N in the forest soils was the slope aspect. Changes in the slope and intensity of sunrays associated with different slope aspect of the slope affect temperature and humidity fluctuations, which increases the variability of C and N stockpile (Wiesmeieret al. 2019). The north-facing slopes have more favourable humidity conditions than the south-facing slopes (Rawlik et al. 2019). According to Jasińska et al. (2019), litter decomposes faster on north-facing slopes than on south-facing slopes. The reason for that may be different species preferences of plants that influence the decomposition process. In our study, higher dehydrogenases activity was observed in the north-facing slope soils, and this finding can be explained by more stable thermal conditions. The south-facing slopes, despite more favourable thermal conditions, are exposed to stronger insolation, which leads to periodic drying of the accumulated surface humus (Bardelli et al. 2017). Periods of drought cause a decrease in the activity of soil microorganisms, which consequently leads to a slowdown in the decomposition of soil organic matter and the formation of a thick layer of humus. This relationship is supported by other authors who observed that north-facing slopes show higher enzymatic activity (Huang et al. 2015). In our study, we used the CDI and NDI to characterise the intensity of carbon and nitrogen flow from organic to mineral horizons. In soils located on the south-facing slopes, the CDI and NDI were significantly higher, which confirmed the slower mineralisation process.

Conclusions

Our results confirmed the significant influence of the altitude factor on the carbon and nitrogen stocks in the surface horizon of the soils studied. The C stock increased in soils at 1000 m a.s.l. At the highest positions, i.e. at an altitude of 1200 m a.s.l., the stock of carbon and nitrogen decreased due to worsening thermal conditions and lower productivity of vegetation. The soils at the lowest position of altitude gradient showed the lowest reserves of C and N, which was directly related to the rate of soil decomposition of organic matter. At lower position, under more favourable thermal conditions, microbial decomposition was more intensive. There were no statistically significant differences in carbon and nitrogen stocks between exposure variant. In our study, we used dehydrogenases activity to assess the biological activity of soils, which reflected the influence of location factors. The activity of dehydrogenases clearly decreased with altitude; additionally, in the comparison of altitude variants, the activity of dehydrogenases was higher in the soils of colder exhibitions. Knowledge of the carbon accumulation process will allow to optimise the management of forest resources.

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