

KATARZYNA SZOPKA*, CEZARY KABALA, ANNA KARCZEWSKA, PAWEŁ JEZIERSKI,
ADAM BOGACZ, JAROSŁAW WAROSZEWSKI

*Wroclaw University of Environmental and Life Sciences, Institute of Soil Sciences and Environmental Protection
Grunwaldzka Str. 53, 50-357 Wroclaw, Poland*

The pools of soil organic carbon accumulated in the surface layers of forest soils in the Karkonosze Mountains, SW Poland

Abstract: Differentiation of soil organic carbon (SOC) concentrations and pools in topsoil horizons of forest soils in the Karkonosze Mountains was examined in relation to environmental and human-induced factors, with special focus on altitudinal gradient, related climatic conditions, and a zonality of vegetation. The samples were collected from the forest litter and soil layers 0–10 cm and 10–20 cm, in 621 plots arranged in a regular network of monitoring established in the Karkonosze National Park. The concentrations of SOC were determined in laboratory and used for calculation of SOC pools. Four elevation zones were distinguished for analysis: 500–750 m, 750–1000 m, 1000–1250 m, and >1250 m. The concentrations of SOC in forest litter (38.3–44.1%) showed an insignificant increasing trend with altitude. The concentrations of SOC in the layers 0–10 cm and 10–20 cm, were in a very broad range 0.27–47.6%, thus indicating a high differentiation, and also tended to insignificantly increase along with altitude. The largest share of accumulated SOC pools was proved to be present in the layer 0–10 cm, except for the highest zone >1250 m in which forest litter contains slightly larger amounts of SOC. The pools of SOC accumulated in the 20 cm thick topsoil and forest litter turned out to vary considerably (3.6–58.2 kg·m⁻²), but the mean values and medians in particular elevation zones fall in a narrow range 10.5–11.9 kg·m⁻², close to the values reported from the Alps. The lack of statistical significance of reported tendencies was explained by a monitoring sites-oriented random soil sampling, i.e. in forest stands of various age, species-composition and degradation degree.

Keywords: soil organic matter, forest mountain soils, altitude

INTRODUCTION

The amounts of organic matter in soils and its quality play crucial role in the functioning of all terrestrial ecosystems (Dziadowiec 1992, Licznar et al. 2002). Soil organic matter is a source of carbon for microorganisms and nutrients for higher plants, influences soil structure and sorption properties, controls solubility and availability of elements, determining thereby the stability of ecosystems (Gałka and Łabaz 2013a, 2014c). Soil organic matter is also an important sink for atmospheric carbon dioxide, thus influencing directly a global carbon cycle (Lal 2005). Soil organic matter plays an important role in governing the dynamics of greenhouse gases, as its pools and transformations in terrestrial ecosystems may influence the concentrations of carbon dioxide, as well as those of other greenhouse gases in the atmosphere (Gonet et al. 2007, Martin et al. 2010, Sinoga et al. 2012). According to various reports, soils hold the largest proportion of the terrestrial pools of carbon – more than 75%, that is four times the amount of organic carbon stored in all living organisms, including plants (Lal 2008, Martin et al. 2010). In this regard, of particular importance on the Earth are the forest ecosystems that accumulate

more than 80% of all terrestrial aboveground carbon and more than 70% of soil organic carbon (Six et al. 2002, Carletti et al. 2009). The global carbon pool in the temperate forests is estimated at about 100 Gt (Martin et al. 2010). The increase of carbon sequestration in forest ecosystems, including soils, is considered to be one of possible ways to mitigate climate change (Lal 2005, Gałka et al. 2014b).

The basic sources of organic matter in forest soils are both the overground biomass of trees, bushes, and forest floor vegetation, and also belowground plant residues, mainly the death roots (Drewnik 2006, Jamroz 2009, Łabaz and Gałka 2010, Waroszewski et al. 2010, Gałka and Łabaz 2014c). A variety of factors affects the amount and forms of organic matter in forest soils. Among the most important ones are climatic conditions, in particular the temperature and precipitation, related to the latitude and altitude, land topography, soil water regime, bedrock geology, indigenous soil fertility, as well as land use, management practices and contamination (Banfield et al. 2002, Yimer et al. 2006a, 2006b; Vesterdal et al. 2008, Ponge et al. 2011, Gałka et al. 2014a,b; Łabaz et al. 2014). The above mentioned factors influence the primary productivity of biomass and its input into soil, control the rate

* Dr. Eng. K. Szopka, katarzyna.szopka@up.wroc.pl

of plant residues decomposition and govern the processes of organic matter accumulation at various stages of its transformation (Berg and McClaugherty 2008, Andreetta et al. 2016).

In forests, large amounts of carbon are stored in organic horizons (forest floor / forest litter). Forest litter is in a dynamic balance with aboveground vegetation and underlying mineral soil (Drewnik 2000, Hansson et al. 2011). Its thickness and composition depend on the amount and composition of the biomass inflow and the rate of plant residues decomposition (Łabaz et al. 2012, 2014). Forest litter horizons play important role as an organic carbon reservoir (Gałka et al. 2014b), but also in a protection of soil surface against water erosion (Kabała et al. 2013). Inventories of forest floor carbon pools are hampered by large differences in forest floor development between various tree species on the same soils and by the large variation in depth of forest floors at short distances (Schulp et al. 2008). Moreover, the litter horizon is the most dynamically changing part of the forest soil profile that rapidly reacts to all the changes in forest stands, such as tree species composition, forest structure and management, as well as weather fluctuations (Gałka et al. 2014b, Łabaz et al. 2014). Thus, the carbon pools accumulated in the forest litter are strongly differentiated not only in space, but also in time. Reliable quantification of soil organic carbon (SOC) pools in forest soils, and sound characterization of its long-time trends, require therefore a well-developed monitoring system, based on a large number of plots (replicates), necessary to characterize and overcome the spatial differentiation, and repeated soil sampling at regular time intervals (Karczewska et al. 2006).

In recent two hundred years, natural ecosystems in the Karkonosze Mountains were greatly transformed by humans. Native spruce forests and mountain pine shrubs, predominant in the upper mountain forest zone, were transformed into pastures, particularly within local plateaus and flat parts of the slopes. In lower mountain forest zone, the native beech and beech-fir stands were replaced by fast-growing spruce (Danielewicz et al. 2013, Malkiewicz et al. 2016). It has been proved, however, that a transformation of mix-species stands into coniferous monocultures can pose adverse effects on biological diversity of ecosystems, and on soil properties (Szopka et al. 2010, 2011, 2013; Gałka et al. 2013b, 2014a, 2014b; Łabaz et al. 2014, Bojko and Kabała 2016). The composition of tree species in forest stands affects also the pools of soil organic carbon (Gałka et al. 2014b).

Spruce monocultures turned out to be poorly resistant to abiotic and biotic disturbances, particularly frequent in the mountains, and proved highly vulnerable to stress

factors that often caused their damages. Within last two decades of 20th century, the Karkonosze Mts and neighbouring mountain ranges experienced a severe problem of forest decline called “ecological disaster”, caused by many coinciding biotic and abiotic factors (Manion 1991, Danielewicz and Zientarski 1995). Paradoxically, the rapid forest decline on huge mountain areas situated on both sides of the Polish-Czech border provided a chance to observe the natural plant and forest succession in the areas of strict protection, as well as to actively reconstruct the forest stands that fit better than spruce to local habitats (Danielewicz et al. 2013).

Therefore, a comprehensive system of environmental monitoring has been planned and established in the Karkonosze National Park to provide an actual and reliable (statistically proven) information on the current state of ecosystems and ongoing changes, to evaluate the effects of the previous management and predict further consequences of the conservation efforts (Raj and Zientarski 2007). The system involves collecting the crucial data on soil properties, including organic carbon concentrations. The aim of this study was to characterize the spatial differentiation of SOC concentrations and pools in the forest soils in the Karkonosze Mts in relation to the main environmental factors, such as the climate-elevation gradient and vegetation zonality partly changed by human impacts.

MATERIAL AND METHODS

Study area

The Karkonosze Mts, the central and highest (Mt Śnieżka, 1602 m a.s.l.) range of the Sudety Mountains, are in their main part developed from Carboniferous granites, upraised during the Variscan orogeny. The granite massif is surrounded by Paleozoic metamorphic rocks, including gneisses, schists, and greenstones (Aleksandrowski et al. 2013). The Karkonosze Mts are influenced by suboceanic climate, with significant impacts of continental air masses. The mean annual air temperature decreases from 7.9°C in the foothills to 0.4°C on the top of Mt Śnieżka. The mean annual precipitation increases from 700–750 mm in the foothills to approx. 1500 mm in the highest elevation zone (Gramsz et al. 2010).

Specific climate of the Karkonosze Mts directly affects the vertical vegetation zonality. The foreland zone (<500 m a.s.l.) was originally covered with broadleaf and mixed forests. Until now, only very small and isolated enclaves of native forests have survived in this zone, whereas most of the area was transformed into arable lands and meadows. The lower

mountain forest zone (500–1000 m a.s.l.), potentially a habitat for *Luzulo-Fagetum* and *Abieti-Piceetum* communities, is covered mainly with spruce monocultures, which replaced native forests in course of economically-oriented forest management in 19th and 20th centuries (Danielewicz et al. 2013). The upper mountain forest zone (1000–1250 m a.s.l.) is, due to its climate, naturally dominated by *Calamagrostio villosae-Piceetum* community with Norway spruce as the prevailing tree species. The species composition in the spruce forests of this zone is relatively little transformed and mostly of natural origin (Danielewicz et al. 2013). However, the spruce stands in the upper zone seriously suffered from the large scale forest decay (“ecological disaster”) in the 1980–1990s and in many sites remain now in a regenerative stadium.

General soil characteristic

Vertical soil zonation is well developed in the Karkonosze Mts, in relation to vertical zonation of climate conditions and vegetation (Kabała et al. 2013). The sub-mountain zone (<500 m a.s.l.), in a direct surroundings of the Karkonosze National Park, is covered mainly with Haplic/Stagnic Luvisols (IUSS Working Group WRB 2015). Dystric Cambisols prevail in the lower forest zone (500–750 m a.s.l.), with gradually increasing share of Podzols, which dominate the higher forest and subalpine zones. However, Follic Albic Podzols dominate in the intermediate forest zone, whereas Stagnic Albic Podzols prevail in the upper forest zone. The main soil groups in the subalpine zone are Histic Podzols, Dystric Histic Gleysols, and Dystric Fibric/Hemic Histosols. The borders between soil zones are not sharp and depend on the local slope morphology, water regime, and present-day activity of geomorphological processes (Kabała et al. 2012, Waroszewski et al. 2015, Bojko and Kabała 2016). Typically, soils contain significant admixtures of rock fragments (>2 mm), thus a qualifier Skeletic is also applicable in most soil groups throughout the mountain slopes.

A common feature of the mountain slopes is the surface coverage with stones and rock blocks, ranging from 0 up to 98%, and generally increasing with the altitude (Szopka et al. 2010). Soils in the Karkonosze Mts have relatively coarse texture, with low content of silt and clay fractions, and loamy sand and sandy loam prevail in the texture classes (Szopka et al. 2010). The content of silt and clay fractions is relatively higher in the lower altitudinal zones (<750 m a.s.l.) because of selective transport of fine materials and colluvial accumulation in the lower slopes (Egli et al. 2014,

Bojko and Kabała 2016, Waroszewski et al. 2016). The higher silt content in some soils of the upper zones may result from prevalence of physical over chemical weathering under cold climate (Weber et al. 2012).

Soils in the Karkonosze Mts typically have acidic or strongly acidic reaction that is related both to the granitic parent rocks, poor in bases, humid climate, and forest vegetation with prevalence of conifer species (Kabała et al. 2013). Bojko and Kabała (2016) have shown significant impact of land use and vegetation on the topsoil pH that decreased in the order: arable fields > grasslands > beech stands > mountain pine shrubs > spruce stands. Typically, the pH values are the lowest in the forest litter horizon or topsoil humus horizon, and increase with depth in the soil profile, in all altitudinal zones (Bojko and Kabała 2016).

Experimental procedures

The field observations and soil sampling for laboratory analyses were carried out in the sites of forest monitoring in the Karkonosze Mts National Park. The forest monitoring system consists of 630 sites, and further 230 sites are established in the subalpine zone, above the timberline (not involved in this study). The monitoring sites are the circles, established on an area of 50 square meters each, arranged in a 200×300 m grid (Figure 1). Such a dense grid was determined by high spatial diversity of forest habitats in the Park (Danielewicz et al. 2013).

Basic description of environmental factors, necessary for site classification, was carried out in the field (including the dominant tree species composition, slope micro-relief, surface coverage with rock outcrops and stones/boulders, soil type). Soil samples were collected at 621 of 630 sites, using the split-tube samplers in order to minimize damages of soil surface within monitoring areas. Sampling depth was based on the assumption that the uppermost soil horizons have a critical importance for habitat evaluation and for observation of the ecosystem transformation (Karczewska et al. 2006). Therefore, the litter and mineral soil horizons at the depths 0–10 and 10–20 cm were sampled. The samples of forest litter were collected if only the litter was present. A mean thickness of organic horizon was assessed in the field. In case of organic (peat) soils, the samples were collected at two depths only, namely at 0–10 and 10–20 cm. The SOC accumulated in the uppermost 20 cm – thick layer has a primary importance for the further monitoring purposes, as it provides the most suitable database for quantification of possible changes in SOC concentrations and pools.

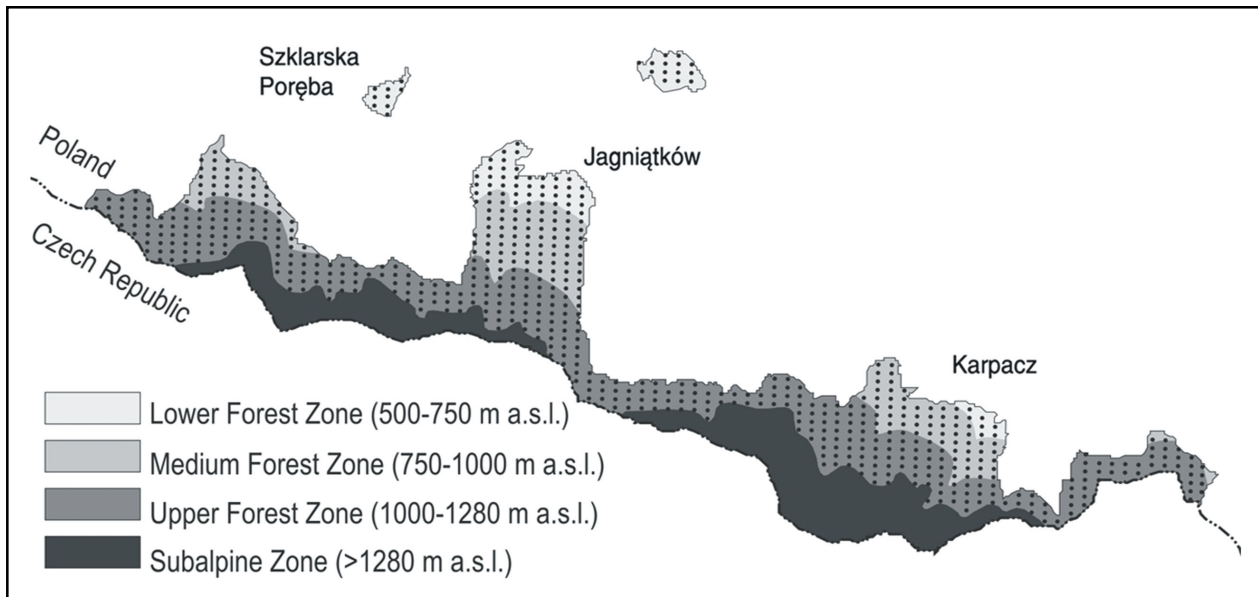


FIGURE 1. Spatial distribution of the forest monitoring (and soil sampling) sites in the Karkonosze National Park

The decision on the soil sampling strategy and sampling depths was preceded by initial field tests (Karczewska et al. 2006). The sampling by genetic horizons seems more reliable in detailed pedological studies; however, it does not guarantee a comparability across the altitude and vegetation zones, micro-relief and land-use forms (Bojko and Kabała 2016). Therefore, soil sampling by standardized depths was chosen for this work.

The concentrations of SOC in the fine earth fraction (<2 mm) of mineral samples were determined using the oxidometric (Tyurin) method (using the sulphuric acid – potassium dichromate solution as oxidizing agent, with external heating), whereas the loss on ignition method was used for organic samples and the results were recalculated into SOC using the coefficient 0.5 as suggested by Bojko and Kabała (2014).

On the basis of SOC concentrations in soil layers 0–10 and 10–20 cm, its pools accumulated down to the depth of 20 cm were calculated for each sampling site. Soil bulk density was assessed using the model by Prevost (2004), who predicted the values of soil density from organic matter content in the Canadian boreal forest. The pools of SOC in the forest litter (expressed in $\text{kg}\cdot\text{m}^{-2}$) were calculated from the SOC concentrations determined in the samples and the mass of litter per square meter. The pools of SOC accumulated in particular soil layers on the surface of 1 m^2 were calculated as follows:

$$\text{SOC}_p (\text{kg}\cdot\text{m}^{-2}) = \text{SOC}_c (\text{g}\cdot\text{kg}^{-1}) \cdot S (\text{m}^2) \cdot d (\text{cm}) \cdot \sigma (\text{g cm}^{-3}) \cdot (1-p) \cdot (1-r) / 100$$

where: SOC_p stands for SOC pools (stocks), SOC_c – SOC concentrations, d – thickness of soil layer, σ – soil bulk density, p – factor of soil surface coverage with rocks and stones, and r – factor of skeleton contribution in a soil layer (Szopka et al. 2010).

Cumulative pools of SOC accumulated on the surface of 1 m^2 in particular site were calculated by summing the data obtained for soil litter and the layers 0–10 cm and 10–20 cm.

To allow the spatial analysis, the monitoring sites were originally divided into three groups, defined operationally according to vertical forest zones in the Karkonosze Mts (Figure 1): the upper forest zone (>1000 m a.s.l.), the intermediate forest zone (750–1000 m a.s.l.), and the lower forest zone (500–750 m a.s.l.). However, the specific character of the uppermost forest zone, and its transition into subalpine pastures and mountain pine shrubs, were the reasons to distinguish two separate sub-zones 1000–1250 and >1250 m a.s.l.

The basic statistical characteristics (mean concentration, median, standard deviation) and 95% confidence intervals of SOC and its pools accumulated in soils in different zones were calculated. The mean values were compared using a one-way factorial analysis of variance (ANOVA) with Tukey's post hoc test at $p < 0.05$. The homogeneous groups of means that do not differ significantly between altitudinal zones were indicated in figures using the lower case letters a, b, c, d. Capital letters were used for indication of significantly different pools of SOC accumulated in various soil layers within each of the altitudinal

zones. The sets of data were transformed, when necessary, to approach a close-to-normal data distribution. All statistical calculations were performed using the STATISTICA (StatSoft Inc.) software package.

RESULTS

Forest litter thickness

Contrary to our expectations, based on several reports from the other mountains (Łabaz et al. 2014), an altitude-related trend in a forest litter thickness is not clearly marked in the Karkonosze Mts, up to the altitude of 1000 m a.s.l. (Figure 2). This is due to a large variability of the litter thickness in all of altitude zones, that varied in the broad ranges: 1–11 cm, 1–12 cm and 1–15 cm, at 500–750, 750–1000, and 1000–1250 m a.s.l., respectively. The thicker forest litter horizons occur under pure spruce stands, whereas the thinner ones were reported from the broadleaf stands, as well as from degraded (open) spruce stands, and

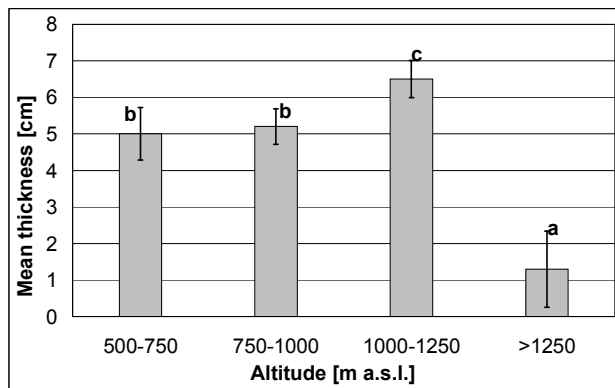


FIGURE 2. Mean thickness of forest litter as related to altitudinal zones. Error bars represent 95% confidence intervals. Lower case letter a, b, c indicate statistically homogeneous groups (according to Tukey's post-hoc test, $p < 0.05$)

numerous stands under transformation or reconstruction.

The mean litter thickness in the uppermost forest zone, established as 6.5 cm, is slightly, but significantly ($p < 0.05$) higher than that in the lower zone (5.0–5.2 cm), and decreases rapidly to ca 1.3 cm above the timberline (Figure 2), which must be related to much lower compactness of spruce canopies and lower height of spruce trees in the transition to subalpine zone (Kabała et al. 2013).

Soil organic carbon concentration

Although the concentrations of SOC vary greatly between distinguished soil layers: forest litter, 0–10 cm, and 10–20 cm (Table 1), the clear patterns of SOC distribution in the soils of the Karkonosze Mts can be revealed from a closer analysis (Figure 3). As expected, the SOC concentrations are the highest, and relatively least differentiated, in the forest litter horizons. The mean SOC concentrations in the forest litter are

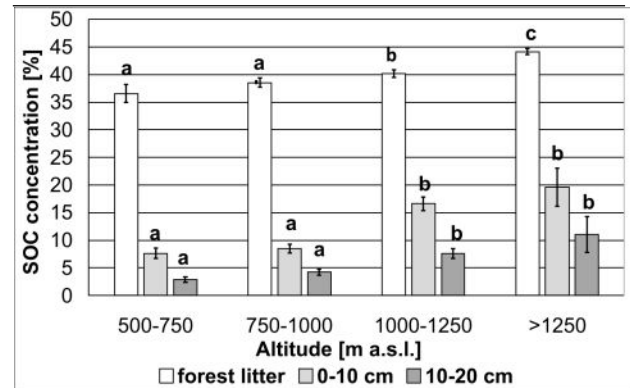


FIGURE 3. The concentrations of SOC in distinguished soil layers (forest litter, 0–10 cm and 10–20 cm) across the altitudinal zones in the Karkonosze Mts. Explanations as in Figure 2

TABLE 1. The concentrations of SOC in soil layers across the altitudinal zones

Altitude (m a.s.l.)	Sampling depth (cm)	SOC concentration				
		minimum	maximum	mean	median	standard deviation
(%)						
500–750	forest litter	18.60	46.4	36.60	38.30	7.25
	0–10 cm	2.05	22.0	7.66	6.46	4.09
	10–20 cm	0.50	12.4	2.87	2.12	2.32
750–1000	forest litter	15.60	49.1	38.50	40.00	5.77
	0–10 cm	2.06	47.6	8.53	7.07	5.47
	10–20 cm	0.66	29.9	4.20	2.52	4.00
1000–1250	forest litter	17.40	49.9	40.20	42.30	6.37
	0–10 cm	1.78	45.6	16.60	13.30	11.2
	10–20 cm	0.27	46.4	7.59	4.90	8.17
>1250	forest litter	42.40	46.1	44.20	44.10	1.71
	0–10 cm	4.63	46.9	19.60	17.30	10.7
	10–20 cm	1.52	41.8	11.10	7.48	9.86

TABLE 2. Total pools of SOC accumulated in a 20 cm thick topsoil layer plus in forest litter

Altitude (m a.s.l.)	SOC pools (kg·m ⁻²)				
	minimum	maximum	mean	median	standard deviation
500–750	5.03	19.2	10.5	10.3	3.07
750–1000	4.92	22.5	11.5	11.4	3.46
1000–1250	3.64	58.2	11.8	11.3	4.67
>1250	5.61	19.8	11.9	11.6	3.53

in a range 38.3–44.1% and tend to increase with the altitude, the differences being, statistically significant (at $p < 0.05$) (Figure 3). The concentrations of SOC in topsoil horizons 0–10 cm and 10–20 cm are, obviously, much lower than those in forest litter, and most of the data remain in the ranges typical for mineral soil layers. However, both the mean concentrations and the maximum values should be considered as relatively high, which indicates favourable conditions for accumulation of plant residues. The sites from which the highest values were reported, were typically those relatively wet, in which accumulated organic matter had peaty or murshic character. Such conditions occur much more commonly above 1000 m a.s.l. (Table 1) and this fact is quite well reflected in high share of organic soils and high maximum values of SOC concentrations (up to 46.9 and 41.8% in the layers 0–10 and 10–20 cm, respectively). As a result, the mean SOC concentrations increase significantly with an altitude, both in the layer of 0–10 cm (from 7.7 to 19.6%) and in 10–20 cm (from 2.9 to 11.1%), if comparing the zones 500–1000 m and >1250 m. In fact, not all the mean values of SOC concentrations in particular soil layers differ significantly between the subsequent altitudinal zones; statistically significant differences were confirmed between the zones below and above the elevation of 1000 m a.s.l (Figure 3). It

may be finally concluded, that the mean SOC concentrations in all distinguished soil layers increase with increasing altitude, being the lowest – for all the soil layers – in the zone <500 m a.s.l., and the highest – in the zone >1250 m a.s.l. Moreover, the differences between SOC concentrations in a forest litter and topsoil horizons (0–10 cm and 10–20 cm), tend to decrease with increasing altitude, which is clearly related to a wider occurrence of shallow organic soils in a colder and moister climatic conditions of the upper mountain zone.

The pools of SOC in the Karkonosze Mountains soils

In contrast to the much higher concentrations of SOC in the forest litter compared to soil horizons 0–10 cm and 10–20 cm, the calculated pools of SOC turned out not to differ significantly among those soil layers (Table 3, Figure 4). The mean values of SOC pools accumulated in the forest litter, determined for

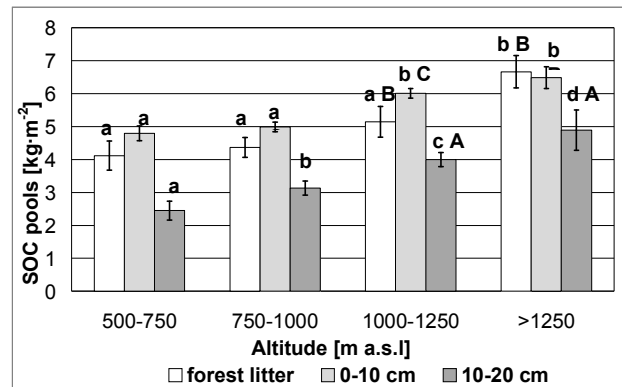


FIGURE 4. The pools of SOC accumulated in distinguished soil layers across the altitudinal zones in the Karkonosze Mts. Explanations as in Figure 2. The capital letters (A, B, C) indicate lack of significant differences between the pools of SOC accumulated in various soil layers within each of altitudinal zones

Altitude (m a.s.l.)	Sampling depth (cm)	SOC pools (kg·m ⁻²)				
		minimum	maximum	mean	median	standard deviation
500–750	forest litter	0.79	10.2	4.12	3.81	1.94
	0–10 cm	2.05	7.04	4.79	4.70	0.98
	10–20 cm	0.64	6.08	2.45	2.09	1.25
750–1000	forest litter	1.10	9.33	4.37	3.96	2.13
	0–10 cm	2.06	7.91	4.99	4.91	1.01
	10–20 cm	0.80	7.44	3.13	2.33	1.52
1000–1250	forest litter	0.78	43.4	5.14	4.26	4.27
	0–10 cm	1.87	7.87	6.01	6.20	1.32
	10–20 cm	0.36	7.89	4.00	4.10	1.95
>1250	forest litter	5.46	8.61	6.67	6.30	1.50
	0–10 cm	3.98	7.90	6.49	6.66	1.00
	10–20 cm	1.68	7.80	4.89	5.03	1.87

TABLE 3. The pools of SOC (kg·m⁻²) accumulated in particular soil layers across the altitudinal zones

particular altitudinal zones, ranged from 4.12 to 6.67 $\text{kg}\cdot\text{m}^{-2}$, and accounted for 29 to 36% of the total SOC pools (Table 3). The mean pools of SOC in the layer 0–10 cm turned out to be somewhat higher than those in the forest litter with differences statistically insignificant, in the zones 500–750 m a.s.l and >1250 m a.s.l. (Figure 4). They ranged between 4.79 and 6.49 $\text{kg}\cdot\text{m}^{-2}$, and contributed to 35–42% of total SOC pools. As expected, the pools of SOC accumulated in separate layers proved to decrease with the depth in soil profile, and were significantly lower in the layer 10–20 cm compared to 0–10 cm. Relative mean values, determined for particular altitudinal zones, ranged from 2.45 to 4.89 $\text{kg}\cdot\text{m}^{-2}$. In general, the pools of SOC in all distinguished layers show a clear tendency to increase with altitude (Figure 4); however, the differences between the zones, when comparing all the pairs of altitudinal zones, were only in some cases statistically significant due to large differentiation of individual results (Figure 4). The most pronounced differences of SOC pools between the zones were observed in the layer 10–20 cm.

The mean value of SOC pools accumulated in soil forest litter in the Karkonosze Mts (5.1 $\text{kg}\cdot\text{m}^{-2}$) is higher than reported from Bohemian forests – 1.99 $\text{kg}\cdot\text{m}^{-2}$ (Cienciala et al. 2006), similar to that reported from the Stołowe Mts – 4.05 $\text{kg}\cdot\text{m}^{-2}$ (Gałka et al. 2014b), but significantly lower than in forests of Alberta (Canada) – 14.8 $\text{kg}\cdot\text{m}^{-2}$ (Banfield et al. 2002). The values of SOC pools in the forest litter of the Karkonosze Mts remain in the range of pools reported from the Himalaya Mts, i.e. 2.3–35.4 $\text{kg}\cdot\text{m}^{-2}$ (Martin et al. 2010).

The total pools of SOC accumulated within a top soil layer 0–20 cm plus those in the forest litter vary in a very broad range 3.64–58.2 $\text{kg}\cdot\text{m}^{-2}$, but the mean values (and medians) determined separately for various zones, fall in a narrow range 10.5–11.9 $\text{kg}\cdot\text{m}^{-2}$ (Table 2). Moreover, the minimum and maximum

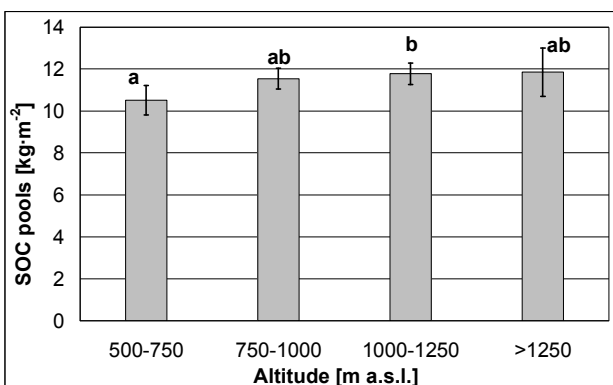


FIGURE 5. Total pools of SOC accumulated in soils (in a 0–20 cm top soil layer plus in the forest litter) as related to altitudinal zones in the Karkonosze Mts. Explanations as in Figure 2

values in various zones are quite similar, with the exception of maximum SOC pools in the zone 1000–1250 m a.s.l. that is exceptionally high. Therefore, although the mean pools of SOC tend to increase with altitude, this trend is very weak. The only statistically significant differences were confirmed between the total pools of SOC accumulated in soils in the upper forest zone 1000–1250 m a.s.l. compared to the lowest forest zone 500–750 m a.s.l. (Figure 5).

DISCUSSION

Altitude- and climate- related increase of SOC concentrations in soils were often reported from mountain areas (Garten and Hanson 2006, Ponge et al. 2011, Sinoga et al. 2012, Prietzel and Christophel 2014, Bojko and Kabala 2016) or from latitude-oriented sequences, e.g. in Alaska (Johnson et al. 2011). In some cases, this trend may have “ever-growing” nature (Carletti et al. 2009, Martin et al. 2010, Gałka et al. 2014b), but several authors report also the growing trend up to a specific threshold line, above which SOC concentrations in soils either remain stable or subsequently tend to decrease (Bojko and Kabala 2016). Increasing SOC concentrations in soils with increasing altitude in the Karkonosze Mts should probably be related to increasing share of Norway spruce in forest stands. It has already been confirmed that SOC content in soils is higher under coniferous tree species (spruce or mountain pine) compared to grass communities or beech stands, although reported differences were in many cases statistically insignificant (Paluch and Gruba 2012, Gałka et al. 2014b, Bojko and Kabala 2016). The other explanation highlighted by many researches is a direct dependence on the climate conditions that are related to the altitudinal zones. It was clearly shown that SOC content tends to increase with elevation under particular type of vegetation (Gałka et al. 2014b; Bojko and Kabala 2016), which clearly indicates the effects of decreasing soil biological activity and related decrease in the rate of organic residues decomposition under lower air and soil temperatures (Couteaux et al. 2002, Egli et al. 2009).

In contrast to many other studies that indicated a well expressed increase of SOC pools with an altitude in the mountain forests (Garten et al. 2006, Li et al. 2010, Gałka et al. 2014b), the result obtained in this study from the Karkonosze Mts confirmed only a weak increasing tendency of SOC pools with the altitude. Significant differences between the total pools of SOC accumulated in soils have only been confirmed between the lowest and the highest altitudinal zones. Statistical insignificance of differences

between the intermediate zones results undoubtedly from a large variability of data within the zones, that in general exceeds the differences between the zones. The differences along the elevation gradients reflect a changing balance of soil carbon inputs and losses that are potentially related to the changes in both abiotic (temperature, precipitation) and biotic (forest litter quality, biological activity) factors (Garten et al. 2006). The influx of aboveground biomass and root mortality are the two primary processes that contribute variously to soil carbon inputs along elevation gradients (Garten et al. 2006). An increase in SOC pools along with increasing elevation could either be caused by the greater SOC inputs in combination with relatively constant rate of SOC decomposition or, on the contrary, by decreasing decomposition with altitude in combination with the constant biomass inflow (Garten et al. 2006). We believe that the balanced combination of above mentioned models is applicable in the Karkonosze Mts.

The mean value of SOC pools accumulated in all the topsoil horizons (including forest litter) of the forest soils in the Karkonosze Mts, assessed as $11.4 \text{ kg}\cdot\text{m}^{-2}$ is similar to the values reported from various other mountain ranges. Garten et al. (2006) calculated the average stocks of SOC present in the 30 cm-thick topsoil horizons in the Appalachian Mts in the range 4.35 to $12.2 \text{ kg}\cdot\text{m}^{-2}$. The mean pools of SOC in the upper 30 cm thick layer of soils in the Himalaya Mts have been approximated at $16.2 \text{ kg}\cdot\text{m}^{-2}$ (Li et al. 2010). The mean SOC pools of 10.9 and $11.5 \text{ kg}\cdot\text{m}^{-2}$ were reported by Prietzel and Christophel (2014) from German Alps and from Bavarian Forest Soil Monitoring Network, respectively. Gingrich et al. (2007) reported the mean SOC pools at $11.4 \text{ kg}\cdot\text{m}^{-2}$ in Austrian and Swiss forest soils, and Hagedorn et al. (2010) reported $15.5 \text{ kg}\cdot\text{m}^{-2}$ in Swiss Alps.

Comparison of carbon pools accumulated in soils, reported by various authors, faces problems due to the different profile depths considered in the studies, that vary from 20 cm, by 30–50 cm, up to 100 cm, as well as due to including or excluding the forest litter (Gałka et al. 2014b). The other problem is a proper determination of soil bulk density, in particular in organic horizons, that in various studies was either estimated or measured (Prietzel and Christophel 2014). The different data on SOC pools reported by many authors from various mountain regions may also reflect their real differences caused by different historical forest management, different altitude or latitude of mountain regions, contrasting soil properties etc. (Prietzel and Christophel 2014).

The lack of statistical confirmation of several tendencies reported in this study is, additionally, a simple

consequence of sampling methodology. On the contrary to various problem-oriented research works, in which the samples are collected from specifically defined, hypothesis-related locations, this research was based on a regular sampling network, irrespective of the factors that apparently affect SOC accumulation, such as the age of forest stands, specific local conditions, as well as various extent of forest degradation, and different stages of its reconstruction.

Moreover, a regular monitoring network implied that soil samples were in some sites collected from particularly thick forest stands. This may be of particular importance for the concentration of SOC in the samples. It has been claimed (Prietzel and Christophel 2014) that various studies in which the soil profiles were excavated in the central spaces between the trees, not close to the tree trunks, may underestimate the SOC pools. This is due to the fact that the rooting systems of European beech, Norway spruce, and probably most other tree species develop spatially heterogeneously, resulting in larger SOC pools close to tree trunks and smaller in in-between areas (Prietzel and Christophel 2014).

CONCLUSIONS

The study indicated that the concentrations of SOC in the forest litter and in the top soil layers 0–10 cm and 10–20 cm, as well as total pools of accumulated SOC tend to slightly increase along with the elevation gradient, and are the lowest in the 500–750 m a.s.l. and 750–1000 m a.s.l. altitudinal zone and the highest in the zone >1250 m a.s.l. These trends are very weak, and partly statistically insignificant, which results from a large variability of data within altitudinal zones, that in general exceeds the differences between the zones.

Although the concentrations of SOC in the litter horizon are much higher than those in the 0–10 cm and 10–20 cm layers, the largest part of SOC pools accumulated in soils of the Karkonosze Mts is apparently confined mainly to the layer 0–10 cm, except for the highest altitudinal zone >1250 m. The contributions of particular soil layers, including the forest litter, to the total SOC pools indicate, however, very high variability, and therefore the differences between the contributions of the layers in the zones: 500–750 m a.s.l. and >1250 m a.s.l. have not been confirmed statistically.

The pools of SOC accumulated in the 20 cm thick topsoil layer plus in the forest litter vary in a very broad range 3.6 – $58.2 \text{ kg}\cdot\text{m}^{-2}$. The mean values (and medians) determined for distinguished altitudinal zones fall, however, in a narrow range 10.5 – $11.9 \text{ kg}\cdot\text{m}^{-2}$,

very close to the values reported from the Alps. The total pools of SOC accumulated in soils in the upper forest zone 1000–1250 m a.s.l. are significantly higher than those in the lowest forest zone 500–750 m a.s.l.

The week statistically significant of tendencies concerning SOC pools accumulated in soils in various altitudinal zones, reported in this study, appears to be a consequences of sampling methodology conditioned by regular sampling network. The samples were collected from specifically defined locations in the Karkonosze Mts, irrespective of the factors crucial for SOC accumulation, including the age and the state of forest stands (i.e. degraded and non-degraded forest ecosystems).

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Zasoby węgla organicznego zakumulowane w poziomach powierzchniowych gleb leśnych na terenie Karkonoskiego Parku Narodowego (południowo-zachodnia Polska)

Streszczenie: Badaniami objęto poziomy powierzchniowe gleby leśnych Karkonoskiego Parku Narodowego, gdzie w końcu XX wieku nastąpiło masowe wymieranie drzewostanów. Materiał glebowy pobrany został z 621 punktów stałego monitoringu ekosystemów leśnych rozmieszczonych w siatce 200×300 m z trzech poziomów: z poziomu próchnicy nadkładowej oraz z warstw 0–10 cm i 10–20 cm. Analiza zawartości węgla organicznego w badanych glebach została przeprowadzona dwiema metodami. Dla próbek organicznych – metodą wyżarzania w temperaturze 550°C, natomiast dla próbek mineralnych oznaczony został węgiel organiczny metodą oksydometryczną Tiurina. W badanych glebach przeprowadzono analizę zawartości węgla organicznego oraz jego zasobów w poziomach powierzchniowych gleb w czterech strefach wysokościowych: strefie regla dolnego od wysokości 500 do 750 m n.p.m., górnej części regla dolnego od 750 do 1000 m n.p.m., w reglu górnym 1000–1250 m n.p.m. oraz górnej partii regla górnego > 1250 m n.p.m. Zawartość węgla organicznego w poziomach ściółki waha się w granicach 38.3–44.1% i wzrasta wraz z wysokością. Zawartość węgla organicznego w poziomach 0–10 cm i 10–20 cm cechuje się dużym zróżnicowaniem zawierającym się w przedziale od 0,27 do 47,6% i również nieznacznie wzrasta wraz ze wzrostem wysokości n.p.m. Największe zasoby węgla organicznego stwierdzono w poziomach 0–10 cm we wszystkich strefach wysokościowych z wyjątkiem strefy najwyższej > 1250 m n.p.m., gdzie największe zasoby węgla organicznego zakumulowane są w poziomach ektohumusu. Średnie zasoby węgla organicznego, oszacowane do głębokości 20 cm (wraz z poziomem ściółki) wynoszące 10.5–11.9 kg·m⁻² są zbliżone do zawartości podawanych dla gleb leśnych Alp. Brak wysokościowego trendu zmian zasobów SOC, często obserwowanego w innych obszarach górskich może wynikać stąd, że w ramach regularnej sieci monitoringowej próbki pobiera się na ustalonych powierzchniach, niezależnie od wieku i stanu drzewostanu (w tym zdegradowanych, regenerowanych itd.), podczas gdy w innych badaniach próbki pobierane są w drzewostanach dojrzałych i typowo ukształtowanych.

Słowa kluczowe: glebowa materia organiczna, górskie gleby leśne, wysokość