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Soil Organic Matter Accumulation and Carbon Fractions along a Moisture Gradient of Forest Soils

Ewa Błońska * and Jarosław Lasota

Department of Forest Soil Science, Faculty of Forestry, University of Agriculture, Al. 29 Listopada 46, 31-425 Krakow, Poland; rllasota@cyf-kr.edu.pl

* Correspondence: eblonska@ar.krakow.pl

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Abstract: The aim of the study was to present effects of soil properties, especially moisture, on the quantity and quality of soil organic matter. The investigation was performed in the Czarna Różga Reserve in Central Poland. Forty circular test areas were located in a regular grid of points (100 × 300 m). Each plot was represented by one soil profile located at the plot's center. Sample plots were located in the area with Gleysols, Cambisols and Podzols with the water table from 0 to 100 cm. In each soil sample, particle size, total carbon and nitrogen content, acidity, base cations content and fractions of soil organic matter were determined. The organic carbon stock (SOCs) was calculated based on its total content at particular genetic soil horizons. A Carbon Distribution Index (CDI) was calculated from the ratio of the carbon accumulation in organic horizons and the amount of organic carbon accumulation in the mineral horizons, up to 60 cm. In the soils under study, in the temperate zone, moisture is an important factor in the accumulation of organic carbon in the soil. The highest accumulation of carbon was observed in soils of swampy variant, while the lowest was in the soils of moist variant. Large accumulation of C in the soils with water table 80–100 cm results from the thick organic horizons that are characterized by lower organic matter decomposition and higher acidity. The proportion of carbon accumulation in the organic horizons to the total accumulation in the mineral horizons expresses the distribution of carbon accumulated in the soil profile, and is a measure of quality of the organic matter accumulated. Studies have confirmed the importance of moisture content in the formation of the fractional organic matter. With greater soil moisture, the ratio of humic to fulvic acids (HA/FA) decreases, which may suggest an increase in carbon mobility in soils.

Keywords: carbon distribution index; moisture gradient; soil organic matter fraction

1. Introduction

Accumulation of organic carbon in soils is currently discussed for many reasons. With the increased pool of carbon stored in terrestrial ecosystems, a reduction of carbon dioxide emissions into the atmosphere and prevention from climate changes are observed [1,2]. In the carbon cycle on Earth, soil is its most important reservoir. It is estimated that carbon contained in soil constitutes 75% of the total pool of organic carbon, exceeding twice the resources of carbon in the atmosphere [3]. The accumulation of organic carbon in forest soils depends on many factors, but predominantly on climatic conditions [4], soil properties [5], soil moisture [6,7], the type of plant cover and type of forest management [8–11]. The site conditions and plant coverage are strongly related to each other. Here, the site conditions play the main role via driving formation of certain species composition and the structure of plant cover, thus determining the type and direction of soil formation processes [12]. Among the physical properties of the soil, clay fraction content acts in the formation of soil organic matter (SOM) accumulation. Many authors have studied the influence of clay and silt content on the protection of SOM, and have found a relationship between the content of SOM and soil texture, mainly

with the content of fine fractions (silt and clay) [13,14]. According to Wosten et al. [15], the accumulation and stabilization of soil carbon are associated with the content of clay; however, it may also depend on the soil moisture. Bauer et al. [16] and Meersma et al. [17] reported a strong influence of soil moisture on the decomposition of SOM, and consequently, on the carbon accumulation in the soil. SOM decomposition dynamics are influenced by pH making it an important variable, as an increase in SOM content is connected with changes of other soil parameters, namely pH [18].

By specifying the total content of soil carbon (C) [19] or by estimating the available fractions of SOM [20], the quantity and quality of SOM can be determined. To evaluate the changes in soil C dynamics due to agricultural use, the use of SOM chemical fractions was more effective than the determination of total SOM in Guimarães et al.'s [21] study. The SOM fraction can be used as an indicator of changes in the soil. The amount of SOM fractions reflects the potential mobility of C in the soil and the rate of SOM decomposition [22].

Until now, a limited number of studies reporting the relationship between the forest site condition, the accumulation of SOM, and fractions of humic substances has been published. There is a lack of studies on the effect of different moisture levels, soil properties, and natural forest plant communities on the quantity and quality of SOM in temperate climates. We hypothesize that: (1) soil moisture is an important factor in the accumulation of organic carbon in the temperate zone, and the highest accumulation of carbon was connected with a swampy variant of soils; (2) moisture has an effect on the proportion of carbon accumulation in the organic horizon to the accumulation in the mineral horizons; and (3) fractional composition of the organic matter reflects the rate of SOM decomposition in forest soils and depends on soil moisture.

2. Materials and Methods

2.1. Study Area

The study was performed in the Czarna Różga Reserve in Central Poland (Figure 1). The reserve area is 185.6 ha, and within the limits of the reserve stands is the dominant species common alder (*Alnus glutinosa*), which are of natural origin. The silver fir (*Abies alba*), pedunculate oak (*Quercus robur*), common hornbeam (*Carpinus betulus*) and common ash (*Fraxinus excelsior*) play the role of admixtures. The study area is characterized by the following climatic conditions: the average annual rainfall is 649 mm, the average daily temperature of the warmest month (July) is 17.8 °C and the coldest month (January) is −3.4 °C, and the length of the vegetation season lasts 200–210 days. Sample plots were located in the area with a predominance of fluvioglacial sand and loam with Gleysols, Cambisols and Podzols [23]. The groundwater level is the basic reason for differentiation of soil subtype and vegetations communities.

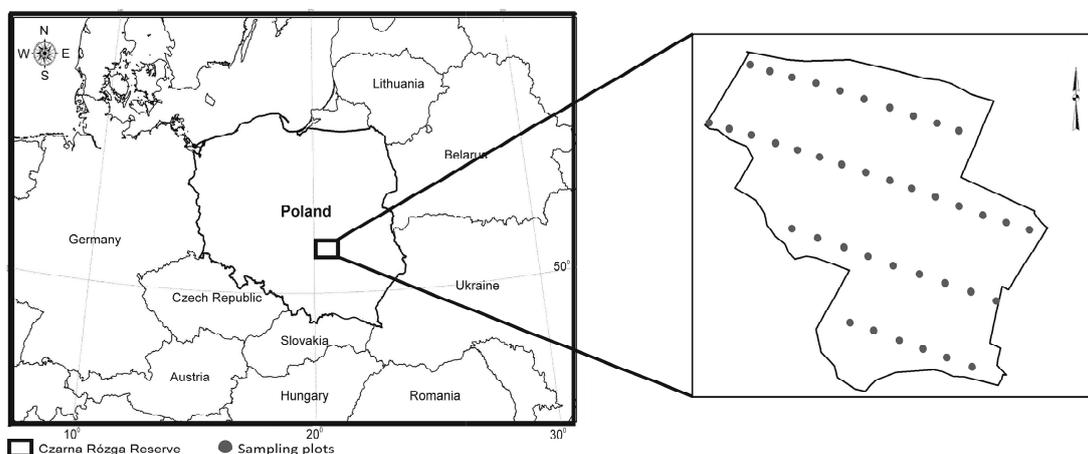


Figure 1. Study sites location (Czarna Różga Reserve in Central Poland).

2.2. Sampling Scheme

Forty circular test areas with a surface of 0.1 hectare were established within the area of the reserve. Test surfaces were located in a regular grid of points (100 × 300 m) (Figure 1). Each plot was represented by one soil profile located at the plot's center. The surface horizons (organic—O, mineral—A, or organic/mineral—AM) and the mineral topsoil (AE or AG) horizon were sampled. The subsoil gleyic horizon (G) was sampled from the bottom of the topsoil horizon to 60 cm deep. The surface horizons' samples constituted a cumulative sample from five subsamples around the soil profile.

On each test surface (Table 1), site conditions including vegetation types, soil types, and moisture levels (based on the groundwater depth and using soil moisture monitoring sensors in the daily interval in May and June) were recorded. The obtained results revealed three types of vegetation communities (*Abietetum albae*, *Tilio-Carpinetum ficarietosum* and *Fraxino-Alnetum*) within the reserve and water table from 0 to 100 cm in soil profiles. The three variants of soil moisture content (first variant with water table 80–100 cm (WT_{80–100}), second variant with water table 40–50 cm—moist, and last variant with water table 0–30 cm—swampy) were distinguished. In further analysis, the above sequence of soil moisture content (WT_{80–100}, moist and swampy) was considered. Ten areas that represent the *Abietetum albae* from Stagnosols and Podzols have been identified for the WT_{80–100} variant. The moist variant represents the *Tilio-Carpinetum ficarietosum* (19 areas). Gleysols dominated this variant. The third swampy variant (11 areas) is represented by the *Fraxino-Alnetum* dominated by Mollic Gleysols.

Table 1. Characteristic of vegetation and soils in groups of studied areas.

Moisture Gradient	Plant Communities	Dominant Stand Species	Dominant Ground Cover Species	Type of Soil	Depth of Groundwater Level (in the Spring) (cm)	Humus Type
WT _{80–100}	<i>Abietetum albae</i>	Silver fir	<i>Maianthemum bifolium</i> <i>Luzula pilosa</i> <i>Thuidium tamariscinum</i> <i>Polytrichum attenuatum</i>	Podzols Stagnosols	80–100	mor
Moist	<i>Tilio-Carpinetum ficarietosum</i>	Common hornbeam, Common alder	<i>Aegopodium podgraria</i> <i>Galeobdolon luteum</i> <i>Hepatica nobilis</i> <i>Impatiens noli-tangere</i>	Gleysols	40–50	mull
Swampy	<i>Fraxino-Alnetum</i>	Common alder	<i>Ficaria verna</i> <i>Valeriana simplicifolia</i> <i>Caltha palustris</i> <i>Carex remota</i>	Mollic Gleysols	0–30	mull sticky

WT_{80–100}—variant with water table 80–100 cm.

2.3. Laboratory Analysis of Soil

Soil samples obtained in the field were dried and sieved through 2.0 mm mesh. Using the potentiometric method, the pH of the samples was analyzed in H₂O and KCl. By using a laser diffraction technique (Analysette 22, Fritsch, Idar-Oberstein, Germany), the soil texture was determined. Carbon (C_t) and nitrogen (N) contents were measured with an elemental analyzer (LECO CNS TrueMac Analyzer) (Leco, St. Joseph, MI, USA). Using the method of Kononowa and Bielczikowa, fractional composition of humus was determined in which extraction is performed in a mixture of 0.1 M NaOH and 0.1 M Na₄P₂O₇ [24]. In order to obtain a humin (Hm), humic acid (HA), and fulvic acid (FA) fraction, the chemical fraction was conducted. The relationships HA/FA and (HA+FA)/Hm were also calculated. Exchangeable Ca, Mg, K and Na were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) (iCAP 6500 DUO, Thermo Fisher Scientific, Cambridge, UK) in 1 M ammonium acetate at pH 7.0 extracts. The sum of base cations (BC) and effective base saturation (BS)

were calculated. Available phosphorus was determined by Bray–Kurtz’s method. The hydrolytic acidity was determined in the samples after extracting 5 g of soil with 30 mL 1 mol·L⁻¹ (CH₃COO)₂Ca (shaking time 1 h), followed by filtration. After extracting 5 g of soil with 30 mL KCl, exchangeable acidity was determined. Soil on the filter was washed several times by extractant solution, up to a volume of 200 mL. About 25 mL of the obtained solution was titrated by potentiometric titration (automatic titrator, Mettler Toledo Inc., Columbus, OH, USA) to a pH of 8.2. For determining the exchangeable aluminum and hydrogen, NaF was added to the KCl extract and titrated with NaOH. Total cation exchange capacity (CECt) was calculated as a sum of base cations (BC) and hydrolytic acidity (Ah); and effective cation exchange capacity (CECe) was calculated as a sum of base cations (BC) and exchangeable acidity (Aex). Using samples with intact structure collected to metal cylinders, bulk density was determined via the drying-weighing method [25].

The soil organic carbon stock (SOC_S) was calculated as a sum of its total content at particular soil horizons. In each of the analyzed soil samples, the SOC_S was calculated in the soil block area of 1 m² and a depth from the surface to 60 cm. The calculation of SOC_S for the particular depths was made by summing the SOC_S at subsequent genetic soil horizons according to the formula:

$$\text{SOC}_S = C \times D \times m / 10 \text{ (Mg} \cdot \text{ha}^{-1}\text{)} \quad (1)$$

where C is the organic carbon content at the subsequent genetic horizon (%), D is the bulk density (g·cm⁻³), and m is the thickness of the horizons (cm).

Moreover, a Carbon Distribution Index (CDI) was provided and calculated from the ratio of the carbon accumulated in organic horizons and the amount of organic carbon accumulated in the mineral horizons up to 60 cm according to the formula:

$$\text{CDI} = \frac{C \text{ accumulated in organic horizons } [\text{Mg} \cdot \text{ha}^{-1}]}{C \text{ accumulated in mineral horizons to 60 cm depth } [\text{Mg} \cdot \text{ha}^{-1}]} \quad (2)$$

2.4. Statistical Analysis

Basic descriptive statistics, arithmetic mean and standard deviation were used to estimate the soil properties’ variability. Tukey’s honest significant difference (HSD) test was used to assess differences between means for carbon accumulation in soils. To evaluate the relationships between stock of soil carbon, other soil properties, forest species, and moisture, the Principal Components Analysis (PCA) method was used. Multiple regression models were developed to describe the relationship between the estimated values of carbon content and other soil properties. The statistical significance of the results was verified at the significance level of alpha = 0.05. All statistical analyzes were performed with Statistica 12 software (2012).

3. Results

The investigated soils are characterized by diversification of properties (Table 2). The values of pH H₂O and pH KCl were in the range from 3.85 to 7.30 and from 3.04 to 5.78, respectively. A significantly greater pH was noted in soils of moist and swampy variants (Table 2). For cation content, a similar dependence was recorded (Table 2). The greater Ah and Aex were observed in soils with water table 80–100 cm (Table 3). The texture of the investigated soils was dominated by sand (on average 50–72% in the deeper horizons) and silt (on average 23–42% in deeper horizons) with addition of clay (on average 5–8% in the deeper horizon) (Table 3). The sand content (only in the deepest horizons) was significantly greater in WT_{80–100} variant (Table 3). The silt and clay content (only in the deepest horizons) was higher in soils of moist and swampy variants (Table 3). The analyzed soils clearly differ in their moisture content (Table 4). Statistically significant higher soil moisture content was recorded in the soils of the swampy variant (mean soil moisture of the surface humus horizon was 46.85%). The lowest soil moisture content was recorded in the soils of the WT_{80–100} variant (Table 4).

Table 2. Chemical properties of study soils.

Moisture Gradient	Horizon	pH H ₂ O	pH KCl	Ah	Aex	Al	P	Ca	K	Mg	Na	BC	BS	CECt	CECe
WT ₈₀₋₁₀₀	O	3.85 ^b ± 0.37	3.04 ^b ± 0.35	49.68 ^a ± 18.74	10.14 ^a ± 3.43	306.98 ± 243.27	58.75 ^a ± 32.41	6.88 ^b ± 3.30	0.69 ^a ± 0.24	1.21 ^a ± 0.58	0.09 ^a ± 0.08	8.89 ^b ± 3.84	16.49 ^b ± 8.82	58.58 ^a ± 20.86	19.03 ^a ± 6.07
	AE	3.87 ^c ± 0.16	3.07 ^c ± 0.18	12.14 ^a ± 4.91	4.19 ^a ± 0.84	193.96 ± 79.65	8.67 ^a ± 4.90	0.94 ^b ± 0.32	0.05 ^a ± 0.03	0.13 ^b ± 0.09	0.02 ^b ± 0.01	1.13 ^b ± 0.41	7.15 ^b ± 4.57	13.26 ^a ± 6.07	5.32 ^b ± 1.82
	G	4.51 ^b ± 0.41	3.81 ^b ± 0.33	3.49 ^a ± 1.00	2.21 ^a ± 0.63	95.36 ± 41.21	61.46 ^a ± 46.18	0.36 ^b ± 0.19	0.01 ^b ± 0.01	0.03 ^b ± 0.02	0.01 ^b ± 0.01	0.41 ^b ± 0.37	10.03 ^b ± 6.19	3.91 ^b ± 0.87	2.62 ^b ± 0.54
Moist	A	4.94 ^a ± 0.73	3.98 ^a ± 0.69	27.57 ^{a,b} ± 2.10	3.04 ^b ± 1.80	69.90 ± 9.37	19.18 ^b ± 12.18	19.95 ^a ± 12.86	0.36 ^b ± 0.29	1.6 ^a ± 1.15	0.09 ^a ± 0.06	22.04 ^{a,b} ± 14.22	45.65 ^a ± 20.06	49.61 ^a ± 31.46	25.08 ^a ± 14.23
	AG	5.64 ^b ± 0.84	4.69 ^b ± 0.79	7.97 ^{a,b} ± 6.17	1.27 ^b ± 0.99	35.45 ± 68.05	3.85 ^b ± 3.69	16.07 ^a ± 14.54	0.06 ^a ± 0.04	0.93 ^a ± 0.87	0.06 ^a ± 0.04	17.12 ^a ± 12.15	60.75 ^a ± 23.38	25.10 ^a ± 19.31	18.39 ^a ± 15.02
	G	6.85 ^a ± 0.73	5.26 ^a ± 0.58	1.87 ^b ± 0.65	0.66 ^b ± 0.17	4.14 ± 5.25	1.27 ^b ± 0.72	8.30 ^a ± 5.07	0.07 ^a ± 0.05	0.60 ^a ± 0.40	0.04 ^a ± 0.02	9.01 ^a ± 5.52	76.92 ^a ± 15.04	10.88 ^a ± 5.61	9.67 ^a ± 5.44
Swampy	AM	5.71 ^a ± 0.78	4.40 ^a ± 1.50	13.01 ^b ± 11.01	1.66 ^b ± 1.01	14.99 ± 5.84	30.70 ^{a,b} ± 28.43	28.73 ^a ± 15.79	0.34 ^b ± 0.28	1.74 ^a ± 1.12	0.10 ^a ± 0.07	30.90 ^a ± 16.96	68.52 ^a ± 18.79	43.92 ^a ± 25.71	32.57 ^a ± 17.45
	AG	6.72 ^a ± 0.61	5.67 ^a ± 0.58	3.92 ^b ± 1.75	0.62 ^b ± 0.22	3.76 ± 6.59	8.86 ^a ± 5.88	21.73 ^a ± 12.85	0.10 ^a ± 0.08	1.09 ^a ± 0.72	0.07 ^a ± 0.05	22.99 ^a ± 13.05	82.32 ^a ± 12.04	26.92 ^a ± 14.75	23.62 ^a ± 13.45
	G	7.30 ^a ± 0.69	5.78 ^a ± 0.67	1.75 ^b ± 0.91	0.71 ^b ± 0.29	4.11 ± 1.01	5.09 ^a ± 4.47	10.59 ^a ± 7.06	0.12 ^a ± 0.07	0.70 ^a ± 0.53	0.04 ^a ± 0.02	11.40 ^a ± 7.59	83.53 ^a ± 9.73	13.16 ^a ± 8.22	12.11 ^a ± 7.47

mean ± standard deviation, small letters (a, b, c) in the upper index of the mean values mean significant differences in soil horizons between the moisture variant; WT₈₀₋₁₀₀, moist and swampy—soil moisture gradient; hydrolytic acidity (Ah) (cmol(+).kg⁻¹); hydrolytic acidity (Aex) (cmol(+).kg⁻¹); Ca, K, Mg and Na (cmol(+).kg⁻¹); Al, P (mg.kg⁻¹); total cation exchange capacity (CECt) (cmol(+).kg⁻¹); effective cation exchange capacity (CECe) (cmol(+).kg⁻¹); base cations (BC) (cmol(+).kg⁻¹); base saturation (BS) (%).

Table 3. The particle size [%] and bulk density [$\text{g}\cdot\text{cm}^{-3}$] of study soils.

Moisture Gradient	Horizon	Sand Fraction					Silt Fraction			Clay	Sum of Fraction		BD
		VCS	CS	MS	FS	VFS	Csi	Fsi	Sand		Silt		
WT _{80–100}	O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.41 ^b ± 0.21
	AE	0.4 ^a ± 0.3	15.5 ^a ± 8.8	30.5 ^a ± 2.6	15.0 ^a ± 4.0	9.2 ^a ± 2.4	10.9 ^a ± 3.7	14.6 ^a ± 4.5	3.8 ^a ± 1.3	70.7 ^a ± 8.4	25.5 ^a ± 7.3	1.14 ^a ± 0.11	
	G	1.3 ^a ± 0.7	24.8 ^b ± 10.5	31.5 ^a ± 3.2	10.6 ^a ± 3.8	3.5 ^a ± 1.3	7.4 ^b ± 3.0	15.9 ^b ± 6.2	4.9 ^b ± 1.8	71.6 ^a ± 9.1	23.4 ^b ± 7.6	1.34 ^a ± 0.01	
Moist	A	1.1 ^a ± 1.0	10.9 ^a ± 8.4	19.7 ^a ± 11.4	18.9 ^a ± 8.1	11.26 ^a ± 5.3	11.6 ^a ± 7.2	11.6 ^a ± 9.1	2.7 ^a ± 2.0	62.0 ^a ± 30.1	23.3 ^a ± 15.7	0.83 ^a ± 0.25	
	AG	0.5 ^a ± 0.2	8.9 ^a ± 6.1	20.1 ^b ± 10.6	17.5 ^a ± 3.5	10.8 ^a ± 3.7	16.8 ^a ± 6.8	21.2 ^a ± 9.5	4.3 ^a ± 2.1	57.0 ^a ± 17.5	37.9 ^a ± 15.9	1.21 ^a ± 0.08	
	G	0.3 ^a ± 0.1	7.8 ^a ± 5.7	23.7 ^a ± 11.5	14.4 ^a ± 3.2	4.9 ^a ± 2.0	14.0 ^a ± 6.5	27.1 ^a ± 10.9	7.7 ^a ± 2.9	51.1 ^b ± 18.8	41.1 ^a ± 16.3	1.35 ^a ± 0.02	
Swampy	AM	1.3 ^a ± 0.8	13.0 ^a ± 3.0	19.3 ^a ± 12.9	16.3 ^a ± 10.8	7.1 ^a ± 6.0	6.9 ^a ± 5.1	6.9 ^a ± 6.3	1.9 ^a ± 1.0	64.7 ^a ± 33.3	15.1 ^a ± 11.0	0.69 ^{a,b} ± 0.31	
	AG	n.d.	9.1 ^a ± 7.1	20.3 ^{a,b} ± 12.4	18.2 ^a ± 5.5	9.5 ^a ± 3.9	14.8 ^a ± 7.3	21.9 ^a ± 12.9	5.3 ^a ± 2.9	57.8 ^a ± 22.2	36.8 ^a ± 19.4	1.07 ^a ± 0.19	
	G	n.d.	5.7 ^a ± 2.6	22.7 ^a ± 12.6	15.4 ^a ± 6.8	5.6 ^a ± 3.4	12.9 ^b ± 8.6	28.7 ^a ± 11.1	7.8 ^a ± 3.5	49.5 ^b ± 19.8	41.6 ^a ± 18.7	1.31 ^a ± 0.08	

n.d. no determine, mean ± standard deviation, small letters (a, b, c) in the upper index of the mean values mean significant differences in soil horizons between the moisture variant, WT_{80–100}, moist and swampy—soil moisture gradient; VCS—very coarse sand, CS—coarse sand, MS—medium sand, FS—fine sand, VFS—very fine sand, Csi—coarse silt, Fsi—fine silt; BD—bulk density.

Table 4. Humus substances, organic carbon and nitrogen content, moisture of study soils.

Moisture Gradient	Horizon	C	N	C/N	HA	FA	Hm	HA/HF	HA+HF/Hm	SOCs	CDI	Moisture
WT _{80–100}	O	241.87 ^a ± 74.21	12.45 ^a ± 5.28	19.6 ^b ± 2.8	11.9 ^a ± 6.78	4.43 ^a ± 2.28	n.d.	2.74 ^a ± 1.12	n.d.			
	AE	35.07 ^a ± 19.41	1.75 ^a ± 1.15	21.1 ^b ± 3.1	3.08 ^a ± 1.44	0.63 ^a ± 0.61	0.47 ^a ± 1.03	4.70 ^a ± 1.38	8.00 ^a ± 5.03	14.09 ^{a,b} ± 2.98	0.837	16.43 ^c ± 3.42
	G	4.87 ^{a,b} ± 2.01	0.24 ^a ± 0.07	20.3 ^b ± 2.5	0.81 ^a ± 0.44	0.82 ^a ± 0.45	0.3 ^a ± 0.03	1.05 ^a ± 1.10	54.30 ^a ± 22.90			
Moist	A	101.10 ^b ± 49.29	6.80 ^a ± 3.79	14.2 ^a ± 1.7	3.15 ^b ± 3.04	3.41 ^a ± 3.55	9.79 ^a ± 10.41	1.80 ^a ± 2.31	0.68 ^b ± 0.84			
	AG	24.29 ^a ± 13.80	1.84 ^a ± 1.04	13.2 ^a ± 1.2	1.37 ^b ± 0.73	1.69 ^a ± 2.10	1.89 ^a ± 2.53	2.25 ^b ± 1.96	1.63 ^b ± 1.25	12.61 ^b ± 3.71	0.299	30.08 ^b ± 4.86
	G	3.95 ^b ± 2.30	0.33 ^a ± 0.18	11.8 ^a ± 1.1	0.99 ^a ± 1.12	0.72 ^a ± 0.94	0.25 ^a ± 0.26	3.31 ^a ± 1.18	11.47 ^a ± 8.98			
Swampy	AM	135.96 ^{a,b} ± 107.11	10.09 ^a ± 7.02	12.8 ^a ± 1.6	4.67 ^{a,b} ± 3.55	2.91 ^a ± 3.72	5.51 ^a ± 7.63	3.84 ^a ± 2.41	1.40 ^{a,b} ± 0.68			
	AG	44.13 ^a ± 34.29	3.31 ^a ± 2.39	13.1 ^a ± 1.2	2.26 ^{a,b} ± 1.56	1.34 ^a ± 1.65	1.08 ^a ± 1.47	2.51 ^b ± 1.06	3.40 ^b ± 2.20	19.02 ^a ± 1.82	0.329	46.85 ^a ± 3.28
	G	8.51 ^a ± 4.31	0.64 ^a ± 0.51	12.8 ^a ± 1.6	0.79 ^a ± 0.72	0.99 ^a ± 0.90	0.31 ^a ± 0.28	2.98 ^a ± 1.47	16.18 ^a ± 12.45			

mean ± standard deviation, small letters (a, b, c) in the upper index of the mean values mean significant differences in soil horizons between the moisture variant; WT_{80–100}, moist and swampy—soil moisture gradient; C and N ($\text{g}\cdot\text{kg}^{-1}$); HA carbon of humic acids (% C), FA carbon of fulvic acids (% C), Hm carbon of humin (% C); SOC soil organic carbon stock ($\text{Mg}\cdot\text{ha}^{-1}$); CDI carbon distribution index; moisture (%); n.d.—no determine.

The differences in the carbon content of the examined soils were clearly noted. A statistically higher carbon content in the surface horizons was noted in the soils of the WT_{80–100} variant. The average content of carbon in the surface horizon of this variant was 241.87 g·kg⁻¹, and was 101.10 g·kg⁻¹ and 135.96 g·kg⁻¹ in the soils of the moist and swampy variants, respectively (Table 4). The highest carbon content in the lower lying horizons was recorded for soils of the swampy variant. The mean carbon content at these horizons was 44.13 g·kg⁻¹ and 8.51 g·kg⁻¹, respectively. In the case of WT_{80–100} and moist variant of soils in the deeper horizons, the carbon content was 35.07–4.87 g·kg⁻¹ and 24.29–3.95 g·kg⁻¹, respectively. Similar dependencies concerned nitrogen content (Table 4). The lowest C/N, which expresses the degree of organic matter distribution, was recorded in the soils of the swampy and moist variants (the C/N ratio ranged from 11.8 to 14.2). The highest C/N ratio, from 19.6 to 20.3 depending on the horizon, was recorded in the WT_{80–100} variant of soils (Table 4). Soil organic matter (SOCs) concentration in the 0–60 cm soil horizon differed significantly among moisture gradients and followed the order: swampy > WT_{80–100} > moist variants. The average SOCs up to a depth of 60 cm in the soils of moist variant is lower and is estimated at 12.61 Mg·ha⁻¹. The higher accumulation was found in the soils of WT_{80–100} variant, where the average SOCs was 14.09 Mg·ha⁻¹. A significantly greater accumulation was noted in the soils of swampy variant (19.02 Mg·ha⁻¹). The ratio between carbon accumulation in the organic horizon and carbon accumulation in the mineral horizons, up to 60 cm of soils (CDI) of estimated variants, is notably diverse (average 0.299–0.837). The lowest values of CDI are found in the soils of moist variant in which the CDI indicator is 0.299. The soils of swampy variant are characterized by higher values of the CDI index—0.329, and the CDI index of soils of WT_{80–100} variant approached 1.0 and is 0.837 (Table 4).

Concentrations of C in fulvic acid (FA), humic acid (HA) and humin fractions in the different soil horizons of different moisture variants are presented in Table 4. Mean values of HA, FA and humin varied from 11.9% to 0.79%, 4.43% to 0.63%, and 9.79% to 0.25%, respectively. In the fractions of SOM, humic acids dominate over fulvic acids and humins. Soils of the WT_{80–100} variant are characterized by the highest content of humic and fulvic acid (Table 4). Significant differences between the soils in terms of humic acid were observed in two surface horizons (swampy variant = WT_{80–100} variant > moist variant = swampy variant). No significant differences between soil variant in terms of fulvic acid and humin were noted (Table 4). All SOM fractions decreased significantly with depth for all variants of soil. The HA/FA ratio ranged from 4.70 to 1.05. The lowest HA/FA ratio regardless of depth was in the soil of WT_{80–100} variant, and the highest in the soil of moist and swampy variant. The relationship of the sum of C humic and fulvic acids to C humin (HA+FA/Hm) assumes the values of 54.3–0.68 (Table 4). In the soil of WT_{80–100} variant, the highest HA/FA ratio and HA+FA/Hm, as compared to moist and swampy variant, was recorded and was statistically significant (Table 4).

Multiple regression models explained 89% of the variance in the C content (Table 5). C content was largely dependent on hydrolytic acidity and moisture. The relationships between carbon content, hydrolytic acidity and moisture are shown in Figure 2. The increase in C accumulation in soils correlated with high moisture and high acidity.

A projection of the variables on the factor-plane clearly demonstrated a correlation between the variables and soil moisture (supplementary variables). Two main factors had a significant total impact (60.62%) on the variance of the variables in soil. Factor 1 explained 35.76% of the variance of the examined properties and Factor 2 explained 24.86% of the variance (Figure 3). The soil of moist and swampy variants had a higher pH. In contrast, the soils of WT_{80–100} variant were characterized by a high C/N ratio. The soils of WT_{80–100} variant contained more humic acids. The fulvic acids and humins were connected with nitrogen content.

Table 5. Multiple regression analysis for carbon content based on soil characteristic. R^2 describes the percentage of explained variance, β is the regression coefficient for the given equation parameter and p is the significance level for the equation parameter.

	R^2	Equation Parameter	β	p
C	89%	Ah	5.257	0.000001
		Moisture	1.897	0.000001

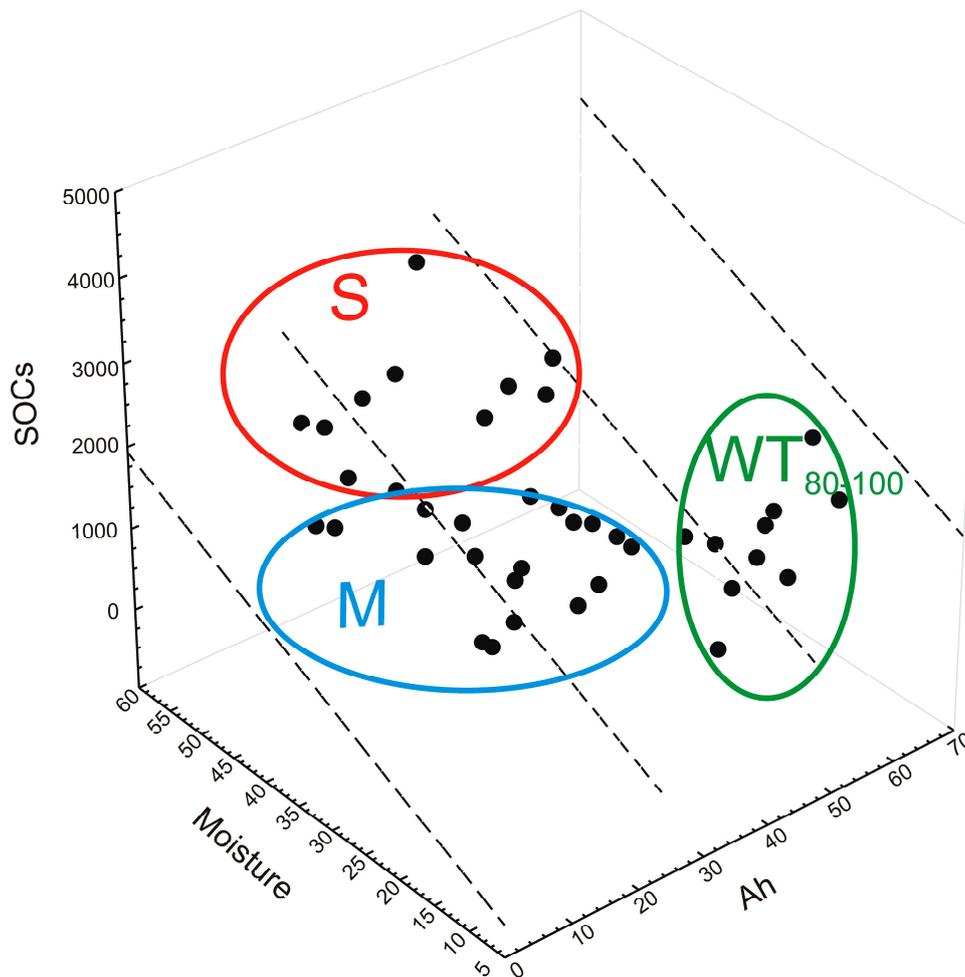


Figure 2. Three-dimensional plot of the relationship between soil organic carbon stock (SOCs), moisture and hydrolytic acidity (Ah) of soils (circles with WT₈₀₋₁₀₀—group of plots with water table 80–100 cm, circles with M—group of moisture plots, circles with S—group of swampy plots); regression plane marked by black lines.

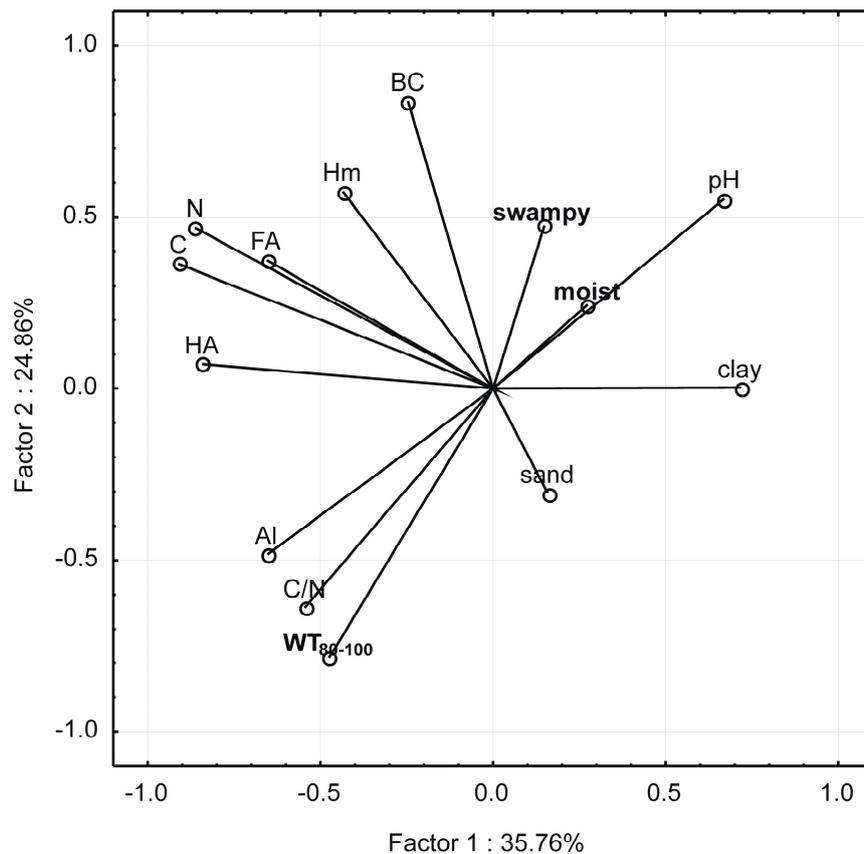


Figure 3. Diagram of Principal Components Analysis (PCA) with projection of variables on a plane of the first and second factor in the surface horizon (WT_{80-100} , moist and swampy—soil moisture gradient; HA—humic acids, FA—fulvic acids, Hm—humins).

4. Discussion

Results present in this study demonstrate that soil moisture is a factor that most strongly influences the carbon accumulation in forest soils. Compared to the soil with water table from 80 to 100 cm and moist soils, those with the highest moisture content (swampy variant) are characterized by the higher C accumulation. Soil organic matter (SOCs) concentration differed significantly among moisture gradient and followed the order: swampy > WT_{80-100} > moist variants. The greater SOM accumulation in the soils is affected not only by the high moisture, but also periodic deficiency of water. Our results show the high SOC stock on the sites with low moisture (WT_{80-100} variant) and in swampy variant, and that site condition promoted lower rate decomposition. The high SOC stock in the soils of WT_{80-100} variant is affected by greater acidity (surface horizons are not enriched due to low groundwater level). In the soils of swampy variant, there is an effect of anaerobic processes: the soils better aerated in the moist variants are characterized by faster and more efficient decomposition of SOM. Jandl et al. [26] and Stendahl et al. [27] related the accumulation of SOC with site conditions. A large stock of carbon can be associated with the accumulation of organic matter in acidic environments. A similar situation was noted for the soils of the WT_{80-100} variant where surface horizons were under coniferous species influence. Tree species affect pH, and the specific composition of organic matter may lead to the modification of soil acidity and nutrient pools [28–30]. pH is an important variable that influences SOM decomposition dynamics [31]. Our results confirmed the importance of moisture and acidity of soils on soil organic matter accumulation. In our study, 89% of the variance in the C content was explained by the hydrolytic acidity and moisture of the soils. Li et al.'s [32] results indicated that moisture level had an effect on carbon accumulation. At the same time, the increase of soil's acidity results in deterioration of the conditions of decomposition of dead organic matter, slowing down

their humification rate and microbial activity. On the other hand, the increase in organic matter accumulation results in an increase in sorption capacity, which, under acidic forest soil condition and lower level of groundwater, includes aluminum and hydrogen ions. The increase in soil moisture was favorable for the accumulation of water soluble carbon. In our study, soils in the swampy variant are characterized by the highest accumulation of C, which can be combined with the accumulation of organic debris in the peat-forming process. These studies confirm earlier findings, that although the peat covers only 3% of the Earth's surface, it constitutes an important reservoir of carbon [33,34]. Under anaerobic conditions, 2–6 times less CO₂ was produced than under aerobic conditions [35]. Furthermore, the presence of water in the soil profile facilitates dissolution of minerals, and during the capillary transport, also their transportation to higher horizons where they can form stable conjunctions to the humic substances. In addition, higher soil moisture results in higher biomass production of trees and plant cover of lower layers of the stand, which results in increased accumulation of organic material into the forest floor and soil.

In our study, CDI was used to evaluate the distribution of carbon accumulated in the soil profile and as a measure of quality of the accumulated organic matter. The advantage of accumulation of carbon in the mineral horizons over accumulation in the organic horizons indicates a greater efficiency of the processes of organic matter decomposition. In numerous studies [36], the greater resistance of SOM, in combination with soil minerals, is observed. In comparison to the accumulation occurring in the organic horizons, the predominance of carbon accumulation in the mineral horizons can be observed in soils of moist and swampy variants. The soils of moist variants were occupied by a very diverse species composition; the presence of admixture species—mainly hornbeam, alder and maple—provides abundant input of easily decaying organic matter to the soil. The positive impact of hornbeam on the accumulation of SOM was also described by other authors [31,37]. Stand mixing improves soil properties, especially the quality of SOM and biochemical properties [38]. The dominance of coniferous species in the forest (WT_{80–100} variant) changes the CDI index. In coniferous forests with fir, the C accumulation in the mineral horizons is reduced in relation to the total accumulation in the whole soil profile. The reason for the higher accumulation of C at the organic horizons is undoubtedly the slow decomposition of organic debris. Litter decomposition is particularly influenced by decomposer organisms [39]. The conifer litter decomposes slower than that from hardwood species [40]. The soils of coniferous forests are characterized by low pH, and the decomposition of litter is mainly conducted by fungal organisms. Fungi dominate in acidic soils, whilst bacteria in soils are characterized by a neutral or alkaline pH [41].

Forest soils in the studied moisture content gradient differ in the accumulation of carbon and the fractional composition of the soil organic matter. In the studied soils, a large proportion of humic acids were found, which prevailed in the moist variants. This is in line with Tavares and Nahas' study [42]. More humic acids than fulvic acids indicate the potentially low mobility of carbon accumulated in the surface soil horizons [21]. In our studies, the ratio of humic to fulvic acids (HA/FA) changes as moisture content of soils increases, suggesting an increase in carbon mobility in these soils. More humic acids than fulvic acids indicate high humification rates. The differences in soil moisture contents influences the amounts and chemical composition of the soil humic fraction [32]. The results implied that a high moisture level was unfavorable for the accumulation of humic fraction in the soil. In our experiment, we used the ratio between the sum of humic and fulvic acids and humin ((HA+FA)/humin) as an indicator of loss of SOM through the soil profile. The highest ratio ((HA+FA)/humin) was determined in the soils with the lowest moisture. As the soil moisture content increased, the ratio decreased. The lower ratio ((HA+FA)/humin) indicates the sufficient humin level in the soils with the highest moisture content.

5. Conclusions

In the soils under study, in the temperate zone, moisture is an important factor in the accumulation of organic carbon in the soil. The highest accumulation of carbon was observed in soils of swampy

variant, while the lowest in the soils of moist variant. In the soil of swampy variant, the anaerobic conditions affect the organic matter decomposition leading to slower processes. The increased accumulation of C in soils of WT_{80–100} variant is caused by other factors. Large accumulation of C in the soils of the WT_{80–100} variant results from the thick organic horizons that are characterized by lower organic matter decomposition and higher acidity. In the WT_{80–100} variant, the higher acidity is simultaneously an effect of the stand species composition and lack of water neutralization. The proportion of carbon accumulation in the organic horizons to the total accumulation in the mineral horizons expresses the distribution of carbon accumulated in the soil profile, and is a measure of quality of the organic matter accumulated. The advantage of accumulation at the mineral horizons over accumulation at the organic horizons confirms a greater efficiency of decomposition processes of organic matter, which, thanks to more advanced transformations and connecting with mineral soil, can be considered stable. Studies have confirmed the importance of moisture content in the formation of the fractional organic matter. The increase in soil moisture content changes the ratio of humic to fulvic acids (HA/FA), which may suggest an increase in carbon mobility in soils.

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