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Original Research

Assessment of TOC-SOM and SOM-TOC Conversion in Forest Soil

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Abstract

We analyzed relations between the content of total organic carbon (TOC) and the content of soil organic matter (SOM) in 47 soil profiles dug out in dry coniferous forests, fresh coniferous forests, and mixed deciduous-coniferous forests. Soils in the analyzed sites are derived from sands. In each soil horizon, bulk density (BD), pH, soil texture, and TOC and SOM were determined. Correlation between the content of TOC and SOM was significant in all layers ($p<0.05$), with correlation coefficients varying from 0.98 in the O horizon to 0.45 in the C horizon. The regression coefficient of linear equations for the SOM-to-TOC conversion decreased with soil depth. In the horizons occurring to a depth of ca. 20 cm (O, A, E), the regression coefficient for TOC as a predictor of SOM is 1.985, and for SOM as a predictor of TOC is 0.498, when R^2 equals 0.989. In the B horizons, which form a layer to the depth of 30-50 cm, these coefficients amounted to 1.912 and 0.459, respectively. In the deeper layers, the relationship between TOC and SOM seems to be less evident. It was established that TOC determined is consistent with TOC calculated on the basis of the SOM-to-TOC conversion.

Keywords: forest soil, soil organic carbon, soil organic matter, SOM-to-TOC and TOC-to-SOM conversions

Introduction

Accumulation and decomposition of soil organic matter determine the quality of soils as well as the carbon cycle in the environment. Methods of organic matter (OM) determination have been developed since the 19th century, and the process has continued up to this day. A simple method is the ignition of OM in the soil and determination of its content on the basis of loss of soil mass (LOI, loss-on-ignition method). However, soil loss during the ignition process could be overestimated due to evaporation of tightly bound water or decomposition of mineral compounds, it may also be underestimated because of incomplete ignition. Many authors [1-7] have been working in recent years on the assessment of the LOI method in relation to temperature, duration of ignition, mass of ignited sample, content of clay particles in the soil, and soil pH. The authors agree that the LOI method is simple and cheap and may be commonly used, especially to determine the content of organic matter in acid soils developed from sands and light clay, which are characterized by the very low content of particles smaller than 0.002 mm.

Methods of determination of the TOC in soils based on wet digestion by an application of a strong oxidant and indication of released CO_2 were developed at the same time. The most known methods are: the Walkley-Black and Tiurin methods, which have been modified, especially in respect to the indication of CO_2 [8]. Chatterjee et al. [7] summarized ca. 90 works written by various authors, whose subject were methods of TOC determination. According to the authors, the wet digestion methods vary with respect to

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the concentration and composition of the oxidant used as well as the temperature, duration of ignition and methods of determination of the released CO_2.

According to Chatterjee et al. [7], the TOC content is measured more precisely by using automated dry combustion, no matter what ignition temperature and method of detection of CO_2 is applied. Application of the automated dry combustion allows precisely determining C content in a well homogenized soil sample, which still does not mean that the actual C content in the analyzed soil is reflected equally precisely. The authors suggest that the future belongs to the development of *in situ* methods of determining the SOC pool [7].

The TOC content has been and still is a basis to calculate the content of soil organic matter by applying the conversion coefficients that are based on the content of C in organic matter. The TOC-SOM conversion was critically assessed by Pribyl [9], who based his opinion on the review of ca. 120 publications from the past 120 years, paying particular attention to the widely used coefficient amounting to 1.724, which is based on the assumption that SOM contains 58% of carbon. Already in the 19th century it was noticed, and in the following years corroborated, that the content of carbon in SOM varies depending on biochemical composition of SOM, hence the TOC-SOM conversing factors between the years 1880 and 2001 run from 1.3 up to 15, depending on the author and analyzed soils. Pribyl [9] states that these differences result from low precision in determining TOC in soils and the C content in SOM. From most of the works mentioned by Pribyl [9], it follows that the TOC-SOM conversion rate is 1.9. The rate of 2 results from theoretical considerations assuming that the C content in SOM is about 50%. However, Read [10] already in 1921 noticed that in SOM of the top soil layers, the content of carbon was about 50%, and in deeper horizons fell to even 20%.

A decrease in the C content in SOM deeper in the soil profile was also noted by other authors [1, 6, 11, 12]. Chabbi et al. [13] consider that variability of the C content in SOM in the soil profile may be caused by different contributions of particular compounds that form the SOM.

The possibility of estimating TOC and SOM contents based on the analysis of TOC or SOM has been and still is an object of study. Howard and Howard [1] established the TOC-SOM conversion by investigating regression between the contents of TOC and SOM in more than 500 soil samples. They found that values of regression coefficients for the TOC-SOM conversion varied depending on the soil type. De Vos et al. [3] determined the possibility of the SOM conversion as indicated by the LOI to TOC relation, on the basis of regression equation. According to the authors, the SOM-to-TOC conversion coefficient for the organic layer in coniferous forest is 0.571, whereas in a deciduous forest it amounts to 0.581.

Perie and Ouimet [6] also analyzed the regression between TOC and SOM in forest soils to a depth of 50-60 cm. The regression models indicated that the coefficients for the SOM-to-TOC conversion decreased with the soil depth.

The aim of our studies was to assess the TOC-SOM and SOM-TOC conversions on the basis of regression relations between SOM and TOC in soil horizons of 47 forest soil profiles.

Materials and Methods

In the previous work [14], we analyzed accumulation and distribution of soil carbon in 23 forest soil profiles in the following five areas: Lubsko (6 profiles), Janów Lubelski (3 profiles), Tuchola (3 profiles), Swornegacie (8 profiles), and Miłomłyn (3 profiles). In the study presented in this work we used soil samples collected during the previous investigation. Furthermore, soil samples were also taken in the following other three areas: Gubin (7 profiles), Spychowo (10 profiles), and Puszcza Borecka (7 profiles). In total, we analyzed ca. 250 soil samples collected from individual genetic soil horizons of 47 profiles, located in 8 different stands (Fig. 1). The selected plots represent four sites: dry pine forest, fresh pine forest, mixed coniferous-deciduous forest and mixed deciduous-coniferous forest.

The profiles were dug down to the clearly visible bedrock (100-120 cm). Description of soil profiles under each of the stands was made according to the Forest Soil Typology in Poland [15]. The following soil types were analyzed: Haplic Podzol at the Lubsko and Janów Lubelski plots, Albic Arenosol at the Gubin, Tuchola, Spychowo, and Swornegacie plots, Haplic Arenosol at the Miłomłyn and Puszcza Borecka plots. Description of the habitats and basic characteristics of the soils are presented in Table 1.

The soil samples were air dried, sieved through a 1-mm mesh, and pulverized. TOC was measured with a TOC-5000A autoanalyzer (Shimadzu model) by ignition at 1000ºC. The content of organic matter was determined using the loss-on-ignition (LOI) method, through heating 2-5 g of soil taken from the O, A, and AE horizons and 10 g

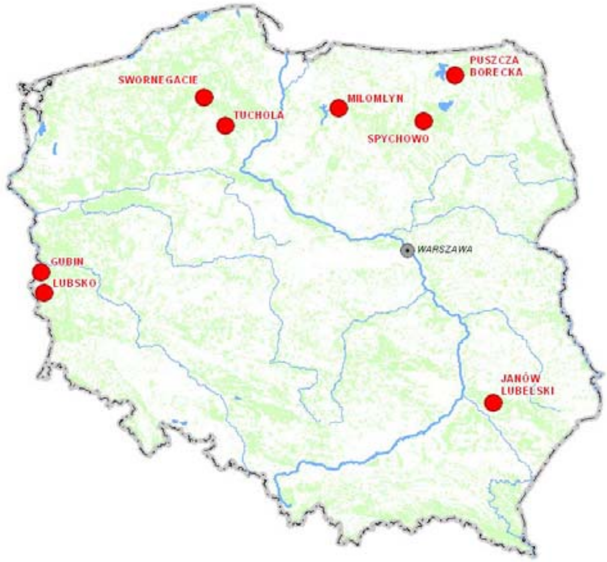

Fig. 1. Location of study plots.

Table 1. Description of studied area and selected properties of soil (mean values and variability coefficient in parentheses).

Site	Site type	Index site, stand quality class	Soil	Horizon	Thicknes s	Bulk density	pH	0.05-0.002	<0.002 mm
								%	%
					cm	$g \cdot cm^{-3}$	min-max	min-max	min-max
Lubsko	Dry pine forest *Cladonio-Pinetum*	low, IV	Haplic Podzol derived from sands of fluvial accumulation	O	5 (21)	0.12 (17)	3.3-4.3		
				AE	13 (28)	1.38 (3)	4.3-4.8	3-4	0-3
				Bfe	15 (32)	1.50 (5)	4.6-5.0	2-4	0-1
				BC	37 (40)	1.68 (2)		0-2	0
				C	n.d.	1.65 (2)		1	0
Gubin	Dry pine forest *Cladonio-Pinetum*	low, IV	Albic Arenosol derived from fluvioglacial sands	O	5 (30)	0.15 (10)	3.3-4.1		
				AE	9 (36)	1.33 (18)	3.7-4.4	2-3	1-2
				Bfe	19 (49)	1.46 (7)	4.4-4.7	3-5	1
				Bv	25 (32)	1.54 (5)	4.5-5.0	1-2	1
				BvC	30 (4)	1.63 (3)	4.5-5.0	2-4	0
Janów Lubelski	Fresh pine forest *Peucedano-Pinetum*	medium, III	Haplic Podzol derived from fluvioglacial and dune sands	O	5 (23)	0.13 (22)	3.3-3.7		
				AE	7 (44)	1.38 (9)	3.7-4.0	2-3	1
				E	7 (41)	1.55 (3)	4.5-4.7	1-2	1
				Bfe	13 (42)	1.48 (4)	4.6-5.0	1-2	0-1
				BC	40 (25)	1.65 (3)	4.8-5.1	0-1	0
				C	n.d.	1.64 (2)	n.d.	0	0
Tuchola	Fresh pine forest *Leucobryo-Pinetum*	low, IV/III	Albic Arenosol derived from outwash plain sands	O	4 (16)	0.11 (11)	3.5-4.3		
				AE	6 (31)	1.38 (7)	3.6-4.1	2-3	0-1
				Bv	16 (37)	1.58 (3)	4.4-4.7	1	0
				BvC	32 (22)	1.71 (4)	4.6-5.6	0-1	0
				C	n.d.	1.69 (1)	n.d.	0	0
Swornegacie	Fresh pine forest *Leucobryo-Pinetum*	medium, III/II	Albic Arenosol derived from glacial sands and gravels	O	5 (25)	0.16 (12)	3.5-4.5		
				AE	12 (45)	1.48 (7)	3.8-4.9	1-3	2-3
				Bv	23 (40)	1.66 (4)	4.7-5.6	1-3	2-3
				BvC	30 (35)	1.70 (3)	4.9-5.7	1-4	1
				C	n.d.	1.68 (3)	5.1-5.9	1-3	0
Spychowo	Fresh pine forest *Peucedano-Pinetum*	medium, III	Albic Arenosol derived from outwash plain sands	O	4 (19)	0.11 (17)	2.5-3.9		
				AE	10 (30)	1.28 (13)	3.8-4.1	1-3	1
				Bv	30 (15)	1.52 (8)	4.2-4.3	1-2	0
				BvC	28 (36)	1.60 (5)	4.5-5.0	1	0
				C	n.d.	n.d.	n.d.	n.d.	n.d.
Miłomłyn	Mixed coniferous-decidous forest, *Vaccinio-Piceetum*	high, II/I	Haplic Arenosol derived from fluvioglacial sands	O	3 (35)	0.12 (11)	4.0-4.2		
				A	10 (46)	1.26 (9)	4.0-5.0	4-6	1-2
				Bbr	13 (36)	1.47 (8)	4.9-5.2	3-4	1
				Bv	23 (28)	1.58 (5)	5.1-5.6	3-4	1
				BvC	37 (32)	1.61 (3)	5.5-5.9	1-3	0-1
				C	n.d.	1.56 (2)	n.d.	1-2	0
Puszcza Borecka	Mixed deciduous-coniferous forest, *Querco Piceetum*	high, II/I	Haplic Arenosol derived from glacial sands and loamy sands	O	1 (n.d.)	0.18 (n.d.)	3.8-4.3		
				A	10 (48)	1.19 (10)	4.5-5.0	9-12	1-4
				Bbr	16 (16)	1.50 (7)	5.0-5.5	6-11	1-4
				Bv	12 (20)	1.52 (4)	5.5-5.8	5-7	1-3
				BvC	20 (45)	1.61 (4)	5.5-6.0	3-7	1-3
				C	n.d.	1.67 (4)	n.d.	4-9	1-5

of soil from the B and C horizons at 450ºC in a muffle furnace for 4 hours. Previously, samples were dried at 105ºC and weighed to estimate water content. The loss of mass after ignition of the soil at 450ºC (decreased by the loss obtained after drying of the soil at 105ºC) was assumed as the SOM content in the analyzed soils. All analyses were carried out in duplicate in the accredited IOŚ-PIB laboratory.

The results were statistically analyzed. Taking into account similar characteristics of soils derived from sands that occur in habitats of coniferous forests, the analyses of relationships between SOM and TOC were characterized in relation to the distinguished soil horizons, excluding the types of soils and habitats.

Mean values and standard deviations (SD) were calculated to measure variability of examined traits. Pearson's correlation coefficient and simple linear regression were used for evaluation of relationships between pairs of traits. Level of significance for all analyses was set at $p<0.05$. Equations of regression TOC-to-SOM and SOM-to-TOC conversions were calculated for individual soil horizons. Next, if the differences between slopes of regression functions were not significant, the datasets were joined into groups of horizons. Comparisons of slopes of regression functions between the datasets were calculated using multiple regression. The analyses were performed using Statistica 9.0 software (StatSoft).

Results

The soils sampled in pine stands of dry pine, fresh pine, and mixed coniferous-deciduous forests are characterized by a low (0-6%) content of clay and silt. An exception are soils taken from the Puszcza Borecka plot with 1-5% clay and 3-12% silt particles. The soils examined are acidic, and pH in the upper layers is 3-4, while in the bedrock it increases to 5-6. Typologically they belong to Podzols and Arenosols (Table 1).

The TOC and SOM content decreases repeatedly from the O to C horizons, which is accompanied by an increase in the diversity in the C content within each horizon (from 14-20% in the O horizon to even 50-60% in the BvC and C horizons). This variation is not appreciable, taking into account that the samples were collected from 47 different profiles located in 8 different study areas (Table 2).

The Pearson's correlation coefficients between the TOC and SOM in the O, A, AE, and E horizons amount to 0.88-0.98 and decrease in the B horizons (Bbr, Bfe, Bv, BvC) to 0.75-0.90, and in the C horizon to 0.45, while the correlation coefficients are significant at the 0.05 level for all soil horizons (Table 3).

The linear regression equations of SOM=a+b·TOC and TOC=a+b·SOM showed that the regression coefficients (b) for TOC as a predictor of SOM in most soil horizons range from 1.80 to 2.26, while for Bbr horizon it amounts to 1.50 and for Bfe and BvC horizons they amount to 3.21 and 3.52, respectively. The regression coefficients for SOM as a predictor of TOC in the O, A, AE, and E horizons hover at ca. 0.5 (0.42-0.52), and from the Bfe horizon they decrease together with depth to 0.093 in the C horizon (Table 3).

Table 2. Mean values and standard deviations for TOC and SOM for soil horizons.

Horizon	n	TOC (%)	SOM (%)
Ol	7	43.54±5.97	82.64±13.76
Ofh	53	40.51±6.12	81.49±12.72
A	15	3.83±1.69	8.77±3.51
AE	44	1.45±0.64	2.84±1.21
E	8	0.55±0.17	1.15±0.32
Bbr	17	1.50±0.52	3.56±0.77
Bfe	14	0.70±0.20	2.41±0.71
Bv	39	0.39±0.12	1.40±0.32
BvC	21	0.10±0.05	0.58±0.21
C	26	0.06±0.04	0.41±0.18

Table 3. Regression and correlation coefficients and R^2 of regression between TOC and SOM for individual horizons.

Horizon	Conversion factors		R^2	Correlation coefficient
	TOC to SOM	SOM to TOC		
Ol	2.265	0.426	0.97	0.98
Ofh	1.826	0.423	0.77	0.88
A	1.975	0.459	0.91	0.95
AE	1.836	0.515	0.95	0.97
E	1.804	0.483	0.87	0.93
Bbr	1.503	0.444	0.67	0.82
Bfe	3.212	0.252	0.81	0.90
Bv	1.927	0.290	0.56	0.75
BvC	3.517	0.166	0.58	0.76
C	2.202	0.093	0.21	0.45

All correlations are significant at $p<0.05$

Next, the horizons were joined into groups and the regression equations were calculated. In the group of O, A and E horizons, with TOC contents from ca. 0.5 to 43%, the regression coefficient for TOC as a predictor of SOM is 1.985. In the group of diagnostic horizons (Bbr, Bfe, Bv) the regression coefficient for TOC as a predictor of SOM is 1.912, while in the group of BvC and C it amounts to 3.159 (Fig. 2). Values of R^2 for these functions decrease from the group of O+A+E horizons to BvC+C horizons.

The results show that in the ca. 20 cm deep soil layer (O, A, E horizons), the SOM-TOC conversion is defined by the equation: TOC = 0.498·SOM + 0.038. In the B diagnostic horizons (Bbr, Bfe, Bv), down to ca. 30-50 cm soil depth: TOC = 0.459·SOM - 0.258. In BvC and C horizons: TOC = 0.148·SOM + 0.003, but the contents of TOC and SOM are low, hence the R^2 value for the regression is lower than for other groups (Fig. 2).

The determined TOC and the one calculated on the basis of the regression equation for the horizon groups were compared (Fig. 3). Errors (residuals for regression) between determined and estimated TOC based on SOM to

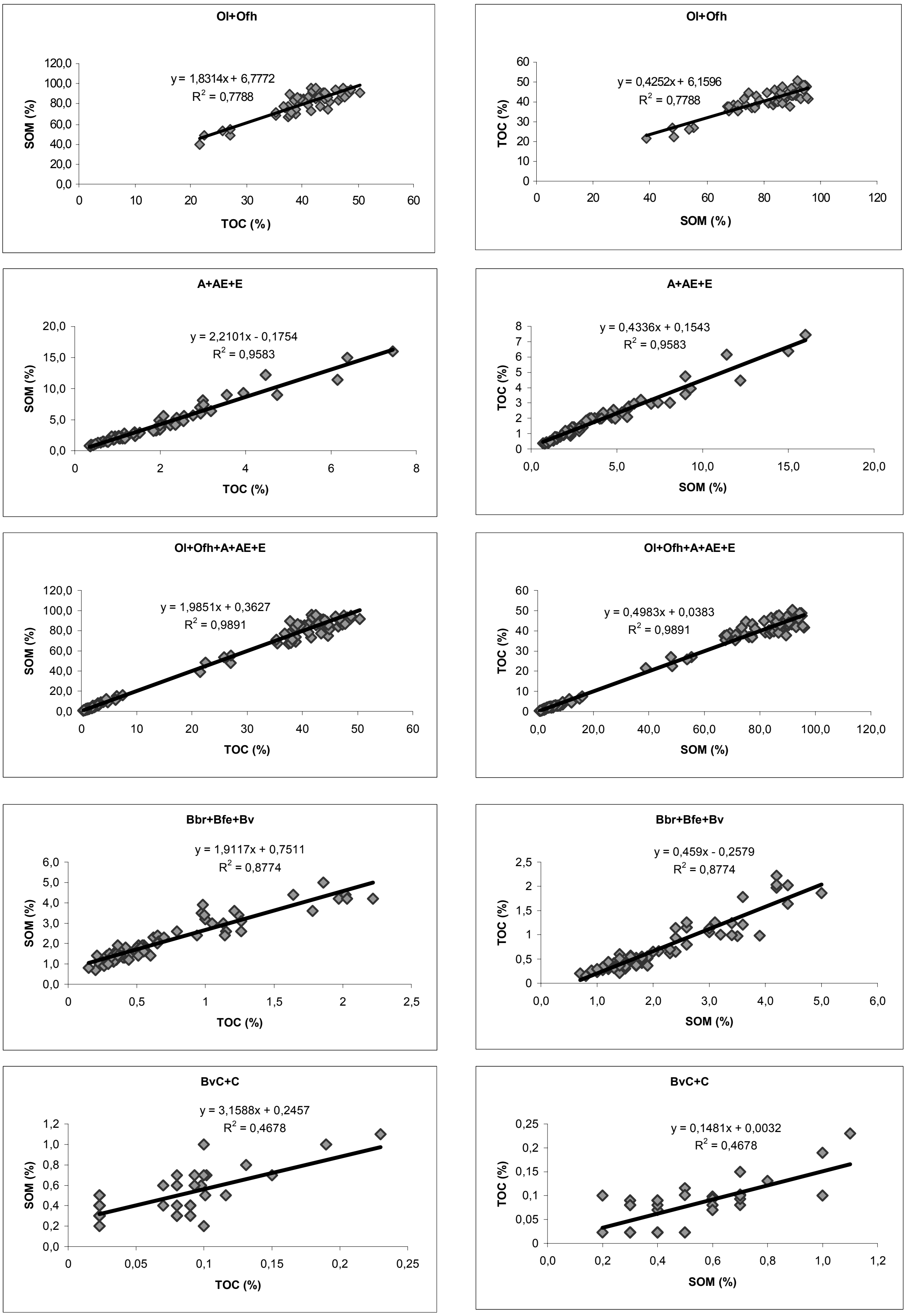

Fig. 2. Linear regression between TOC and SOM for joined horizons.

TOC conversion increase with the decreasing of TOC content with soil depth (Fig. 4).

The TOC/SOM ratio, which indicates the content of TOC in SOM, in the O, A, AE, and E horizons, runs from 0.45 to 0.55 and is similar to the value of the SOM-TOC conversion coefficient for these horizons. In the Bbr, Bfe, and Bv horizons the TOC/SOM ratios amount to 0.3-0.4, while in the BvC and C horizons it decreases to the value 0.15, which corroborates C content in SOM decreases with soil depth. The value of SOM/TOC ratio increases from ca. 2 in the O, A, AE, and E horizons to even ca. 10 in the C horizon (Fig. 5).

Discussion

Estimation of the SOM content in soils on the basis of TOC content has been used for over 100 years [9]. The TOC to SOM conversion is based on the content of carbon in organic matter, which was and still is controversial since the SOM is a mixture of various compounds having different carbon contents. According to Schnitzer [quotation taken from 9], lipids have the highest carbon content, but its share in the mass of SOM is low (2-6%). Fulvic acids have the highest share in SOM, followed by humic acids, whose C content varies from 30 to 60%. The share of various compounds in SOM depends on the initial material flowing into the soil, the degree of its decomposition, soil forming processes and other factors that influence the intensity of these processes. These interrelations manifest themselves in the variability of SOM carbon content in different soil types developed from various materials, as well as in respective soil horizons in the soil profile [1, 3, 6, 9, 11, 13].

The authors [9, 13] associate the variability of carbon content in SOM mainly with the biochemical composition of SOM, i.e. with the share of compounds having different C content. In our investigation we noticed that in the soil layer between 0 and ca. 20 cm (which consists of the O, A and E horizons), the C content in SOM is ca. 50%, in the B horizons the C content runs from 30 to 40%, and in the BvC horizon it is 28%. Decrease of the C content in SOM in the soil profile also was observed by Jain et al. [11], Varvel et al. [12], and Chabbi et al. [13].

Our previous study showed that in forest soils of coniferous sites, ca. 70% of carbon stock is accumulated in the

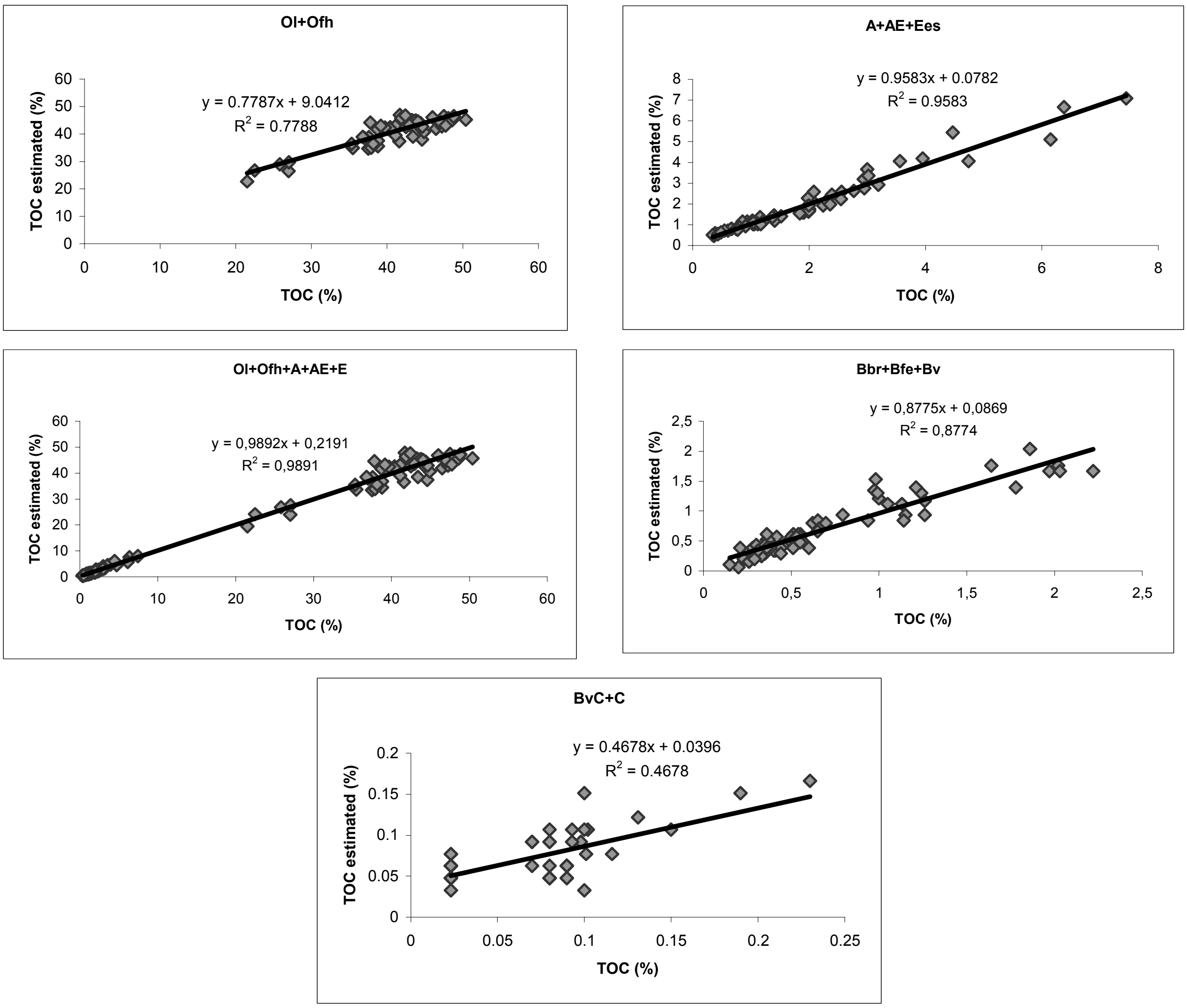

Fig. 3. Linear regression between determined TOC and estimated TOC based on SOM for joined horizons.

O, A, and E horizons and the next 20% in the diagnostic B horizons. At the same time the amount of soluble C increases together with the depth in relation to its total content. This suggests a reduction of C content in SOM with the depth of soil profile [14]. Some authors suggest that the impoverishment of SOM in carbon, especially for the low C content in soil, may be an artifact caused by low precision of the TOC and SOM determination method [3, 9]. Our results also show that together with the decrease in TOC with the depth of soil profile, there is an increase in the coefficient of variation as well. However, the decreasing tendency of C content in SOM with the depth of soil profile appeared. De Vos et al. [3], based on the assessment of accuracy of the SOM determination by the LOI method and TOC determination by the dry combustion method, noted that both methods are comparable; however, standard deviations are higher when TOC content is lower.

The conversion coefficients TOC-to-SOM estimated on the basis of the C content in SOM ranged over the last 120 years from 1.35 to 14.1, depending on TOC determination methods, soil properties, depth and method of soil sampling, and other factors [9]. The relationship between SOM and TOC is generally calculated by regression equations. Howard and Howard [1] obtained the regression coefficient of 1.670 for the TOC to SOM conversion in the upper soil layer and 1.678 in the deeper layers. De Vos et al. [3] estimated that the regression coefficient for SOM to TOC conversion in the forest floor layer of coniferous sites was 0.571, 0.581 in deciduous sites, and in mineral soils it amounted to 0.5783. When soil sampling depth and the content of clay particles in the soils were additionally taken into account, the regression coefficient was 0.5786. De Vos et al. [3] emphasized that these results were similar to those achieved by other authors.

Values of the linear regression coefficients for the conversion TOC (dry combustion) to SOM (LOI) obtained by us run from 1.503 to 3.517, and for the conversion SOM to TOC run from 0.093 to 0.515, depending on the soil horizon (Table 3). After grouping the horizons, the regression coefficient for the conversion of TOC to SOM in the 0-20 cm layer (O, A, E horizons) amounts to 1.985, and for the conversion of SOM to TOC is 0.498, while in the layer to the depth of 30-50 cm (B horizons) these coefficients are 1.912 and 0.459, respectively, and in the deeper occurring horizons (BvC and C) they amount to 3.159 and 0.148, respectively (Fig. 2).

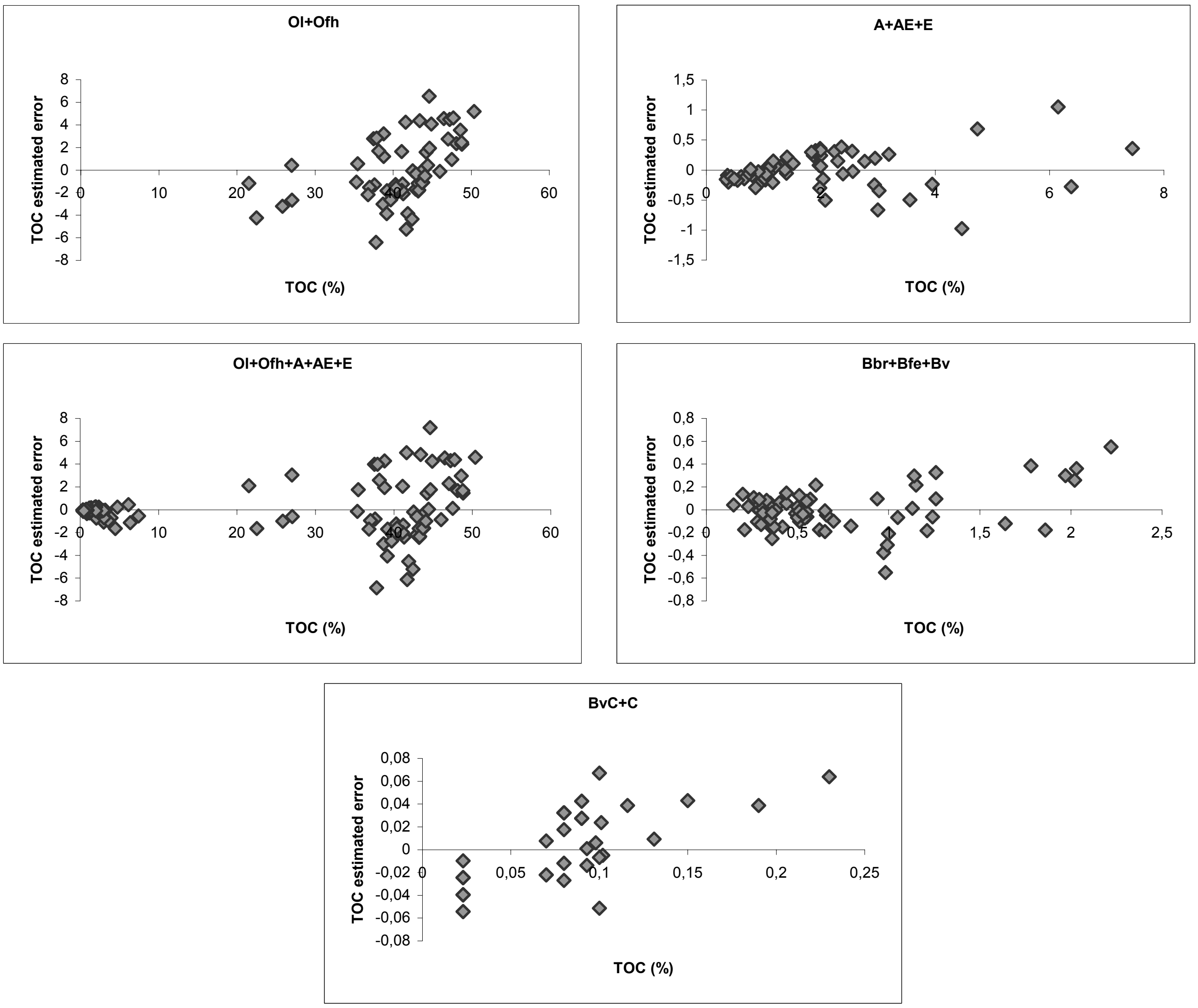

Fig. 4. Errors (residuals for regression) between determined TOC and estimated TOC based on SOM for joined horizons.

Perie and Ouimet [6], based on the analysis of 1,000 forest soils sampled in different habitats, also established that the regression coefficient for the SOM (LOI) to TOC (DC) conversion in soils to a depth of 25 cm run from 0.4908 to 0.4282, at a depth of 25 to 40 cm from 0.3982 to 0.3687, and at a depth of 50 cm the regression coefficient is 0.2712. Varvel et al. [12], based on analyses of cultivated soils, noted that the regression coefficient for the SOM-TOC conversion in the arable layer is 0.451 and decreases with soil depth.

Our results are most similar to the results obtained by Perie and Ouimet [6], despite differences in habitats, stands and soil types. This similarity is probably due to the similarity of materials from which the soils were developed in both cases, and also due to the fact that similar soil layers were taken into consideration.

In our soils, which are derived from sands, with pH <5 and a very low clay content, it is possible to assume that the TOC-to-SOM conversion coefficient for the layer comprising the O, A and E horizons is ca. 2 (1.99), and for the SOM-to-TOC conversion it amounts approximately to 0.50, whereas for the B diagnostic horizons these coefficients approximate the values of 1.91 and 0.46, respectively.

Differences between the determined TOC and the TOC calculated on the basis of regression equations are within the standard deviation for the average determined content. Similar results were obtained by De Vos et al. [3].

According to Pribyl [9], the conversion coefficients are not and cannot be universal, suffice to take into consideration the soil, climate and methodical differences, but they may and should be regionally defined. Similar conclusions were drawn by Abella and Zimmer [16].

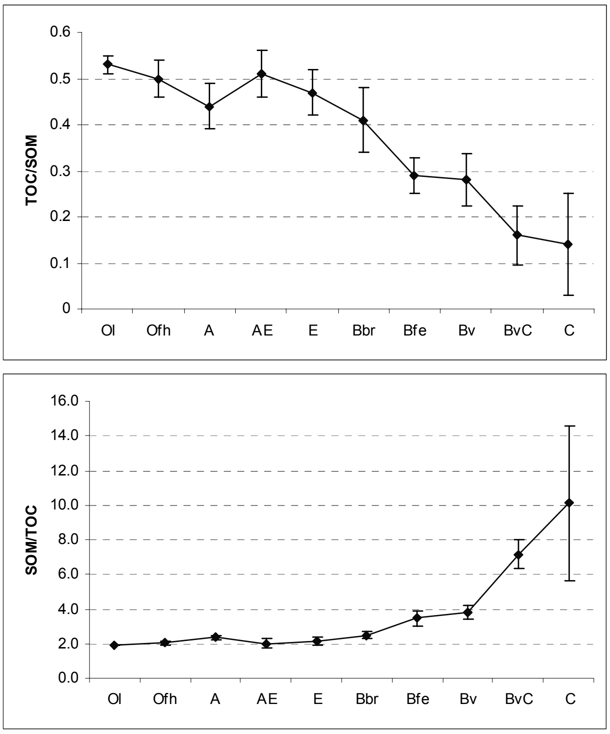

Fig. 5. Relationships between TOC/SOM and SOM/TOC by horizon.

Conclusions

The relationship between TOC and SOM in sandy forest soils with a low clay content and pH < 5 is found to be significant for the soil horizons to the depth of 30-50 cm and less significant in the underlying soil horizons.

In the horizons O, A, and E (soil layer to 20 cm depth), the TOC-to-SOM conversion is defined by the regression: SOM = 1.985·TOC + 0.363, while the SOM-to-TOC conversion by the regression: TOC = 0.498·SOM + 0.038 (R^2 = 0.99). In the B diagnostic horizons (soil layer to 30-50 cm) the equations are defined respectively: SOM = 1.912·TOC + 0.751 and TOC = 0.459·SOM + 0.258 (R^2 = 0.88) (Fig. 2).

In the forest soils derived from sands and clayey sands the TOC content may be estimated by determining the SOM content, and inversely. This is possible for the soil layer where more than 90% of carbon stock is accumulated (down to ca. 50 cm). This has an important practical implication for the determination of SOM by LOI method, as it is simple and cheap. Moreover, in the LOI method the soil sample appears to be more homogenous and representative, since samples of a mass of 3-5 g (or even 10 g) are used as compared to the TOC determination, where samples with a mass lower than 1 g are used. Small sample sizes used with TOC determination may contribute to the variability of results in soils with very low carbon contents.

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