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Pedoecological Regularities of Organic Carbon Retention in Estonian Mineral Soils

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Abstract

Soil organic carbon (SOC) retaining capacities of epipedon (EP), subsoil (SS) and soil cover (SC) as a whole, are soil type specific. Depending on individual and sites characteristics, the generalized humus status indices of soil types (EP and SC thickness and SOC stocks) may vary. Land use and land use change primarily influence the properties and fabric of the EP, but the humus status (SOC concentration and stock, fabric of horizons) of the SS remains practically unchangeable. The mean mineral soils SOC stocks, EP quality and SOC distribution in soil profiles depend mainly on the water regime, mineral composition (texture, calcareousness), development of eluvial processes and the land use peculiarities of soils. The mean area weighted SC SOC stock of Estonian mineral soils is 99.9 Mg ha^{-1}, thereby the mean hydromorphic soils SOC retention capacity considerably exceeds the SOC retention capacity of automorphic soils (means are accordingly 127.5 and 78.9 Mg ha^{-1}). The sustainable management of SOC is based on adequate information about actual SOC stocks and theoretically established or optimal humus status levels of soil types. The aggregate of SOC retained in the mineral soils of Estonia (3,235,100 ha) amounts to 323 ± 46 Tg (1 Tg = 10^{12} g). Approximately 42% of this is sequestered into stabilized humus, 40% into instable raw-humous material and 18% into forest (grassland) floor and shallow peat layers.

Keywords: Carbon Retention Capacity, Land Use, Mineral Soils, Pedoecological Regularities

1. Introduction

Soil organic carbon (SOC) is retained in the soil profile and its horizons in different forms and states and, largely, determines soil functioning and development [1-3]. A prerequisite for the pedoecological study of SOC cycling and dynamics is the quantification of SOC storage by soil types, especially in those soil layers in which most soil organic matter (SOM) is accumulated [4,5]. Every soil type has specific SOC flow throughout the soil cover (SC) depending on ecological conditions [6,7]. The features characteristic of certain soil types may differ in SOC stocks and cycling intensity, in soil edaphon activity, and in vertical distribution of the humus profile [4,8, 9]. Differences also exist in, for example, input composition (biochemical, ash content), in input dynamics, in characteristics of transformation, and in the residence time of SOM in soil [5,8]. Several studies [10-12] have clarified that SOC-retaining capacity depends on the soil moisture regime, clay and carbonate content in fine earth, and on the character of soil management. In comparative analyses and evaluation of local soils SOC-retaining potential, the generalized soil types SOC densities and total stocks of SC received in various ecological regions [13-16] were necessary for our work.

In our previous work, the soil humus status (or functioning of soil in relation to SOC stocks and cycling) was treated separately in arable [17], forest [18] and grassland [19] soils. In these works, the basic characteristics of soil humus status were the thickness and fabric of the epipedon (EP) layer and SC, stocks and concentrations of SOC (and SOM) in different soil horizons and layers, and humus quality, determined by EP types. The main tasks of the actual study were: 1) to generalize the data about SOC stocks by soil types, 2) to analyse the influence of land use change on SOC retention in soil, 3) to elucidate the generalized pedoecological regularities of SOC retention in soil and management, and 4) to identify the share of mineral soils in total Estonian SOC storage.

2. Materials and Methods

2.1. Materials

The sources of the quantitative characteristics of soils and their organic carbon contents were created by using the databases PEDON (characterizing soil profiles by genetic horizons) and CATENA (transects established for research of soil humus status). PEDON was compiled initially in 1967-1985 and was updated twice, in 1986-1995 and 1999-2002. CATENA was developed during field studies from 1987-1992. The bulk density samples used in our study equate to approximately one-tenth of PEDON's and CATENA's soil profiles. Data on Estonian soils' humus status (thicknesses of layers and SOC stocks) in different soil and land use types [17-19], as well as soil productivity and EP types, are taken from our previous papers [20].

2.2. Methods

The study used the macro-morphological quantitative approach (individual soil profiles are characterized on the basis of soil samples taken by soil genetic horizons) to measure SOC stocks in soils. The basic characteristics of soil humus status in our work are the thickness and fabric of EP and SC, and concentrations and stocks of SOC in different horizons of soil profiles. For this study the soil horizon data were generalized in relation to: 1) the EP (including forest floor), 2) the SC, and 3) the subsoil (SS), which were arrived at by subtracting data (X) of EP from SC,

$$X_{SS} = X_{SC} - X_{EP} \quad (1)$$

The SOC stocks were calculated on the basis of bulk density and SOC concentrations (g kg^{-1}) of soil samples (determined by Tjurin [21]), taking into account the presence of coarse fractions in soil horizons. In calculating total stocks by soil types and groups, the soil distribution data received in the course of large scale mapping (1:10,000) were used [22]. The names of soil groups correspond to the World Reference Base for Soil Resources (WRB) [23]. Applying program Statistica 7, two-way Analysis of Variance followed by the Student test of homogenous groups was used to analyse the data.

2.3. Pedoecological Conditions

The climatic conditions of Estonia are typical of the temperate-zone of the Atlantic-continental region, with an annual average air temperature +4 – 6°C and a precipitation rate of 500 – 700 mm [24]. The dominant pedoclimatic conditions are therefore *frigid-udic* and *frigid-aquic* [25]. The principal texture of mineral soils (covering 76% of the Estonian territory) is loam (28%), sand (26%), sandy loam (17%) and clay (5%) [22]. Wet (*aquic*) soils equate to 36% of Estonia's mineral soils, followed by normally moist or fresh (*udic*) soils (23%), moist or endogleyic (15%) and dry (*aridic*) soils (2%). The study did not include organic soils, which form 24% of Estonia's soil cover.

2.4. Areas

As contemporary soil distribution data by land use are unavailable, the study involved the area of forest, arable and grasslands for 1993-1998, a period of stable land-use. At that time, the total area of mineral soils in forest, arable and grasslands measured 2,566,700 ha. The distribution percentage of mineral soils by soil groups and of soil groups by land use are presented in **Table 1**. From

Table 1. Studied mineral soil groups and their distribution by land use.*

Group No	Soil or soil association	Soil code by WRB	% from F + A + G area**	Forest	Arable	Grassland
				soils, in % from soil group area		
I	*Rendzic & Skeletic & Gleyic Leptosols*	LP rz sk gl	1.8	35.4	20.0	44.6
II	*Mollic & Endogleyic&Calcaric & Endoskeletic Cambisols*	CM mo gln ca skn	18.1	28.3	62.4	9.3
III	*Cutanic & Endogleyic Luvisols*	LV ct gln	9.2	20.6	65.0	14.4
IV	*Glossic & Gleyiglossic Albeluvisols*	AB gs gsg	12.8	22.3	74.0	3.7
V	*Haplic & Endogleyic Albeluvisols*	AB ha gln	6.5	51.9	35.2	12.9
VI	*Haplic & Endogleyic Podzols*	PZ ha gln	4.7	100.0	0.0	0.0
VII	*Mollic & Calcic & Eutric Gleysols*	GL mo cc eu	15.4	62.0	29.7	8.3
VIII	*Luvic & Epidystric Gleysols*	GL lv dyp	9.3	68.2	27.7	4.1
IX	*Spodic & Umbric & Dystric Gleysols*	GL sd um dy	7.9	91.6	4.4	4.0
X	*Saprihistic Gleysols*	GL his	6.4	65.3	17.3	17.4
XI	*Fibrihistic Podzols*	PZ hif	2.5	99.5	0.0	0.5
XII	*Eroded Cambisols & Regosols*	RG & CM *eroded*	1.8	0.0	74.0	26.0
XIII	*Deluvial Cambisols & Luvisols*	CM&LV *deluvial*	1.5	0.0	70.9	29.1
XIV	*Eutric & Epigleyic & Histic Fluvisols*	FL eu glp hi	1.5	45.3	6.1	48.6
XV	*Salic Gleysols & Fluvisols*	GL & FL sz	0.6	37.7	0.0	62.3
Total (%),			100.0%	49.6%	40.3%	10.1%
(km^2)			25,667	12,718	10,346	2,603

*Data taken from [22]; **Sum of forest, arable and grassland areas.

the aggregate area of mineral soils the postlithogenic (soil groups I – XI) and synlithogenic mineral soils (groups XII – XV) form correspondingly 94.7% and 5.3%, as divided by Fridland [26]. The share of synlithogenic soils is different by land use, forming 1.7% from forest, 6.2% from arable and 19.1% from grassland areas.

Calculation of total SOC storage on the basis of the recent period of stabilized land use areas (25,667.0 km^2) is justified by the fact that changes in soil properties related to land use changes take several years to be discernible, especially in Nordic areas [27]. There has also been a notable land use changes in the last 15 years [28]. By our estimation, on the basis of different additional information [29], the area with uncertain management of mineral soils is ~6,684.0 km^2. Therefore the total area of Estonian mineral soils is 32,351.2 km^2, which forms 76.3% of the total SC of Estonia.

2.5. Used Terms

The EP (epipedon or topsoil or humus cover) consists of the forest floor (or organic horizon) and/or of humus, raw-humus and peat (*histic*) horizons. The EP embraces the most active soil component, which is closely coupled with plant cover and via which the cycling of the main part of organic carbon takes place. The term EP therefore conjoins different classical soil horizons (organic, humus, raw humus, peat) into one soil layer. The term SC (soil cover or pedon or solum) encompasses the superficial earth layer or total (actual) soil resource influenced by soil forming processes. Therefore the SC consists of EP and SS (eluvial (E) and illuvial (B) horizons). The thickness of the SC is the depth from the surface to the unchanged parent material or C horizon or to the boundary between B and C horizons (in the presence of BC horizon — to the middle of the BC horizon). The SOC retaining capacity, given in SOC weight per area in relation to a certain layer (Mg ha^{-1}), is the amount of SOC which a soil with certain properties is able to retain or capture in conditions of equilibrated soil functioning. In some work the above mentioned parameter is defined as soil carbon density [16].

3. Results

3.1. Thickness of EP and SC

In order to generalize the soil humus status characteristics, 15 mineral soil groups from forests, arable and semi-natural grasslands were tabulated (**Table 2**). The mean EP thickness of soil groups in the study is mostly between 21 – 26 cm. Thinner EP occurs in *Podzols* in which the humus horizon is absent, and in very young coastal soils (soil group XV). Relatively thin EP is also characteristic of strongly podzolized epigleyic soils (groups IX and XI). The thickest EP is characteristic of deluvial or colluvial soils formed by sediment accumulation.

Table 2. Thickness of epipedon (EP) and soil cover (SC) of mineral soils and their comparison by land use.*

Group No	Soil code by WRB	n**	Comparison of EP thicknesses***, (cm)			Mean EP thickness****, (cm)	Comparison of SC thicknesses***, (cm)			Mean SC thickness****, (cm)
			F/A	F/G	A/G		F/A	F/G	A/G	
I	LP rz sk gl	7/12/8	< (4)	< (3)	=	19.0 [cd]	≥ (2)	≥ (4)	=	23.3 [a]
II	CM mo gln ca skn	20/46/10	< (7)	< (5)	> (2)	25.8 [ef]	=	=	=	47.8 [c]
III	LV ct gln	11/8/ -	≤ (7)	—	—	25.6 [ef]	=	—	—	74.2 [fg]
IV	AB gs gsg	18/13/ -	< (7)	—	—	22.3 [de]	=	—	—	92.6 [h]
V	AB ha gln	26/21/8	< (7)	< (3)	> (4)	20.9 [d]	=	=	=	74.3 [f]
VI	PZ ha gln	27/ - / -	—	—	—	5.0 [a]	—	—	—	64.1 [e]
VII	GL mo cc eu	8/6/17	> (4)	≤ (2)	< (6)	25.9 [ef]	=	=	=	39.8 [b]
VIII	GL lv dyp	16/4/3	≤ (1)	≥ (6)	≥ (7)	25.0 [ef]	=	> (18)	> (17)	55.2 [cde]
IX	GL sd um dy	8/2/ -	≤ (7)	—	—	15.6 [c]	≤ (30)	—	—	76.0 [fg]
X	GL his	5/1/ -	≥ (5)	—	—	21.6 [def]	≥ (18)	—	—	46.9 [bcd]
XI	PZ hif	13/ - / -	—	—	—	14.8 [bc]	—	—	—	75.8 [fg]
XII	RG & CM *eroded*	- /168/ -	—	—	—	24.1 [ef]	—	—	—	54.2 [d]
XIII	CM & LV *deluvial*	- /154/ -	—	—	—	43.6 [g]	—	—	—	79.6 [g]
XIV	FL eu glp hi	- / - /14	—	—	—	26.2 [ef]	—	—	—	37.2 [b]
XV	GL & FL sz	- / - /8	—	—	—	9.8 [ab]	—	—	—	15.3 [a]

*Mean thicknesses of EP and SC - for forest [18], arable [17] and grassland soils [19]; **Number of studied soil profiles accordingly in forest, arable and grasslands; ***F - forests, A - arable and G - grasslands; > and < indicate significant ($p < 0.05$) difference and mutual relationship; ≥ and ≤ non-significant ($p > 0.05$) difference, and = the absence of significant difference or the means are very similar; ****Letters following the mean indicate significant differences at $p < 0.05$.

The thickness of mineral soils' SC is mostly between 40 – 80 cm, with a standard deviation of 8 – 25 cm (coefficient of variability (CV) 18–30%). Thinner soils are *Leptosols* (*skeletic, rendzic*), *Fluvisols* (*salic*) and *Gleysols* formed in coastal areas; some poorly developed *Gleysols,* and *Regosols* form in severely eroded arable areas. The CV of shallow soil thicknesses is 40% in most cases. The greatest thickness is characteristic of *Glossic Albeluvisols* and some deluvial soils' SCs. The comparison of EP and SC thicknesses by land use indicates that in most cases the arable soils' EP is significantly thicker than that of forest soils. In the case of SC thicknesses, no substantial difference between natural and cultivated soils was established or, their SC thicknesses are equal and depend more on soil type peculiarities than on land use.

3.2. SOC Stocks of EP and SC

EP SOC stocks, in automorphic soils, vary between 16 – 80 Mg ha^{-1} (**Table 3**). Significantly smaller ($p < 0.05$) SOC stocks accumulate in the EP of automorphic *Podzols* and arable soils degraded by erosion (soil group XII). EP SOC stocks are slightly larger in soils with higher carbonate and clay contents. The EP SOC stocks that accumulate in hydromorphic *Gleysols* and *Fluvisols* (110 – 115 Mg ha^{-1}) are significantly greater ($p < 0.05$) compared with automorphic soils. Exceptions among these hydromorphic soils are strongly podzolized epigleyic soils (groups IX and XI) and moderately developed coastal soils (group XV). Relatively large stocks of SOC are also accumulated in different kinds of deluvial soils (group XIII), but the largest stocks are characteristic of *Sapric Gleysols,* whose EP is composed of *sapric* peat.

SOC retention in mineral soils' SC depends largely on SS thickness and its capacity to retain SOC. The largest SOC stocks in the SS (58 – 70 Mg ha^{-1}) are characteristic of strongly podzolized epigleyic soils (groups IX and XI), in which the humus-illuvial B horizon (Bh) is formed. The smallest SS SOC stocks (5 – 8 Mg ha^{-1}) are characteristic of thin *Leptosols* and of different coastal and eroded soils. The medium range of SOC stocks occur in well-aerated automorphic and deluvial soils' SS (within limits of 25 ± 3 – 4 Mg ha^{-1}) and in *Gleysols* (on average 12 – 15 Mg ha^{-1}). The mean of SOC stock densities in SC are, therefore, smallest in eroded soils and *Podzols* (45 Mg ha^{-1}) and largest in *saprihistic* soils (190 Mg ha^{-1}). SOC stocks in most automorphic and hydromorphic soils are within the limits of 65 – 90 Mg ha^{-1} and 95 – 130 Mg ha^{-1}, respectively.

3.3. Aggregate SOC Stocks in Estonian Mineral Soils

A total of 323 ± 46 Tg (10^{12} g) SOC is retained (**Table 4**) in mineral soils of Estonia. The largest proportion of SOC stock (42%) is situated in forest, 28% in arable, 9% in grassland and 21% in other soils. Aggregate stock of SOC is bound into the forest floor, stabilised soil humus (humus, eluvial and illuvial horizons), raw-humus material and peat or into the SOM situated in different soil profile horizons. The stabilized humus, formed in conditions of *udic* soil moisture regime equates, by our estimation, to ~42% of the mineral soils' total SOM. Approximately 40% is sequestered into raw-humus SOM and the balance, 18%, into forest floor and shallow peat layers, 75% of the total SOC stock is situated in the EP or the active layer and 25% in the SS.

Table 3. Stocks of SOC of epipedon (EP) and soil covers (SC) of mineral soils and their comparison by land use.*

Group No	Soil code by WRB	n**	Comparison of EP SOC stocks*** (Mg ha^{-1})			Mean SOC stocks in EP****, (Mg ha^{-1})	Comparison of SC SOC stocks*** (Mg ha^{-1})			Mean SOC stocks in SC****, (Mg ha^{-1})
			F/A	F/G	A/G		F/A	F/G	A/G	
I	LP rz sk gl	8/12/8	=	=	=	66.7^{d}	> (24)	≥ (29)	=	74.9^{bc}
II	CM mo gln ca skn	22/46/10	=	< (32)	< (31)	67.8^{d}	=	≤ (25)	≤ (27)	89.8^{c}
III	LV ct gln	12/8/ -	≥ (13)	—	—	69.1^{de}	=	—	—	92.6^{cd}
IV	AB gs gsg	19/13/ -	≤ (7)	—	—	44.6^{c}	≤ (5)	—	—	67.1^{b}
V	AB ha gln	28/21/8	≤ (5)	≥ (4)	≥ (9)	45.0^{c}	≤ (7)	≥ (9)	> (16)	70.0^{b}
VI	PZ ha gln	31/ - / -	—	—	—	16.3^{a}	—	—	—	44.5^{a}
VII	GL mo cc eu	15/6/17	> (39)	=	≤ (44)	110.0^{f}	> (37)	=	≤ (41)	122.4^{e}
VIII	GL lv dyp	16/4/3	=	≥ (44)	≥ (57)	115.1^{f}	=	=	=	128.8^{e}
IX	GL sd um dy	7/2/ -	≥ (5)	—	—	37.2^{abc}	≥ (60)	—	—	95.5^{cd}
X	GL his	5/1/ -	=	—	—	155.9^{g}	=	—	—	191.1^{f}
XI	PZ hif	13/ - / -	—	—	—	44.8^{bc}	—	—	—	114.5^{de}
XII	RG & CM *eroded*	- /168/ -	—	—	—	29.5^{b}	—	—	—	36.6^{a}
XIII	CM & LV *deluvial*	- /154 / -	—	—	—	80.5^{e}	—	—	—	105.3^{d}
XIV	FL eu glp hi	- / - /14	—	—	—	110.3^{f}	—	—	—	125.1^{e}
XV	GL & FL sz	- / - /8	—	—	—	51.0^{cd}	—	—	—	56.5^{ab}

*Mean SOC stocks of EP and SC - for forest [18], arable [17] and grassland soils [19]; **Number of studied soil profiles accordingly in forest, arable and grasslands; ***F - forests, A - arable and G - grasslands; > and < indicate significant (p < 0.05) difference and mutual relationship; > and < non-significant (p > 0.05) difference, and = the absence of significant difference or the means are practically equals; ****Letters following the mean indicate significant differences at < 0.05.

Table 4. Total SOC stocks in Estonian mineral soils (Tg ± SE*).

Characteristics**	Automorphic soils	Hydromorphic soils	Totally F + A + G soils	All mineral soils of Estonian SC
Forest land, (10^3 ha)	489.7	782.1	1271.8	-
Arable land, (10^3 ha)	813.0	221.6	1034.6	-
Grasslands, (10^3 ha)	154.3	106.0	260.3	-
Total, (10^3 ha)	1457.0	1109.7	2566.7	3235.1
Forest soils stock, (Tg)	35.5 ± 4.2	101.9 ± 13.5	137.4 ± 17.7	-
Arable soils stock, (Tg)***	65.8 ± 5.5	25.4 ± 8.0	91.2 ± 13.5	-
Grasslands soils stock, (Tg)	13.7 ± 2.2	14.2 ± 3.3	27.9 ± 5.5	-
Total SOC stocks in SC, (Tg)	115.0 ± 11.9	141.5 ± 24.8	256.5 ± 36.7	323.2 ± 46.2
Total SOC stocks in EP, (Tg)	81.3 ± 10.7	111.3 ± 24.3	192.6 ± 35.0	242.7 ± 44.2
Total SOC stocks in SS, (Tg)	33.7	30.2	63.9	80.5
Mwa SOC density of SC, (Mg ha^{-1})	78.9	127.5	99.9	99.9
Mwa SOC density of EP, (Mg ha^{-1})	55.8	100.3	75.0	75.0
Mwa SOC density of SS, (Mg ha^{-1})	23.1	27.2	24.9	24.9
Mwa SOC density of SC of forest soils, (Mg ha^{-1})	72.5	130.3	108.0	-
Mwa SOC density of SC of arable soils, (Mg ha^{-1})	80.9	114.6	88.2	-
Mwa SOC density of SC of grassland soils, (Mg ha^{-1})	88.8	134.0	107.2	-

*Sum of Standard Error; **Abbreviations: Mwa – weighted (by area) mean; SC – soil cover; EP – epipedon, and SS – subsoil; ***The SOC stocks in soil groups XII-XIV supplemented the preliminary data [17] used in calculating the aggregate SOC stocks in arable soils.

The share of automorphic and hydromorphic (situated mostly on lowland) soils in the aggregate SOC storage of mineral soils is 45 and 55% respectively. This is inverse to the share of these soils' areas, which are accordingly 57 and 43%. The data indicate that the SS of hydromorphic soils is relatively poorer in SOC compared to automorphic soils. The share of postlithogenic mineral SC in the sequestration of SOC stocks (94%) is almost total compared to the role of synlithogenic mineral SC (6%).

The area weighted average EP SOC density of hydromorphic soils exceeds the rate of automorphic soils by 1.8 times (**Table 4**). Although the EP thickness of forest soils is significantly smaller than in arable soils, another important influencing factor — the SOC concentrations of forest soils — is generally higher, and consequently, the SOC stocks in EP and SC may be approximately similar in forest and arable soils [17,18].

3.4. Comparative Analysis of Soils' Humus Status

Although some aspects of soil humus status peculiarities were explained on the basis of data given in **Tables 2** and **3**, more comprehensive humus data are presented in **Table 5**. For characterization of soils' humus status differences in connection with land use, the adequate sets were formed separately from forest and arable soils for auto- and hydromorphic soils. The same schema was used for comparative analysis in the humus status of calcareous and non-calcareous soils. The humus status differences between auto- and hydromorphic soils are given in the last section of **Table 5**. Using formula (1) also allows easy determination of the average (weighted by profile number) SS humus status parameters (thickness and SOC stock). The mean data in **Table 5** are weighted by the number of profiles, which are slightly different from the area weighted means (**Table 4**). Only the area weighted means were used for modelling and as benchmarks. But by profile number weighted means are more convenient in explaining influences of land use change, moisture conditions and soil calcareousness on SOC-retaining capacity.

4. Discussion

4.1. Pedo-Ecological Regularities of SOC Sequestration

The generalized area weighted SOC stock density' means of SC, EP and SS may be taken as benchmarks (standards, model contents) in comparative analysis of the SOC retention capacities of different land covers. The SOC-retaining capacity of soil depends on soil type characteristics (EP thickness, moisture regime, texture and carbonate content) and soil management. Smoothed and interpolated by soil types and land use on the background of Estonian postlithogenic mineral soil matrices, the isolines of SOC densities and concentrations may be taken as preliminary humus status parameter standards for different soil types [17,18].

Another aspect in analyses of SOC density levels is treating them according to their primary determining SOC densities properties. For example, a high role in determination of SC SOC stocks belongs to the EP thickness (**Figure 1(a)**). A good correlation ($r = -0.63$, $n = 283$, $p < 0.001$) exists between SOC stocks and cation exchange capacity (CEC, kmol ha^{-1}) of the EP (**Figure 1(c)**). SOC stocks of SC depend not so much on SC depth, as on SS texture, which is expressed by the index of specific surface area (**Figures 1(b)** and **1(d)**).

Table 5. Comparative analysis of soils humus status by land use, soil moisture conditions and calcareousness.

Soil group, characteristic	Indice*	Automorphic soils					Hydromorphic soils				
		n	Thickness (cm)		SOC stocks (Mg ha^{-1})		n	Thickness (cm)		SOC stocks (Mg ha^{-1})	
			EP	SC	EP	SC		EP	SC	EP	SC
Forest soils	Mwp	79	20.0	72.4	52.3	76.4	39	22.0	63.2	103.9	134.0
	SE		0.77	2.70	4.0	4.2		1.01	2.94	9.6	9.1
Arable soils	Mwp	88	26.8	63.2	61.0	84.6	13	23.1	52.2	93.1	104.6
	SE		0.73	2.56	3.8	4.0		1.76	5.09	16.7	15.8
Difference	d		6.8	9.1	8.6	8.1		1.1	11.1	10.9	29.4
Significance of difference	p		<0.001	0.015	0.118	0.167		0.597	0.063	0.574	0.112
Calcareous soils	Mwp	121	24.3	46.7	69.8	89.4	50	25.1	43.4	120.8	133.6
	SE		1.01	1.99	2.9	3.2		0.89	2.75	7.8	7.8
Non-calcareous soils	Mwp	120	17.3	77.1	38.2	63.1	48	19.5	66.8	72.7	111.4
	SE		1.76	2.00	3.0	3.3		0.91	2.81	7.9	8.0
Difference	d		7.06	30.4	31.6	26.3		5.6	23.4	48.1	22.1
Significance of difference	p		<0.001	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	0.050
Automorphic soils	Mwp	241	24.3	61.9	54.1	76.3	-	-	-	-	-
	SE		0.55	1.64	2.84	2.83	-	-	-	-	
Hydromorphic soils	Mwp		-	-	-	-	98	22.3	54.9	97.2	122.7
	SE		-	-	-	-		0.87	2.58	4.45	4.44
Difference	d		1.5	7.0	43.1	46.4		1.5	7.0	43.1	46.4
Significance of difference	p		0.132	0.023	<0.001	<0.001		0.132	0.023	<0.001	<0.001

*Mwp - weighted (by profile number) mean, SE – standard error, d – difference between Mwp-s, n – number of studied profiles and p – significance.

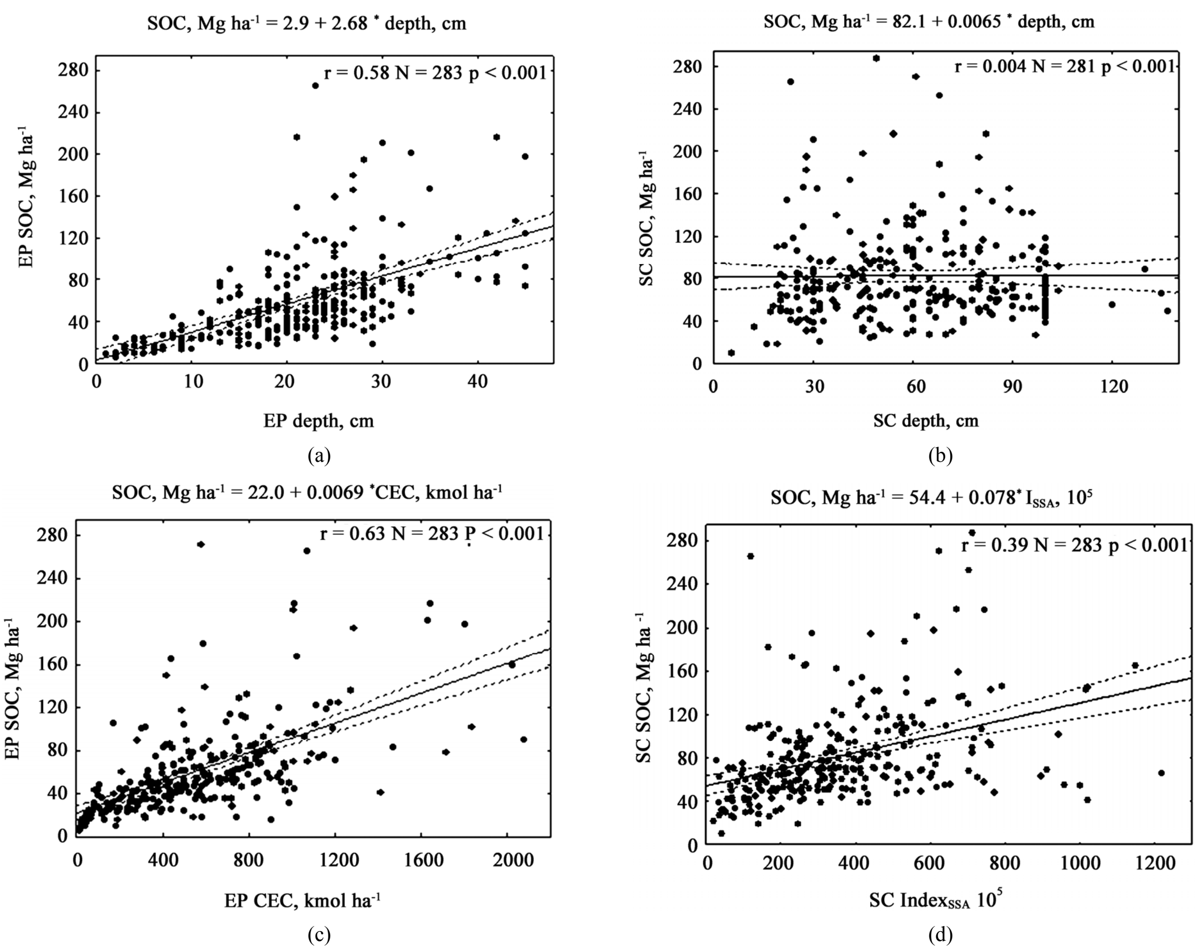

Figure 1. The SOC stocks (Mg ha^{-1}) in EP and SC of mineral soils in relation to depth and selected pedoecological properties. (a) SOC stocks in EP in relation to EP depth (cm); (b) SOC stocks in SC in relation to SC depth (cm); (c) SOC stocks in EP in relation to EP CEC (kmol ha^{-1}); (d) SOC stocks in SC in relation to SC Index of Specific Surface Area (10^5).

The regular changes (dependent upon soil properties) may be observed in mean SOC stocks of mineral soils (**Table 3**). In both postlithogenic calcareous soils (**Table 5**), automorphic (soil groups I – III) and hydromorphic (groups VII and VIII), the SOC stocks in EP and SC exceed SOC stocks of non-calcareous automorphic (groups IV – VI) and hydromorphic soils (group IX). Therefore in non-calcareous soils' SS, the SOC stocks are absolutely and relatively higher (in automorphic 24.9 Mg ha^{-1}, hydromorphic 38.7 Mg ha^{-1}) than in calcareous soils (19.6 and 12.8 Mg ha^{-1}, respectively).

Soil calcareousness is connected with soil profile development (*i.e.*, forming of illuvial and eluvial horizons). From *Leptosols* to *Podzols* (**Table 3**) and from *Eutric Gleysols* to *Dystric Gleysols* the SS' SOC density increases accordingly from 8.2 – 28.2 and from 12.4 – 58.3 Mg ha^{-1}. If the highest EP' SOC stocks (156 Mg ha^{-1}) are characteristic of *Saprihistic Gleysols*, then the highest SS' SOC stocks characterize *Fibrihistic Podzols* (~70 Mg ha^{-1}). Among synlithogenic soils the modest SS' SOC stocks (5 – 7 Mg ha^{-1}) are characteristic of eroded and coastal soils (groups XII and XV), but relatively higher (15 – 25 Mg ha^{-1}) of deluvial soils and *Fluvisols*, which may be classified as buried soils.

Clearly visible is the influence of soil moisture conditions on SOC stocks. The reported data, as well as our previous data prove the increase of SOC stocks in the following sequence of soil moisture conditions: dry < normally moist < gleyed or endogleyic < gley- or epigleyic < histic gleysoils.

ANOVA results show that SOC stocks in soils with *udic* moisture conditions are usually relatively stable, as their stocks in SC (Mg ha^{-1}) vary in different sites by an average of 25–45%. At the same time, SOC densities vary to a larger extent in hydromorphic soils (CV 43–57%). This demonstrates the instability of *Gleysols'* (histic, epigleyic) humus status.

Mean area weighted SC SOC stocks of post- and synlithogenic soils are accordingly 102.5 and 78.3 Mg ha^{-1}. The SOC retaining capacity of postlithogenic auto- and hydromorphic soils exceeds that of synlithogenic auto- and hydromorphic soils accordingly by 2.1 and 1.3 times. Therefore, the normally developed SC' SOC retention capacity exceeds that of synlithogenic soils' SC, which is periodically influenced by different geological processes.

4.2. Influence of Land use on Soil Humus Status

Comparative analysis of the EPs of arable and natural soils (on the basis of soil groups I – V or automorphic soils) shows that the EP of arable soils is on average 6.8 cm ($p < 0.001$) thicker (**Tables 2** and **5**). But in the case of hydromorphic soils, the land use change have not caused substantial increases of EP thickness, which may be explained by transformation of raw-humous SOM into more stabilized form, with increased soil bulk density. The clearest differences between natural and arable soils are observed in the fabric of EP, caused by the presence of forest (grassland) floor on natural areas.

Land use change from forest to arable land causes a decrease in exogenic SOC stocks and homogenization of SOC concentration. As a result, the equalization of stocks occurs in EP. Consequently, the diversity of SC on arable land either decreases or is lost. Land use change does not cause substantial changes in SS fabric and humus status, while the thickness of SC and the level of SOC stocks in the SC remain at approximately the same level (**Table 5**). EP (or topsoil) is always more sensitive to external influences compared with SS. The SOC of SS does not participate actively in soil functioning and may be considered as a buried resource.

The mean area weighted SOC retaining capacities of natural (and semi-natural) areas are higher compared with arable ones (**Table 4**). Some differences in means of SOC retaining capacities (taken by land use) are caused by differences in the soil type and textural composition. For example, the main SOC accumulators into mineral SC on arable lands are *Cambisols, Gleysols, Alb -eluvisols* and *Luvisols*, on forest lands *Gleysols, Podzols, Cambisols* and *Albeluvisols* and on grasslands *Cambisols, Gleysols, Fluvisols* and *Albeluvisols* [17-19]. The predominant mineral soils (> 70%) in Estonian arable land are the more fertile automorphic mineral soil types with loamy textures, whereas the predominant mineral soils (~40%) in forest lands are hydromorphic sandy soils.

4.3. Management of SOC

The goal of sustainable SOC management should be the attaining of SOC stock density optimal to soil type. After determining theoretical SOC density and actual status it is possible to evaluate the existing situation: is there a deficit, excess or optimal SOC stock density in the soil? For this purpose the mean weighted SOC-retaining capacities estimated according to soil types may be used. Additionally, suitable technology and digitized large-scale soil maps with soil distribution patterns should be available.

The accumulation of stable SOC is a slow process. According to Kolchugina and Vinson [30], the implementation of ecologically sound soil management practice results in an increase of forest soil SOC stocks by 0.5% and arable soils by 0.1% per year. With directed soil management the annual SOC storage increase may be in the limits of 0.1 – 0.7 Mg C ha^{-1} [5]. The results of Romanovskaja [31] show that the average loss of SOC from the abandoned arable land reached 0.46 Mg C ha^{-1}

yr^{-1}, but the increase of SOC storages after seven years was expected. The great SOC stocks losses in the first years after a change from forest to arable land use are also reported by other researchers [5,32]. One possible reason may be the greater share of potentially mineralizable SOM in forest soils. According to Semenov et al. [32] the share of easily mineralizable SOM in sod-podzolic forest and arable soils forms, respectively, 6.0% and 3.2% of total SOM.

The turnover period of EP organic carbon is much shorter than in SS and is controllable with soil management, primarily on arable lands. For ecologically-based soil management the identification of soil EP type is essential. The best EP of Estonian arable soils belongs to the neutral mild type. The main constraints of arable EPs may be high acidity, low humus content, low biological activity, unsuitable mineral composition, the raw-humous fabric and unfavourable moisture conditions. These factors, limiting SOC turnover and the level of productivity constraints, may be regulated by improving SOC management. The means for controlling or conversion of EPs into good productive status are soil drainage, liming, equilibrated fertilization and periodic input of new organic matter. Our previous research indicates that with the transformation of forest soils with good productive EP properties (fresh-moist-wet mull and moder) into arable ones, the neutral mild (from mull) and eluvic low-humous (from moder) EP types are formed [17,20].

One possibility of embedding additional carbon (or atmospheric CO_2) into the soil is to increase soil productivity, which subsequently causes SOC stock increases in soil horizons [33,34]. Another opportunity is deep ploughing, which displaces the rich SOC layer mechanically into SS (less active layers) protecting SOC from decomposition and ensuring its prolonged persistence. The optimization of soil humus status should be soil type-specific and arranged in a step-by-step approach, to increase both soil productivity and the annual inflow of new organic matter into the soil.

Though SOC densities in hydromorphic soils are quite high, their quality is low, due to low humus quality. The humus of hydromorphic soils is unstable, chemically unsaturated and weakly condensed [20,35]. Therefore *Gleysols* should be managed very carefully, especially during preparation for cultivation. There is a risk of losing a large part of SC' SOC, which is weakly bound to soil mineral particles. The reversion of low-fertility arable lands to grasslands and their latest afforestation may lead to additional sequestration of atmospheric CO_2 [36].

4.4. Comparing SOC Stocks Densities of Estonian Soils with Soils of other Regions

Comparison of SOC stocks of Estonian SC with other regions of the world [13,37] reveals the characteristics of the Nordic area: SC is relatively thin and poor in humus. Robert [11] assigns a value of 98 – 102 Mg ha^{-1} for the mean SOC stocks of 0.3 m soil layer in a boreal area, which corresponds with our mineral soils weighted average of EP (**Table 4**). The average SOC density of the forest soils 0.3 m layer in Russia equals 81 and for the 1 m layer 114 Mg ha^{-1}; the same parameters for the entire country are accordingly 101 and 180 Mg ha^{-1} [16]. Batjes [38] reported for Central and Eastern Europe *Podzoluvisols, Cambisols* and *Gleysols* 0.3 m layer mean SOC densities, respectively, of 49, 69 and 114 Mg ha^{-1}. Lal *et al.* [8] provided 116 Mg ha^{-1} as the mean SOC stock for grassland ecosystems, which is very similar to the EP density of our lowland mineral soils. Soils with *aquic* water conditions in the north-western USA tend, according to Kern et al. [14], to be similar to the SOC stocks of Estonian *Gleysols* (varying from 90 – 190 Mg ha^{-1}). Puzachenko *et al.* [15] estimated the global pool of SOC to be 1,347 Pg, from which it has been concluded that the mean SOC global density equals 109.5 Mg ha^{-1}.

5. Conclusions

1) SOC retaining capacities of EP and SC as a whole are soil type-specific. The average humus status indices of soil types (EP and SC thickness and SOC stocks) may be used as benchmarks in sustainable SOC management.

2) Land use and land use changes primarily influence the properties and fabric of the EP. In the humus status (SOC concentration and stock, fabric of horizons) of SS, the differences between native soil and cultivated soil of the same type are practically absent.

3) The mean mineral soils SOC stocks, EP quality and SOC distribution in soil profile depend mainly on water regime, mineral composition (texture and calcareousness), development of eluvial processes and peculiarities of land use.

4) The aggregate of SOC retained in the mineral soils of Estonia (3,235,100 ha) amounts to 323 ± 46 Tg. Approximately 42% of this is sequestered into stabilized humus, 40% into instable raw-humous material and 18% into forest (grassland) floor and shallow peat layers. Some 75% of the total SOC stock is situated in biologically active EP and 25% in SS, characterized by long SOC turnover periods.

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