Stocks of organic carbon in Estonian soils

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Abstract. The soil organic carbon (SOC) stocks (Mg ha^{-1}) of automorphic mineral (9 soil groups), hydromorphic mineral (7), and lowland organic soils (4) are given for the soil cover or solum layer as a whole and also for its epipedon (topsoil) layer. The SOC stocks for forest, arable lands, and grasslands and for the entire Estonian soil cover were calculated on the basis of the mean SOC stock and distribution area of the respective soil type. In the Estonian soil cover (42 400 km^2), a total of 593.8 ± 36.9 Tg of SOC is retained, with 64.9% (385.3 ± 27.5 Tg) in the epipedon layer (O, H, and A horizons) and 35.1% in the subsoil (B and E horizons). The pedo-ecological regularities of SOC retention in soils are analysed against the background of the Estonian soil ordination net.

Key words: carbon retention capacity, carbon stock, land use, pedo-ecological regularities, soil ordination net.

INTRODUCTION

Soil organic matter and soil organic carbon (SOC) sequestered in it are major factors in soil formation, development, and functioning (Van Cleve & Powers 1995; Paustian et al. 1997; Smith et al. 1997; Lal et al. 1998a; Pulleman et al. 2000; West & Post 2002). The quantification of SOC retention in soil cover and its flow through the soil cover is of utmost importance in the investigation of organic carbon cycling (Eswaran et al. 1993; Kern 1994; Bernoux et al. 2002; Halvarson et al. 2002; Nemeth et al. 2002; Zhou et al. 2003). Numerous recent publications disclose the distribution of SOC in European soils (Arrouays et al. 2001; Robert 2001; Rusco et al. 2001; Krogh et al. 2003; Sleutel et al. 2003; Van-Camp et al. 2004; Zdruli et al. 2004; Jones et al. 2005; Lettens et al. 2005). Unfortunately, the total SOC stocks for various countries are determined differently, which complicates the comparison of the results obtained.

Depending on the ecological conditions, each soil type has a specific character of SOC flow (input => sequestration and throughput => output) throughout the soil cover (Körchens et al. 1998; Neill et al. 1998; Yakimenko 1998; Janzen 2006). The SOC flow in the composition of organic matter begins with litter falling on or into the soil, continues with its disintegration, transformation into humus and accumulation, and ultimate disappearance, via consumption by soil organisms, complete mineralization or illuviation into the subsoil, or eluviation out of the soil cover. The SOC stocks and flows characteristic of certain soil types may differ greatly (Post et al. 1982; Kern et al. 1998; Percival et al. 2000; Gijsman et al. 2002), in input composition (biochemical and ash content), input dynamics, characteristics of deposition, and present soil status. Differences also exist in the interaction of soil organic matter with the edaphon, and with the solid, liquid, and gaseous phases of soils. As a result, SOC may be sequestered in soil horizons in different forms and states, with varied residence times or turnover intensity and relationships with nitrogen (Batjes 1996; Falloon et al. 1998; DeBusk et al. 2001; Shaffer & Ma 2001). The extremes of SOC flow may range from complete input mineralization (on biologically active soil) to resting in a non-decomposed state (raised bog peats), with various intermediate types of humus and transformation processes. In the present work the differing features of SOC are referred to as soil humus status, meaning the functioning of soil in relation to the SOC flow throughout the soil cover.

Our main tasks were (1) to determine the SOC stocks in the main soil types and the entire soil cover of Estonia; (2) to analyse the proportion of epipedon (topsoil) and subsoil in SOC retention in the soil profile, and (3) to elucidate the generalized ecological regularities of SOC retention depending on soil and land use types. Data about SOC stocks in the soil are an essential prerequisite for further research into the annual cycling of SOC in different soil types.

MATERIALS AND METHODS

Area covered by soils

First of all, it was necessary to establish the territory covered by soils in Estonia. Unfortunately, no precise data on the distribution of land stock by land use in recent decades are available. Therefore different sources were used to ascertain land areas by category (Meiner 1999; Paal et al. 1999; Arold 2005).

The total area of Estonia is 45 228 km^2 (SOE 2005). However, widely divergent data can be found concerning the area of inland water bodies (from 2070 to 2830 km^2) and areas without soil cover (e.g. buildings, roads, and industrial units). Our rough estimate (in consultation with the Estonian Land Board specialist K. Teiter) for the inland water area was 2168 km^2 and for buildings and roads, 660 km^2. Thus the territory covered by soils (or soil cover) is about 42 400 km^2, including green urban regions, roadside belts, dumps and pits on mined areas, and temporarily inundated coastal areas. Our proposal for the SOC calculation area approximates the area covered by large-scale (1 : 10 000) digital soil maps (ca 42 000 km^2).

Databases

The quantitative characteristics of the humus status of soils originate mainly from the soil profile horizons database PEDON and humus status research transect database CATENA created by us. PEDON was originally compiled in 1967–85 and updated in 1986–95 and 1999–2002. CATENA was created during itinerant field studies in 1987–92. The aim of these databases was to give a complex (on ecosystem level) characterization of main Estonian soil types and study them (in order to be representative) in their typical areas of distribution. PEDON consists of 53 parameters of soil properties, 56 parameters of plant cover, and 25 parameters of metadata, which make it possible to match soil parameters with different ecological classifications, as well as with qualitative and location-related parameters. The main parameters of soil humus status in the above-mentioned databases that are used in our study are the thickness and morphology (fabric) of soil profile horizons, and SOC concentration (g kg^{-1}) and stock (Mg ha^{-1}) by soil horizons or their sub-layers. The SOC stocks of soil horizons were calculated on the basis of the SOC content and bulk density of each soil horizon. The volume of the coarse soil fraction content of each horizon of soil was determined in the field. The SOC content of fine-earth soil samples (particle diameter <1.0 mm) was found in the laboratory after sieving out coarse fractions. In total, data from 751 individual soil profiles were used (their distribution by soil use types is given in Table 1). The SOC content was generally determined for each horizon of the 751 profiles, with an exception of the subsoil of erosion-affected soils, where the SOC content was determined in 10–15% of cases. Bulk density samples were taken from about 10% of the profiles.

In PEDON and CATENA the data on soil texture, SOC concentrations and stocks, different soil properties, content of coarse fractions, and bulk density are given by soil diagnostic horizons (organic, humus, raw-humus, peat, eluvial, illuvial, and/or transitional). We generalized data on individual profiles by land use, soil types, and soil cover layers (epipedon and subsoil). The distribution of soil types over the whole of the Estonian territory is based on large-scale (1 : 10 000) soil mapping data (Table 1; Kokk 1995).

Determination of quantitative characteristics of soil

The SOC concentration was determined using the Tjurin method, based on wet digestion with acid dichromate of organic carbon (Vorobeva 1998), and the particle size distribution of fine-earth was found using the pipette method (Kachinsky 1965). The proportion of rock fragments in soil horizons was estimated by volume. Bulk density was measured for mineral soil horizons (including humus and raw-humus horizons) with 50 cm^3 metallic cylinders, and for forest floor (organic horizons) and thin *histic* horizons with a 25 cm × 40 cm (0.1 m^2) metallic frame. Monoliths measuring from 10 cm × 10 cm × 10 cm to 25 cm × 40 cm × 10 cm were used to determine peat volume weight on about 10% of the study areas. Overall, generalized volume weights from our own and other data sources (mainly data of Estsurvey pertaining to soil type and texture) were used. The bulk densities for mineral soils were generalized on the basis of land use, soil type, soil horizons, and soil texture, and for organic soils by soil type and the degree of peat decomposition.

Calculation of SOC stocks

The stocks of SOC for soil types were estimated on the basis of two soil layers: (1) the epipedon layer (EPL) (or topsoil, or humus cover), which consists of the forest floor (organic) horizon and/or humus, raw-humus and peat (*histic*) horizons and (2) soil cover (SC) (the whole solum), whose depth extends from the surface to the unchanged parent material or C horizon. Therefore the SC consists of the EPL and a subsoil layer (SSL), the latter, in turn, of the eluvial (E) and illuvial (B) horizons. The thickness of the SC is determined by the depth of the boundary between B and C horizons. In the presence of the BC horizon, SC thickness was measured from the surface to the middle of the BC horizon. The weighted

Table 1. The studied soil groups and their distribution (in %)

Group No.	Soil or soil association	Soil code by WRB	*n*[a)]	Total land[b)]	Forest land[b)]	Arable land[b)]	Grass-land[c)]	Other land[c)]
I	*Rendzic & Skeletic & Gleyic Leptosols*	LP rz sk gl	7/12/8	1.2	0.8	0.8	7.1	0.6
II	*Mollic & Endogleyic & Calcaric & Endoskeletic Cambisols*	CM mo gln ca skn	18/46/10	13.8	6.5	25.6	14.1	27.2
III	*Cutanic & Endogleyic Luvisols*	LV ct gln	12/8/0	6.4	2.4	13.5	11.3	3.7
IV	*Glossic & Gleyiglossic Albeluvisols*	AB gs gsg	18/13/3	9.5	3.6	21.3	5.6	7.9
V	*Haplic & Endogleyic Albeluvisols*	AB ha gln	28/21/7	5.0	4.3	5.2	5.6	4.6
VI	*Haplic & Endogleyic Podzols*	PZ ha gln	30/–/–	2.5	6.0	0.0	0.0	0.0
VII	*Mollic & Calcic & Eutric Gleysols*	GL mo cc eu	15/6/22	14.5	12.1	10.3	10.8	21.3
VIII	*Luvic & Epidystric Gleysols*	GL lv dyp	15/3/2	8.1	8.0	5.8	3.0	10.9
IX	*Spodic & Umbric & Dystric Gleysols*	GL sd um dy	8/2/5	5.1	9.2	0.8	2.9	1.4
X	*Saprihistic Gleysols*	GL his	5/1/3	4.7	5.3	2.5	9.6	3.6
XI	*Fibrihistic Podzols*	PZ hif	13/–/–	1.6	3.1	0.0	0.0	0.5
XII	*Eroded Cambisols & Regosols*	RG & CM *eroded*	–/175/0	1.2	0.0	3.1	4.1	0.3
XIII	*Deluvial Cambisols & Luvisols*	CM & LV *deluvial*	–/157/0	0.9	0.0	2.4	3.7	0.0
XIV	*Eutric & Epigleyic & Histic Fluvisols*	FL eu glp hi	6/0/14	0.9	0.8	0.2	5.8	0.2
XV	*Salic Gleysols & Fluvisols*	GL & FL sz	0/–/10	0.7	0.3	0.0	3.3	1.4
XVI	*Sapric & Eutric Histosols*	HS sa eu	13/2/3	13.8	16.1	7.8	9.0	14.5
XVII	*Fluvic Histosols*	HS fv	0/0/11	0.5	0.2	0.6	3.2	0.1
XVIII	*Dystric Histosols*	HS dy	8/–/2	3.7	6.9	0.0	0.8	1.8
XIX	*Fibric Histosols*	HS fi	8/0/0	5.7	13.7	0.1	0.1	0.0
XX	*Protic & Spolic Regosols*	RG pr sp	1/–/–	0.2	0.7	0.0	0.0	0.0

[a)] *n* – forest/arable/grassland; [b)] by Kokk (1995); [c)] by our approximate calculations.

means of the SOC contents (g kg^{-1}) of different soils are determined by dividing SOC stocks by fine-earth mass. In order to calculate *Histosol* SOC stocks for the thickness of the EPL, 30 cm is used, and for the SC, 50 cm is used (Kõlli et al. 2009). Conventional thicknesses were also taken for *Protic & Spolic Regosols* (EPL 10 cm and SC 25 cm). The total SOC stocks in Estonia were calculated on the basis of the distribution area of each soil type and its SOC stocks per hectare.

Terminology

The conventional term 'epipedon layer' (EPL) embraces the most active soil component, which is closely coupled with plant cover and via which the cycling of organic carbon takes place. This term is used when different classical soil horizons (organic, humus, raw humus, peat) are connected into one soil layer. The conventional term 'soil cover' (SC) encompasses the superficial earth layer or total (actual) soil resource influenced by soil formation processes. Both plant productivity and the environmental status of the region depend upon the status and functioning of the SC or soils. A characterizing fabric (or profile) of soil taxonomic units of the EPL and SC is referred to as the epipedon and pedon or solum, respectively; their analogues, from a territorial perspective, are poly-epipedon and polypedon or sola. The quantitative soil characteristic 'SOC retention capacity' (given in Mg ha^{-1}) is the amount of SOC that a certain soil layer is able to retain or capture in equilibrated conditions of soil functioning.

Other methodological remarks

Quantitative data (concentration and stocks) on soils in their initial state are given for classical soil horizons and their subdivisions in the PEDON and CATENA databases. For various pedo-ecological analyses and excerpts of numerical data, the initial soil profile data were recalculated either for soil layers with specific thickness (10, 30, 50, and 100 cm), for soil genetic horizons or for layers that are differentiated according to pedological principles (forest floor, EPL, and SC).

The soil group names and codes (Table 1) are stated in the *World Reference Base for Soil Resources* (WRB; FAO et al. 1998). The correlation of the Estonian soil classification with the WRB is shown against the background of three ordination nets of Estonian soils (Figs 1–3), where the disposition of 20 investigated soil groups is presented. These ordination nets were also used in the generalization of SOC concentration and stocks by various soil layers and in the analysis of

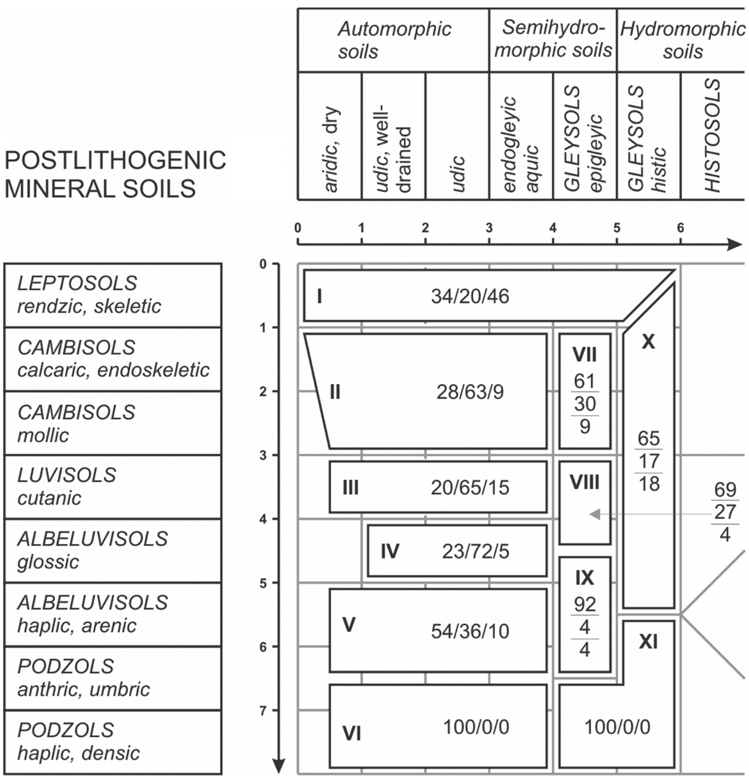

Fig. 1. Location of soil groups I–XI on the ordination net of postlithogenic mineral soils. Scalars: Vertical (0–8), descending from top – genetical-lithological conditions, from calcareous *Leptosols* (<1) to acid *Podzols* (>7). Horizontal (0–6), from left to right – moisture conditions, from dry automorphic (<1) to hydromorphic *histic* soils (5–6). For the composition and percentage of soil groups I–XI in the Estonian soil cover see Table 1.

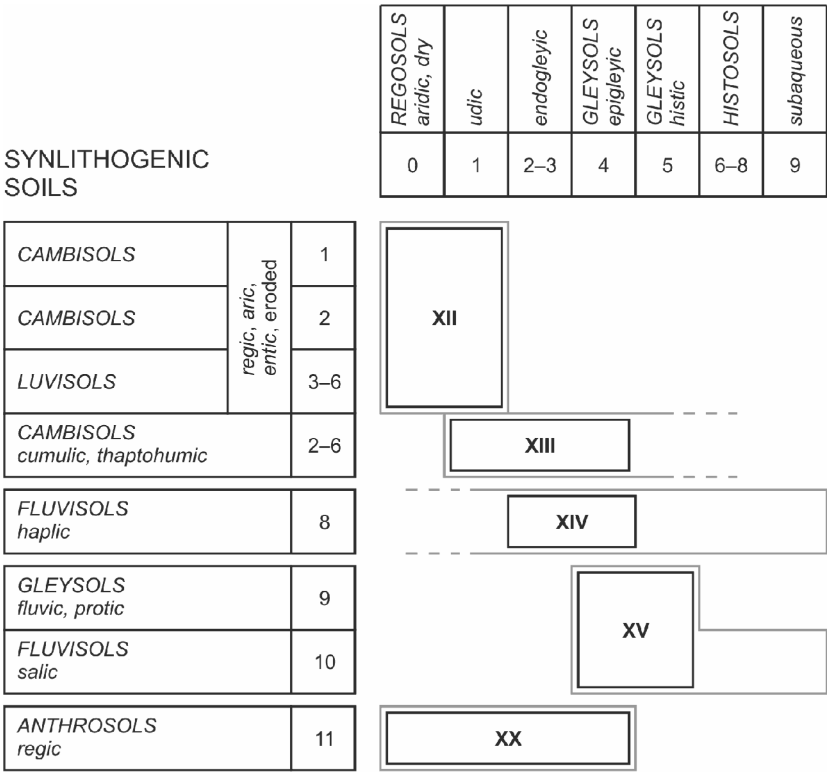

Fig. 2. Location of soil groups XII–XV and XX on the ordination net of synlithogenic soils. Scalars: Vertical (1–11), from top down – discrete genetical-lithological-geological conditions; 1–6, erosion-affected post-lithogenic soils, see Fig. 1; 8, *Fluvisols*; 9, 10, coastal soils; 11, anthropogenic soils. Horizontal (0–9), from left to right – moisture conditions, from dry *Regosols* (0 or <1) to subaqueous soils (9). For the composition and percentage of soil groups XII–XV and XX in the Estonian soil cover see Table 1.

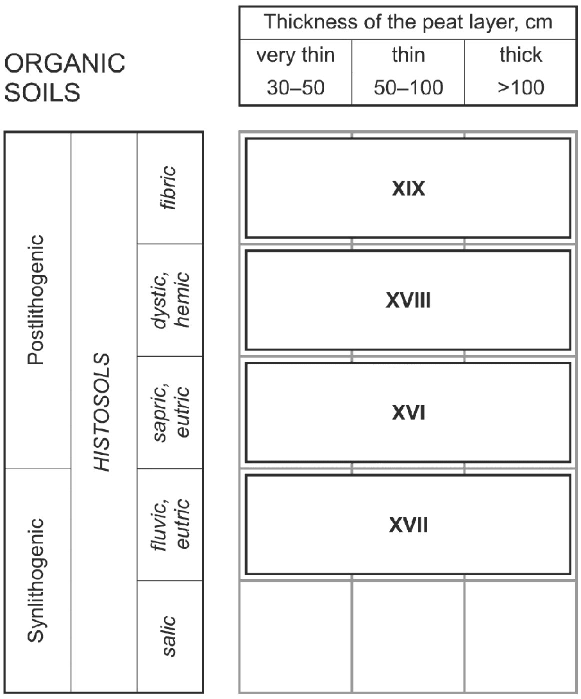

Fig. 3. Location of soil groups XVI–XIX on the ordination net of organic soils. Scalars: Vertical, from top down – character of peat formation, from raised bogs (*fibric*) to *salic* mires. Horizontal, from left to right – thickness of the peat layer. For the composition and percentage of soil groups XVI–XIX in the Estonian soil cover see Table 1.

the pedo-ecological regularities of SOC retention. The Statistica 7 program was used for statistical analysis. The two-way analysis of variance, followed by the Student test of homogeneous groups, was used to process the collected data. The level of statistical significance was set at $p < 0.05$.

RESULTS

Thickness of the epipedon layer and soil cover

Generalized data about the thicknesses of the EPL and SC of the 20 studied soil groups are presented in Table 2. In most cases the average EPL thickness was 21–26 cm, but it may be lower on some *Gleysols* and *Leptosols*. By nature, the EPLs of very young coastal soils and *Podzols* (humus horizon is absent) are much thinner. The EPL thickness of soils is very variable in areas influenced by water erosion, being, for instance, reduced due to erosion or augmented due to ploughing. However, the EPL of deluvial (or colluvial) soils is always thicker.

The thickness of the SC ranges from 43 to 92 cm, with a standard deviation of 8–24 cm. Only the average thickness of *Leptosols*, *Fluvisols*, and coastal soils is smaller. Accordingly, the unique EPL for *Histosols* and *Regosols* (30 and 10 cm) and SC depth (50 and 25 cm) were considered to be conventional.

Organic carbon stocks by soil types

The SOC stocks in relation to the area characterize the SOC retention capacity of soil types. In upland soils with an automorphic (normal and gleyed) moisture regime, the SOC stocks in the EPL are between 45 and 82 Mg ha^{-1}, but somewhat higher in soils with higher carbonate and clay contents (Table 2). The SOC stocks are markedly lower in the EPL of eroded soils (<30 Mg ha^{-1}), *Podzols* (<20 Mg ha^{-1}), and *Regosols* (about 16 Mg ha^{-1}). The EPL SOC stocks of different kinds of *Gleysols* (109–115 Mg ha^{-1}) are higher than those of automorphic soils. The only exception is some non-calcareous acid *Gleysols*, where the SOC stocks are <40–45 Mg ha^{-1}, and weakly developed coastal soils (group XV). The EPL SOC stocks are highest in *Sapric* (and other) *Histosols*, the EPL of which is at different stages of decomposition (*fibric*, *hemic*, *sapric* peat). The carbon stock of *Histosols* per peat volume (i.e. also per EPL) increases with an increasing degree of decomposition and/or bulk density.

The SOC stocks of the SC on automorphic mineral soils range from 43 to 106 Mg ha^{-1}. They are lowest in eroded soils, *Regosols*, and *Podzols*, and highest in *Luvisols* and deluvial soils. The SOC stocks of the SC of mineral *Gleysols*, attained in the presence of calcareous material, are 121–125 Mg ha^{-1} and those, obtained in the presence of *histic* horizons, ≤191 Mg ha^{-1}. The SOC capturing capacity, however, is greatest in *Sapric* and *Dystric Histosols* (206–333 Mg ha^{-1} per a 50 cm layer).

Coefficients of variation (CV) calculated on the basis of standard deviations (Table 2) show that SOC stocks in the EPL vary only a little more than in the SC. In most cases the CV of the EPL ranges from 32 to 56% and that of the SC from 24 to 54%; in a few cases from 56 to 60%. The low variation of the SOC stocks (14–23%) of *Histosols* was caused by similar soil depth (EPL 30 cm and SC 50 cm). *Gleysols* exhibited the highest variability in EPL SOC stocks. The CV of EPL and SC thicknesses of soils was, respectively, 18–35% and 16–41%. It can be concluded that SOC stock variation is caused mostly by the variation in SOC concentration.

Total SOC stocks retained in the soil cover of Estonia

Table 3 demonstrates the proportion of different soil groups in the total SOC stocks of the SC and EPL. Total SOC stocks depend on the SOC retention capacity and

Table 2. Mean thicknesses (cm) and stocks of soil organic carbon (SOC) (Mg ha^{-1}) of epipedon layers (EPL) and soil covers (SC) of the studied soil groups

Group No.	Soil code by WRB	*n*	Thickness in cm (M ± SD) of		SOC stocks (M ± SD), Mg ha^{-1}	
			EPL	SC	EPL	SC
I	LP rz sk gl	27	19.0 ± 5.7^{cd}	23.3 ± 9.2^{a}	$66.5 \pm 33.5^{d–g}$	74.9 ± 40.1^{ab}
II	CM mo gln ca skn	74	25.9 ± 7.8^{f}	47.8 ± 17.1^{c}	$67.8 \pm 35.3^{e–g}$	90.3 ± 39.8^{cde}
III	LV ct gln	20	25.6 ± 5.4^{fh}	74.4 ± 23.5^{hi}	81.6 ± 60.0^{fg}	$105.5 \pm 62.0^{d–g}$
IV	AB gs gsg	34	$21.9 \pm 6.5^{d–g}$	92.4 ± 14.8^{j}	44.6 ± 16.9^{c}	67.1 ± 16.1^{b}
V	AB ha gln	56	20.9 ± 7.3^{d}	74.3 ± 17.3^{h}	45.0 ± 22.9^{c}	70.0 ± 24.1^{b}
VI	PZ ha gln	30	5.0 ± 2.7^{a}	65.1 ± 21.9^{fg}	18.3 ± 9.7^{a}	45.7 ± 20.0^{a}
VII	GL mo cc eu	43	25.5 ± 5.1^{fh}	43.0 ± 17.0^{bc}	114.3 ± 59.0^{h}	122.5 ± 58.2^{gh}
VIII	GL lv dyp	20	$25.7 \pm 4.7^{f–i}$	57.2 ± 23.5^{ef}	115.0 ± 54.3^{h}	125.2 ± 52.8^{gh}
IX	GL sd um dy	15	15.3 ± 6.6^{bc}	71.8 ± 20.7^{ghi}	40.4 ± 18.7^{bc}	90.5 ± 38.6^{cde}
X	GL his	9	$21.7 \pm 4.2^{d–g}$	$46.9 \pm 8.2^{b–e}$	155.9 ± 25.5^{i}	191.1 ± 26.4^{i}
XI	PZ hif	13	14.8 ± 4.1^{bc}	75.8 ± 18.0^{hi}	44.8 ± 19.7^{bc}	$114.5 \pm 45.9^{d–h}$
XII	RG & CM *eroded*	175	24.0 ± 5.0^{efg}	54.1 ± 14.2^{de}	29.5 ± 10.5^{ab}	37.6 ± 12.2^{a}
XIII	CM & LV *deluvial*	157	43.6 ± 11.6^{j}	79.7 ± 14.1^{i}	80.5 ± 39.0^{f}	105.3 ± 38.3^{def}
XIV	FL eu glp hi	20	$26.9 \pm 6.0^{f–i}$	36.3 ± 12.7^{b}	108.8 ± 34.1^{h}	120.8 ± 45.6^{fgh}
XV	GL & FL sz	10	9.7 ± 6.5^{ab}	13.2 ± 11.1^{a}	50.7 ± 28.8^{cde}	56.2 ± 31.9^{ab}
XVI	HS sa eu	18	30.0 ± 0	50.0 ± 0	173.4 ± 28.1^{i}	333.2 ± 57.7^{j}
XVII	HS fv	11	30.0 ± 0	50.0 ± 0	115.2 ± 21.0^{h}	205.5 ± 38.2^{i}
XVIII	HS dy	10	30.0 ± 0	50.0 ± 0	84.3 ± 16.6^{fg}	210.0 ± 43.3^{i}
XIX	HS fi	8	30.0 ± 0	50.0 ± 0	43.5 ± 10.0^{bcd}	139.4 ± 24.6^{h}
XX	RG pr sp	1	10 ± 0	25 ± 0	16.0 ± 8.0	43.0 ± 21.5

The superscript letters next to the data indicate significant difference at the $p < 0.05$ level.

Table 3. The total estimated retention of soil organic carbon (SOC) in the epipedon layers (EPL) and soil covers (SC) (in Gg ± SE) of different soil groups

Group No.	Soil code by WRB	*n*	km^2	Total Gg EPL	±SE Gg EPL	Total Gg SC	±SE Gg SC
I	LP rz sk gl	27	508.8	3 384	328	3 384	392
II	CM mo gln ca skn	74	5 851.2	39 671	2 399	52 836	2 709
III	LV ct gln	20	2 713.6	22 143	3 636	28 628	3 764
IV	AB gs gsg	34	4 028.0	17 965	1 168	27 028	1 108
V	AB ha gln	56	2 120.0	9 540	649	14 840	683
VI	PZ ha gln	30	1 060.0	1 940	188	4 844	387
VII	GL mo cc eu	43	6 148.0	70 272	5 527	75 313	5 453
VIII	GL lv dyp	20	3 434.4	39 496	4 173	42 999	4 056
IX	GL sd um dy	15	2 162.4	8 736	1 044	19 570	2 156
X	GL his	9	1 992.8	31 068	1 694	38 082	1 754
XI	PZ hif	13	678.4	3 039	370	7 768	862
XII	RG & CM *eroded*	175	508.8	1 501	40	1 913	47
XIII	CM & LV *deluvial*	157	381.6	3 072	119	4 018	117
XIV	FL eu glp hi	20	381.6	4 152	291	4 610	389
XV	GL & FL sz	10	296.8	1 505	270	1 668	299
XVI	HS sa eu	18	5 851.2	101 460	3 686	194 962	7 963
XVII	HS fv	11	212.0	2 442	134	4 357	290
XVIII	HS dy	10	1 568.8	13 225	824	32 945	2 149
XIX	HS fi	8	2 416.8	10 513	853	33 690	2 100
XX	RG pr sp	1	84.8	136	68	365	182
Total		751	42 400.0	385 260	27 461[a)]	593 820	36 860[a)]

[a)] Sum of SE.

distribution area of the soil type. Our calculations show that 593.8 ± 36.9 Tg of SOC is accumulated in Estonia's SC (which totals 42 400 km^2): 64.9% (385.3 ± 27.5 Tg) in the EPL and 35.1% in the SSL.

Employing data of previous research (Kõlli & Ellermäe 2003; Kõlli et al. 2004, 2007), we analysed SOC retention peculiarities by land use types (Table 4). In forest lands most of the SOC (56.3%) retained in the SC is found in organic soils, followed by hydromorphic mineral soils (32.4%). On arable lands automorphic mineral soils (53.8%) are the main accumulators of SOC in soil EPL, followed by hydromorphic mineral and organic soils. On grasslands hydromorphic mineral soils hold the first position in this respect. In order to understand the significance of different ways of land use in SOC retention, the area-weighted means of SOC stocks were calculated not only by land use types, but also by soil ecological groups (Table 4).

Table 5 shows the role of five ecological soil groups in the retention of SOC in the EPL and SC in Estonia. The data presented demonstrate the great importance of calcareousness and moisture conditions in the SOC retention capacity of soil. The organic soils, taking up only 23.7% of the SC area, contribute 33.1% of the total EPL SOC and 44.8% of the SC SOC.

DISCUSSION

Soil organic carbon retention capacity

The process of sequestration of organic carbon in soil depends on the soil moisture regime, clay and carbonate content, and method of soil management (Kern et al. 1998; Körchens et al. 1998; Percival et al. 2000; Robert 2001). The amounts of organic carbon accumulated into soil depend on the soil type's SOC retaining capacity. However, the theoretical SOC retaining capacity may differ from the actual SOC content (taken by concentration or by stocks) in soil, with either a scarcity or surplus of SOC. For sustainable functioning of the SC, it is important that the SOC content levels correspond to soil properties and functioning. In the present work the weighted mean stocks and concentrations of SOC of different soils or soil groups are conventionally taken as benchmarks for further elaboration of scientifically proven humus status parameters.

Tables 4 and 6 present the area-weighted means of SOC stocks per hectare (Mg ha^{-1}) by land use types and by ecological soil groups in relation to the EPL, SC, and SSL. Land use substantially influences only the EPL of soil. The SOC accumulation in the SSL of mineral soils depends primarily on the presence of illuviation,

Table 4. The generalized data on soil organic carbon (SOC) retention in Estonian soil cover by land use types

Land use, characteristics	Automorphic mineral soils	Hydromorphic mineral soils	Wetland organic soils	All soils
		Area, km^2		
Forest land	4 897	7 821	7 439	20 157
Arable land	8 130	2 216	961	11 307
Grassland	1 543	1 060	392	2 995
Total	14 570	11 097	8 792	34 459
		Total SOC stocks, Tg[a)]		
Forest land SC	35.5 ± 4.2	101.9 ± 13.5	177.0 ± 9.4	314.4 ± 27.1
Forest land EPL	23.3 ± 3.9	75.9 ± 12.6	80.4 ± 4.1	179.6 ± 20.6
Forest land SSL	12.2	26.0	96.6	134.8
Arable land SC	65.8 ± 5.5	25.4 ± 8.0	31.1 ± 1.5	122.3 ± 15.0
Arable land EPL	47.2 ± 5.0	23.0 ± 8.1	16.1 ± 0.7	86.3 ± 13.8
Arable land SSL	18.6	2.4	15.0	36.0
Grassland SC	13.7 ± 2.2	14.2 ± 3.3	12.0 ± 2.5	39.9 ± 8.0
Grassland EPL	10.8 ± 1.8	12.4 ± 3.6	7.2 ± 1.4	30.4 ± 6.8
Grassland SSL	2.9	1.8	4.8	9.5
		Weighted (by area) mean SOC stocks, Mg ha^{-1}		
Forest land SC	72.5	130.3	237.9	156.0
Forest land EPL	47.6	97.0	108.1	89.1
Forest land SSL	24.9	33.3	129.8	66.9
Arable land SC	80.9	114.8	323.6	108.2
Arable land EPL	58.0	103.8	167.5	76.4
Arable land SSL	22.9	11.0	156.1	31.8
Grassland SC	88.8	134.0	306.1	133.2
Grassland EPL	70.0	117.0	183.7	101.5
Grassland SSL	18.8	17.0	122.4	31.7

[a)] Sum of stocks ± sum of SE (standard error). SC, soil cover; EPL, epipedon layer; SSL, subsoil layer.

Table 5. The retention of soil organic carbon in the epipedon layer (EPL) and soil cover (SC) (Tg ± SE[a)]) by ecological soil groups

Soil group	% of the area	Total in EPL		Total in SC	
		Tg ± SE	%	Tg ± SE	%
Automorphic calcareous	22.5	67.6 ± 6.5	17.5	88.0 ± 7.0	14.8
Automorphic non-calcareous	18.2	31.8 ± 2.1	8.3	49.8 ± 2.4	8.4
Hydromorphic calcareous	28.1	143.7 ± 11.7	37.3	159.5 ± 11.6	26.9
Hydromorphic non-calcareous	7.5	14.6 ± 1.7	3.8	30.5 ± 3.4	5.1
Wetland organic	23.7	127.6 ± 5.5	33.1	266.0 ± 12.5	44.8
Total	100.0	385.3 ± 27.5	100.0	593.8 ± 36.9	100.0

[a)] Sum of SE (standard error).

eluviation, and/or podzolization processes; 22–25 Mg ha^{-1} of SOC is accumulated in the SSLs of *Luvisols* and *Albeluvisols*. The development of soil-forming processes is also reflected in the thickness and the SOC stocks of the SSL: on average only 13–21 Mg ha^{-1} of SOC is found in the SSL of calcareous mineral soils, but 24–50 Mg ha^{-1} of SOC is captured in the SSL of non-calcareous mineral soils. The SSL SOC stocks may be regarded as a buried resource that does not actively participate in soil functioning. In certain situations, however, it is possible to enhance the sequestration of additional atmospheric CO_2 into the soil. *Histosols* are especially rich in retained SSL SOC, with an average of 132–138 Mg ha^{-1} of SOC. The average SOC retention capacity is more than 1.3–2.1 times higher in the EPL of hydromorphic mineral soils (Mg ha^{-1}) than in automorphic soils, but

Table 6. The weighted mean thicknesses (cm) and soil organic carbon (SOC) stocks (Mg ha^{-1}) of the epipedon layer (EPL) and soil cover (SC) by ecological soil groups

Soil group	Thickness, cm ±SD			Mean SOC retention capacity, Mg ha^{-1}		
	EPL	SC	SSL	EPL	SC	SSL
Automorphic calcareous	25.7 ± 7.0	74.7 ± 18.3	49.0	70.6	92.0	21.4
Automorphic non-calcareous	20.5 ± 6.6	91.9 ± 19.4	71.4	41.3	64.8	23.5
Hydromorphic calcareous	24.7 ± 4.9	47.3 ± 17.2	22.6	120.6	133.9	13.3
Hydromorphic non-calcareous	15.6 ± 6.0	67.8 ± 19.2	52.2	45.9	95.8	49.9
Wetland organic	30.0	50.0	20.0	127.0	264.7	137.7
Mean for mineral soils	23.1 ± 6.0	61.8 ± 18.3	38.7	79.6	101.3	21.7
Mean for whole area	24.8	59.0	34.2	90.9	140.0	49.1

SD, standard deviation; SSL, subsoil layer.

the SSL of automorphic and hydromorphic mineral soils have approximately equal SOC retention capacities.

The most powerful SOC accumulators are the SCs of *Histosols*, where an average of 265 (139–333) Mg of SOC is retained per one-hectare 50 cm layer (Tables 2 and 6). Although huge SOC resources exist below the half-metre depth, these layers do not belong to the SC and may be classified as natural peat resources.

Generalized data on the thicknesses of the epipedon layer and soil cover

Significant differences were observed between the mean EPL thicknesses of different soil types, and of arable and forest soils (Table 2). The EPL thickness is greatest in arable soils, at normal moisture conditions ranging from 25 to 29 cm, with a standard deviation of 5–8 cm. The average EPL depth is lower only in arable *Gleysols* and *Leptosols.* In summary, the EPL of eroded soils of arable lands is 3–5 cm thinner than that of uneroded soils. Land use may be decisive in the formation of EPL thickness, but does not influence the SC thickness of postlithogenic soils.

The area-weighted mean EPL thicknesses calculated by large ecological soil groups are presented in Table 6. The mean EPL thickness for Estonia as a whole is 25 cm (23 cm among mineral soils); the SC area-weighted mean thicknesses are 59 and 62 cm. The EPL thicknesses on calcareous soils appear to be somewhat higher than on non-calcareous soil types.

Comparison of the SOC retaining capacities of Estonian soils with soils of other regions

The comparison of SOC stocks per hectare (Mg ha^{-1}) sequestered in the mineral SC of Estonia with other regions (Kern 1994; Bernoux et al. 2002; Zhou et al. 2003) revealed noticeable similarities with other Nordic areas (i.e. relatively thin SC containing low SOC stock). For example, the mean SOC stock of 0.3 m soil layers in boreal conditions, 98–102 Mg ha^{-1} (Robert 2001), matches the weighted mean of the EPL of our hydromorphic mineral soils (Table 4). Although SOC stocks in *Gleysols* are relatively high compared to *Phaeozems* and *Chernozems* (Nemeth et al. 2002), the *Gleysols* have distinctly different (unstable, chemically unsaturated) humus quality. For mean grassland ecosystems, SOC stock is given as 116 Mg ha^{-1} by Lal et al. (1998b), which is very similar to the SOC stocks of our hydromorphic mineral (mostly *Gleysols*) grassland soils (Table 4). Comparative studies of meadow and forest soils in the Russian forest zone (Yakimenko 1998) have demonstrated that grassland ecosystems accumulate more SOC into the 50 cm soil layer than forest systems. Our data proved similar tendencies (Table 4). A comparison of SC SOC stocks of our soils (Tables 2 and 6) with the 50 cm soil layer of the northwestern United States (Kern et al. 1998) exhibited the variability of SOC stocks per hectare within similar limits, being higher (84–110 Mg ha^{-1}) in *Mollisols* than in *Alfisols* (56–86 Mg ha^{-1}). Soils with *aquic* water conditions tend to be similar to our *Gleysols* (SOC varying in the range 90–200 Mg ha^{-1}), as regards SOC stocks per hectare. The CV of the mean SOC stocks of our *Gleysols*, ranging from 20% to 60%, also coincides with data by Kern et al. (1998). The EPL SOC mean stocks of our *Sapric Histosols* (Table 2) closely matches the average superficial 30 cm layer SOC stocks of Canadian *Hemists* and *Saprists* (respectively 182 and 217 Mg ha^{-1}; Tarnocai 1998). The weighted means of SC SOC stocks per hectare of whatever area (forests, arable land, or grasslands) depends largely on the proportion of *Histosols* in mineral soils. It may be concluded that in pedo-ecologically equivalent conditions, SOC sequestration into the SC is quite similar.

Pedo-ecological regularities of SOC retention

The generalized pedo-ecological regularities of SOC retention by postlithogenic forest and arable mineral soils are presented in Fig. 4. The comparison of SOC stocks of the EPL (Fig. 4b, e) and SC (Fig. 4c, f) of different forest and arable soil types against the background of the Estonian postlithogenic soils ordination net revealed clear pedo-ecological regularities in SOC retention capacity (Mg ha^{-1}). By superimposing the postlithogenic mineral soils' ordination net provided with scalars (Fig. 1) with the pedo-ecological regularities ordination net (Fig. 4), we can see that the SOC retention capacity increases from dry and *udic Leptosols* (group I) and from *udic Podzols* (group VI) towards *Gleysols* (groups VII and VIII or GL mo cc eu lv & dyp; Table 1), formed on calcareous material.

The SOC concentrations (g kg^{-1}) of different soils are also generalized against the background of the postlithogenic soils ordination net (Figs 4 and 5). The comparison of SOC concentrations in the humus horizons of forest (Fig. 4a) and arable soils (Fig. 4d) shows that

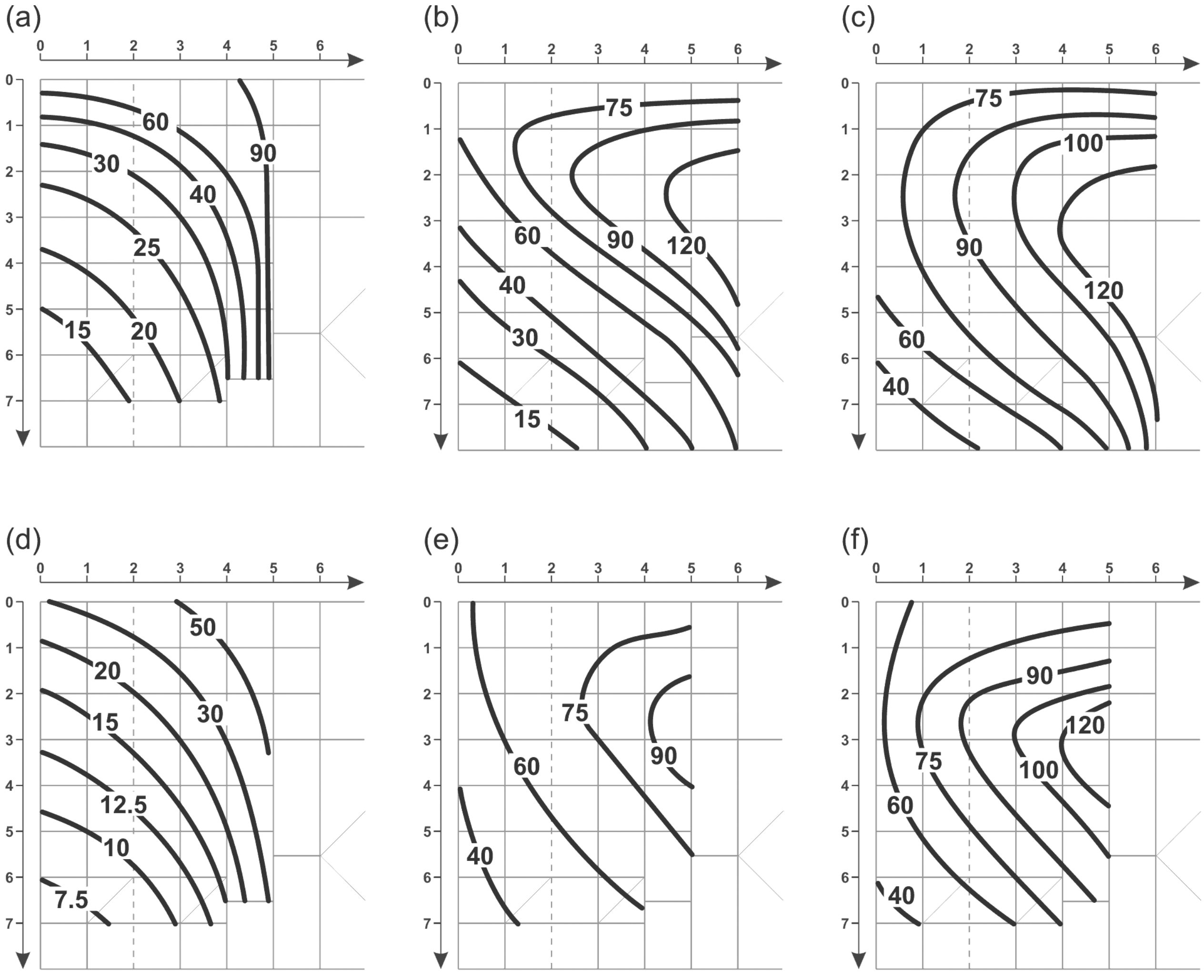

Fig. 4. Isolines of generalized soil organic carbon (SOC) content and stocks in different layers of forest and arable soils on the background of the ordination net of postlithogenic mineral soils. Scalars: Vertical (0–8), descending from top – genetical-lithological conditions, from calcareous *Leptosols* (<1) to acid *Podzols* (>7). Horizontal (0–6), from left to right – moisture conditions, from dry automorphic (<1) to hydromorphic *histic* soils (5–6). For additional explanations of the vertical scalar see the legend on the left side of the scalar and of the horizontal scalar – legend above the scalar in Fig. 1. (a) SOC content (g kg^{-1}) in A horizons of forest soils; (b) SOC stock (Mg ha^{-1}) in the epipedon layer (EPL) of forest soils; (c) SOC stock (Mg ha^{-1}) in the soil cover (SC) of forest soils; (d) SOC content (g kg^{-1}) in the EPL or A horizons of arable soils; (e) SOC stock (Mg ha^{-1}) in the EPL of arable soils; (f) SOC stock (Mg ha^{-1}) in the SC of arable soils.

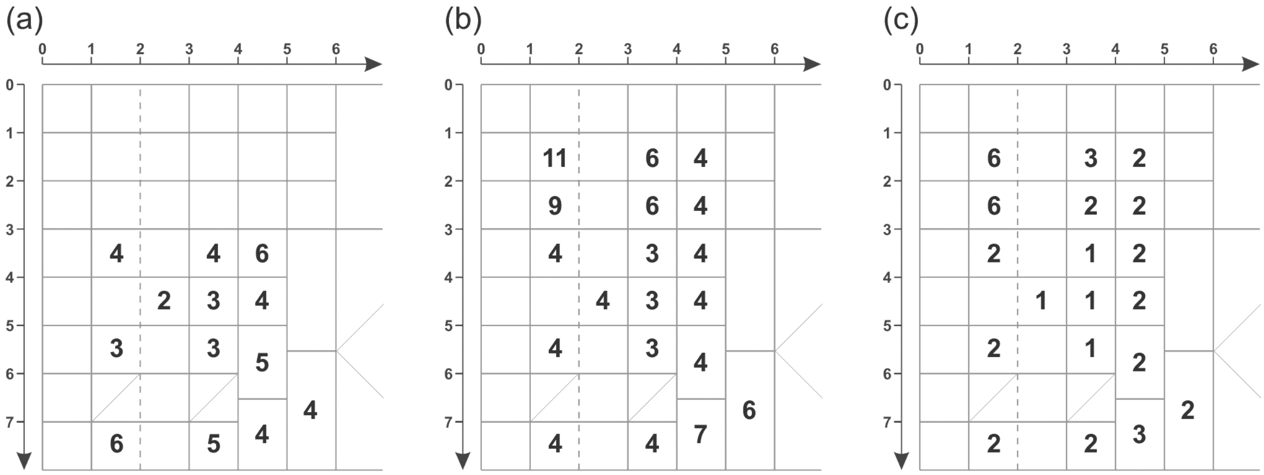

Fig. 5. Generalized soil organic carbon (SOC) contents (g kg^{-1}) in subsoil of postlithogenic mineral soils. Scalars: Vertical (0–8), descending from top – genetical-lithological conditions, from calcareous *Leptosols* (<1) to acid *Podzols* (>7). Horizontal (0–6), from left to right – moisture conditions, from dry automorphic (<1) to hydromorphic *histic* soils (5–6). For additional explanations of the vertical scalar see the legend on the left side of the scalar and of the horizontal scalar – legend above the scalar in Fig. 1. (a) SOC content in eluvial (E, Ea) horizons; (b) SOC content in illuvial (B) horizons; (c) SOC content in transitional (BC) horizons.

SOC content is noticeably (1.5–1.9 times) higher in the A horizons of forest soils than in arable soils. At the same time, their SOC stocks are approximately similar, due to the thinner EPL of forest soils (Table 2). In addition to the EPL of soils, marked concentrations of SOC may be found in eluvial (E, Ea) and various illuvial (B, BC) horizons (Fig. 5).

Land use and SOC retention

The humus status of soils formed in various pedo-ecological conditions may be substantially influenced by agricultural practices (Filcheva & Mitova 2002; Kätterer et al. 2004; Bellamy et al. 2005; Koch & Stockfisch 2006). Land use and/or tillage technology primarily affects the humus status of superficial soil layers. On arable lands *Podzols* and *Histic Gleysols* are absent, but in the course of cultivation, instead of *Podzols*, *Albeluvisols* have formed, and instead of *Histic Gleysols*, various other types of *Gleysols* have developed. The transformation from forest to arable soil considerably increases the SOC stocks per hectare of the EPL of *Haplic Albeluvisols*. In all other cases, cultivation leads to a reduction.

The turnover time of EPL SOC is much shorter than in the SSL, and is controllable by soil management. The sustainable management of soils with additional CO_2 sequestration into the SC is based on adequate information about the SOC retention capacity of different soil types, on the monitoring of their actual humus status, and on suitable soil management technology (Qiguo et al. 1997; Smith et al. 2000; Reicosky 2002). The SC SOC stocks can be increased (1) through increased soil productivity, which enhances the potential to form and accumulate green phytomass, which is later used to increase SOC stocks in deeper horizons (those beneath the most actively functioning soil layers), or (2) through deep ploughing, which mechanically disposes the SOC-rich layer into the less functioning deep layers, resulting in reduced decomposition or long-term SOC capturing in the soil.

The SC composition of arable, forest, and grasslands varies widely according to their soil type distribution (Table 1) and texture. On arable land more fertile upland mineral soil types (with loamy texture) are dominant (totalling 72%). The proportion of organic (37%) and lowland mineral soils (39%) is greatest in forest lands. In soil type composition both arable and forest lands differ from grasslands. The study also revealed that the land use policy of Estonia in the previous century was generally pedo-ecologically acceptable. The best soils were used for crop cultivation, while less productive soils (from an agricultural perspective) remained in their natural state; they were eventually transformed into forest soils. The area of natural grasslands is much smaller than that of forest and arable land. The grasslands which formed on automorphic mineral soils have characteristics of both forest and arable lands, and may be considered as a reserve for these. A number of grasslands are situated on barely afforested soils (e.g. coastal, alluvial, wet deluvial soils and alvars); it is therefore recommended that these be preserved in their natural condition.

CONCLUSIONS

1. Organic carbon stocks in the soil cover (SC) and its epipedon layer (EPL) are soil-type specific and depend mainly on soil carbonate and clay content, moisture regime, pedon fabric, and land use type. The weighted mean humus status indices of soil types may be used as benchmarks in the arrangement of sustainable land use from the soil-based (pedocentric) perspective. Depending on the soil type, the mean soil organic carbon (SOC) stocks for the SC or sola varies within the range of 43–333 Mg ha^{-1}, and for the EPL within 16–173 Mg ha^{-1}.
2. An estimated 593.8 ± 36.9 Tg of organic carbon is sequestered in the SC (totalling 42 400 km^2) of Estonia, 64.9% (385.3 ± 27.5 Tg) of which is found in the EPL and 35.1% (208.5 Tg) in the subsoil layer.
3. Land use change has a substantial influence on the humus status of the superficial part or epipedon of soils. As a rule, with the change in land use from natural to arable status, the thickness of the epipedon increases and SOC concentration decreases; SOC stocks remain approximately equal. The humus status of the subsoil depends primarily on soil-type peculiarities.

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Orgaanilise süsiniku varud Eesti muldades

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On esitatud Eesti automorfsete mineraal- (9 mullagruppi), hüdromorfsete mineraal- (7) ja turvasmuldade (4) orgaanilise süsiniku (MOS) varud (Mg ha^{-1}) muldkatte kui terviku (mullakiht alates maapinnast kuni muutumatu lähtekivimini) ning selle ülemise osa ehk epipedoni kihi (hõlmab kõik pindmised orgaanilise aine akumulatsioonihorisondid: metsakõdu ja huumus-, toorhuumus- ning turbahorisondid) kohta. MOS-i koguvarude arvutamise aluseks on olnud vastava mulla MOS-i mahutamise võime ja mulla leviku pindala, kusjuures on arvestatud ka maakasutuse iseloomu (metsad, põllud, rohumaad). Kokku on Eestimaa muldkattesse (42 400 km^2) akumuleerunud 593,8 ± 36,9 Tg MOS-i, millest 64,9% (385,3 ± 27,5 Tg) asub epipedoni kihis ja 35,1% alusmullas ehk muldkatte välja- ning sisseuhte horisontides. MOS-i mulda akumuleerimise pedo-ökoloogilisi seaduspärasusi on käsitletud Eesti postlitogeensete muldade ordinatsiooniskeemi taustal.