Soil Type and Management Effects on Organic Carbon Stocks and Soil Structure Quality in North Germany.

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Received: 6 August 2019 *Accepted: 1 October 2019*

Abstract

Improvement of carbon sequestration in soils for a more sustainable environment and prevention of climate change require not only knowledge about soil organic carbon (SOC) stocks, but also about interactions between land use and total amount and distribution of carbon. In North Germany (state: Schleswig-Holstein) about 925 soil profiles in the four dominant geological regions [Weichselian glacial region, the sandy outwash region (Lower “Geest”), the Saalian glacial region (Higher “Geest”), and the marshland with alluvial deposits] were sampled down to at least the 90 cm depth. Carbon content, pH, bulk density, and grain size distribution were analyzed for the major characteristic soil horizons. The four dominant geological regions possess different SOC stocks as well as SOC contents. The total amount of SOC stored within the representative soil profiles down to the 90 cm depth was analyzed for three depths: 0 – 30, 30 – 60, 60 – 90 cm; for the total area of Schleswig Holstein (15.369 km^2), they summed to 244 Mt. SOC stocks, however, differed depending on the land use management system and clay content. Arable soils were most sensitive to soil deformation and the higher the clay content the less rigid they were, if the SOC to clay ratio were used as an index for structural quality. Grassland topsoils showed the highest SOC stocks and a mediate structural quality. The latter was highest for forest soils, which, however, had a higher SOC content but, at the same time, a less fertile SOC composition (litter with high C: N ratio). Further research on the carbon composition (labile, active, intermediate, or passive pools) would help to get a better insight into the role of SOC on soil strength and soil functions.

Highlights:

- SOC stocks of North Germany (Schleswig-Holstein) amount to 244 Mt (0 – 90 cm depth)
- SOC stocks differ depending on the land use management system and clay content
- Highest SOC stocks were found in grassland topsoils (0–30 cm depth)
- SOC:clay content ratio of topsoils defines structure strength of soils

- Arable topsoils showed lower SOC:clay content ratios than grassland and forest ones

Key words: soil organic carbon stocks, land use management, tillage systems, soil strength, SOC:clay ratio, Luvisol, Gleysol, Podzol, Cambisol, Anthrosol.

Introduction

Carbon sequestration, time-dependent changes in soil organic carbon content, or the 4 per mille initiative (4p1000, 2017; IPCC, 2006) are intensely discussed in science and policy because of the worldwide increasing problem of climate change, which has consequences for the environment and human life on earth (van Groenigen et al., 2017; Conrad et al., 2017; Zomer et al., 2017). Carbon stock calculations are done to suggest an improved and more sustainable land use. Alterations of soil management systems in the future will be necessary for increased carbon stocks (Chenu et al., 2019; Cosentino et al., 2006; Balesdent and Arrouays, 1999; Wiesmeier et al., 2012).

Batjes (2016) estimates the worldwide soil organic carbon (SOC) stock to 1400 – 1600 Pg, while Lal (2018) stated that the global magnitude (Pg) of SOC is 677 to 0.3 m, 993 to 0.5m, and 1,505 to 1 m depth. Thus, ~55% of SOC to 1 m lies below 0.3 m depth. He furthermore concludes that alterations of soil management systems in the future will be necessary. The reference points for such calculations are the temporal change in global land use since pre-agricultural understanding natural ecosystems to 2015. However, there are no further details concerning soil type specific variations.

Soil organic matter (SOM) not only helps to improve soil structure formation and soil strength, but it also enhances filter and buffer processes in soils including an enhanced nutrient storage, water availability, and equilibrated heat distribution due to thermal processes (Hartge and Horn., 2016). If an improved soil structure and pore continuity, as well as related hydraulic processes, coincide with higher SOM content and organic carbon quality, they can also help to reduce soil losses due to water and wind erosion. However, the terms carbon sequestration and carbon storage, which are often used in the literature, define different processes. Carbon sequestration describes the process of CO_2 storage in soils, because of plant growth and the decay of organic residues over decades. Carbon stock (storage) quantifies the volumetric changes, because of these long-term processes over depth depending on climatic conditions, parent material, and soil types under various land use systems (Lal, 2004; Wiesmeier et al., 2012; Guggenberger et al., 1994). The increase of the organic carbon stock in soils strongly depends on land use systems (Smucker et al., 2010), while the recommendations on how to ameliorate soil structure and to improve the accessibility and availability of particle surfaces depend on the positive aspects of SOM. The organo-mineral bondings, hydrophobicity, or particle coating with organic acids are of major importance (Horn et al., 2017; Feeney et al., 2006; Blume et al., 2016). The definition of carbon sequestration furthermore assumes that the organic material originates from the site itself and is not added from other sites or as processed material like biochar.

An overview on worldwide research activities concerning soil organic carbon (SOC) stocks was given during the FAO conference in Rome 2017. As an outcome, a SOC stock map was developed and presented during the World Soil Day ceremony in December 2017 (FAO, 2017). This map quantifies the SOC stocks in the top 30 cm of soils worldwide, as the most dominant but also sensitive soil volume for carbon stock. The world average of about 677 Pg SOC, stored in the top 30 cm of the soil, however, also shows the dilemma, as this layer is most sensitive for management-induced decomposition. Both the ecological as well as economic recommendations assume that additional consideration of the deeper soil layers and a more management specific quantification can help to calculate the SOC storage more reliably, and to describe the effects of SOC on a sustainable soil structure.

SOC stocks can, therefore, be considered twofold: (i) they improve physical, chemical, and biological processes in soils, (ii) these positive effects also depend on the long-term connection between the mineral and the organic phase to be sustainable. Johannes et al. (2017) dealt with the SOC: clay ratio concerning mechanical structure strength and the link to the maintenance of soil functions, and discussed how far SOC stocks can be linked to physical soil properties and functions. They conclude: “the SOC : clay ratio decreases with decreasing soil structure quality. The SOC : clay ratio of > 1:8 is the average for a very good structure quality. A SOC: clay ratio of 1:10 is the limit between good and medium structural quality, thus it constitutes a reasonable goal for soil management by farmers”. This would be a suitable approach, although it is only an indirect link to quantify soil degradation or deformation. In recent years, a new countrywide approach to quantify SOC stocks was introduced in Germany (Walter et al., 2016). It enables SOC stock calculations under well-defined analytical procedures. The benefit of an identical analysis approach coincides, however, with a limited, although well defined, number of soil analyses. They could easily be extended to a smaller scale, if additional, state-based, datasets could be included.

The approach, how to link SOC stocks over depths with qualitative structure classification systems, was hitherto not considered on a state scale with various geological parent materials. However, it may help to define sustainable land use systems on a regional scale (Horn and Kutílek, 2009). It is therefore the aim of this paper to analyze adequate datasets on the state scale in Schleswig-Holstein. How far can site and depth-dependent distributions of SOC under arable, forest, and pasture/grassland management be quantified and linked with soil structure properties expressed as the SOC:clay ratio?

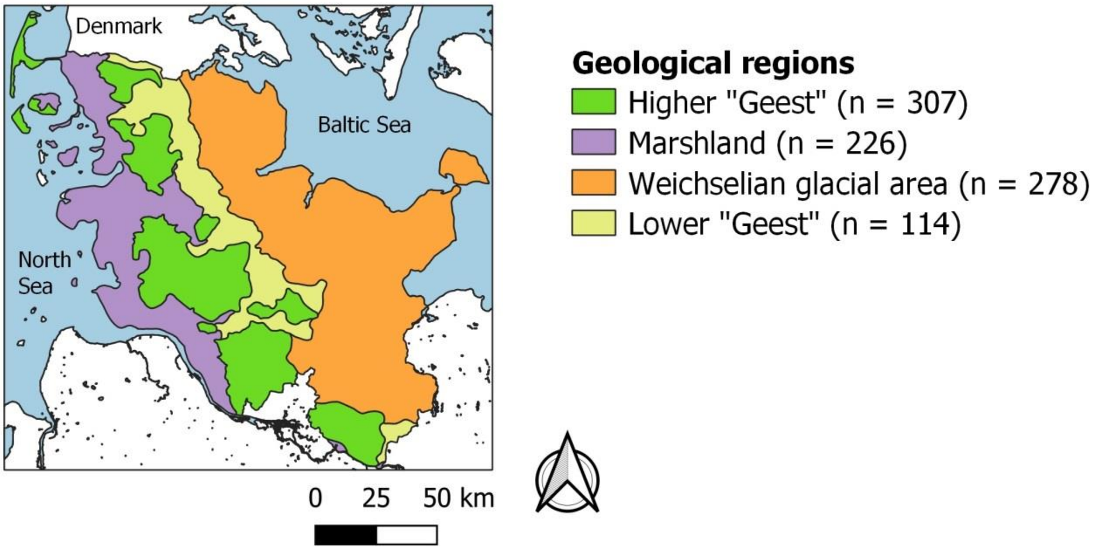

Figure 1. *Geographical map representing the 4 geological regions of Schleswig-Holstein (North Germany) with the number (n) of sampled soil profiles. Map basis: BKG (2010).*

Materials and Methods

The dataset was collected in between the year 1970 and 2015 during various research programs in Schleswig Holstein by the State Institute of Agriculture, Resource and Landscape Planning (LLUR). It includes 925 soil profiles with a complete soil type description, physical, and chemical data down to at least the 90 cm depth under arable, grassland, and forest land-use. Soil management systems, like conventional and conservation tillage, are also included in the dataset, but they were, unfortunately, not differentiated. Therefore, the corresponding datasets are accumulated using the term "arable land". The soil samples were collected from the four geological regions of North Germany in the state Schleswig-Holstein (Figure 1): the Weichselian region in the East, the sandy outwash region (Lower "Geest"), the Saalian glacial region (Higher "Geest") in the center, and the marshland with alluvial deposits in the West of Schleswig-Holstein. The Weichselian glacial deposits contain fertile Luvisols and Cambisols and "Colluvic" Anthrosols, but also Gleysols and lowland Histosols, while the outwash region is dominated by Brunic Arenosols or Cambisols depending on soil texture, Podzols, Gleysols, as well as (Rheic and Ombric) Histosols. The Saalian glacial region is approximately 150,000 years older than the Weichselian region and is characterized by mainly loamy and sandy carbonate free Brunic Arenosols or Cambisols, Stagnosols, Podzols, Gleysols, and Rheic Histosols,. Finally, the marshland includes different types of Fluvic Gleysols, Histosols (the regional distribution and the total area are documented in Table 1). The marsh area involves in total 2,854 km²; the sandy outwash region extends to 2,010 km² the Saalian glacial region to 3,766 km²; and the Weichselian glacial area to 6,740 km². Long-term mean temperature of Schleswig-Holstein is 8.8° C and long-term mean precipitation sum is 840 mm, while the latter averagely decreased from the western coast (marsh, ca. 900 mm) to the eastern coast (Weichselian glacial area, ca. 700 mm) (between 1981-2010, DWD, 2017).

Disturbed and undisturbed soil samples were analyzed, and the data included in this paper like grain size distribution, SOC and bulk density are for soil samples that were taken from different depths, but mostly horizon-specific down to at least 90 cm from all soil profiles. While the methodology remained the same for calculating the bulk density, the techniques for determining the carbon content changed depending on the project over the sampling years (dry combustion for elemental analysis or wet combustion according to the Lichterfelder method as well weighting loss of ignition). For more details see Blume et al. (2010) and Hartge and Horn (2016). SOC stocks (t/ha) were calculated from carbon contents (%) multiplied by bulk density (g/cm³) and soil horizon thickness (cm) and summarized over the depth sections: 0 – 30, 30 – 60, 60 –90 and totally 0 – 90 cm.

Results

- Effect of geological origin, soil type, and land use management on carbon storage.

The four dominant geological regions possess different SOC stocks (Table 1). The total amount of SOC stored within the representative soil profiles down to the 90 cm depth sums up to 244 Mt for Schleswig-Holstein. This sum is limited to the dominant soil types in the four regions, which, in general, cover around 90 % of the total soil surface area of 15,369 km² (Table 1). This resulted in a mean carbon density of 159 t/ha in Schleswig-Holstein. The highly fertile Weichselian glacial area with the largest extent stores the highest amount of SOC followed by the marshland and the higher "Geest" (Saalian glacial area). While 60 – 70 % of the mostly highly fertile soils in the Weichselian glacial area and marshland are mainly used for crop production (arable land), the less fertile soils of the "Geest" are more represented by permanent grassland and forestry land use (Figure 2). The lowest SOC stocks were calculated for the sandy outwash region, the Lower "Geest", although the permanent grassland and forest sites are abundant here, which can be attributed to the low storage capacity of the sandy parent material. Within all regions peat soils, like lowland and highland Histosols, always store the largest amount of SOC down to depth. As expected, the total stocks in all regions are always the highest in the Histosols, while, surprisingly, relatively low SOC-stocks were found in the most fertile Luvisols derived from glacial material. Due to the mass movement by erosion, the Anthrosols derived from colluvic material have high amounts of SOC down to the 90 cm depth, which is also the case for (Gleyic) Podzols due to the accumulation of organic acids in the B-horizons. The various forms of Fluvic Gleysols in the marsh region always show high SOC stocks down to depth.

If we compare the overall SOC stock distribution with depth in the Weichselian region, nearly 60 % are stored in the top 30 cm, followed by 25 % in the 30–60 cm depth. The same distribution can be found in the sandy outwash (lower "Geest"), and in the higher "Geest" (Saalian origin). The most equal distribution over depth is visible in the marsh soils due to the geogenic origin of the organic material in the sediments.

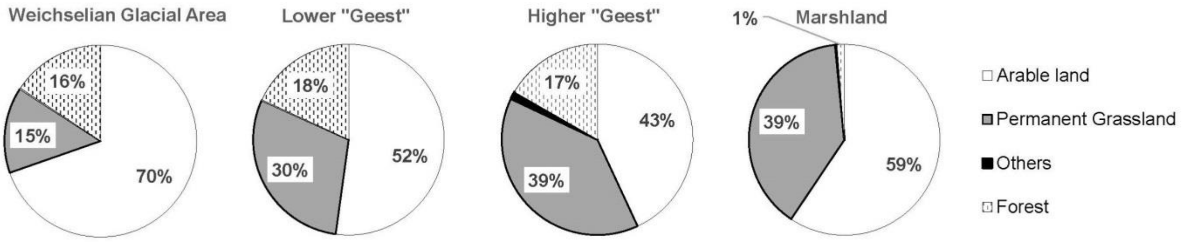

Figure 2. *Relative share of the 3 main land use management systems (arable land, permanent grassland, and forest) on the total agricultural and forestry area in Schleswig-Holstein (authors' own representation according to MELUND (2018) and Federal Statistical Office, 2015)*

The SOC contents and SOC stocks of the topsoil are related to land use management: arable, grassland, and forest. In all four regions, the grassland topsoils always store the highest amounts of SOC, while the lower and the higher "Geest" also store the highest amounts (Figure 3), with up to 140 t/ha in the top 30 cm in the lower "Geest" area. Significantly, smaller amounts are stored in the arable and forest sites in all four regions.

Table 1. *Depth-specific soil organic carbon (SOC) stocks from 0 to 90 cm depth for the most frequent soil types with a relative area > 3 % in the different geological regions in Schleswig-Holstein. n = number of soil profiles*

Weichselian glacial area

Soil type (WRB, 2014)	Clay (Mean)	Clay (+/-)	Relative area	Absolute area	0-30 cm SOC stock		*n*	30-60 cm SOC stock		*n*	60-90 cm SOC stock		*n*	∑ 0-90 cm SOC stock	
	[%]	[%]	[%]	[ha]	[t ha^{-1}]	[Mt*ha]	*[-]*	[t ha^{-1}]	[Mt*ha]	*[-]*	[t ha^{-1}]	[Mt*ha]	*[-]*	[t ha^{-1}]	[Mt*ha]
Stagnic Luvisol	18.6	5.5	23	153662	62	9.5	*26*	17	2.6	*27*	11	1.7	26	90	13.8
Stagnosol	20.9	13.3	20	134791	79	10.7	*19*	19	2.6	*24*	9	1.3	24	108	14.6
Anthrosol ("Colluvic")	12.4	9.2	16	106485	85	9.0	*13*	71	7.6	*11*	49	5.2	14	205	21.8
Cambisol/Brunic Arenosol	4.9	3.3	12	81548	55	4.5	*21*	15	1.2	*26*	7	0.5	32	77	6.3
Luvisol	15.4	4.8	8	50547	52	2.6	*22*	18	0.9	*26*	9	0.5	28	79	4.0
Rheic Histosol			6	37741	455	17.2	*1*	204	7.7	*5*	175	6.6	6	835	31.5
Stagnic Cambisol	9.1	4.5	4	26958	60	1.6	*7*	17	0.5	*5*	6	0.2	7	82	2.2
Sum			**88**	**591732**		**55**	*109*		**23**	*124*		**16**	*137*		**94**
Others			12	82222											

Lower “Geest“

Soil type (WRB, 2014)	Clay (Mean)	Clay (+/-)	Relative area	Absolute area	0-30 cm SOC stock		*n*	30-60 cm SOC stock		*n*	60-90 cm SOC stock		*n*	∑ 0-90 cm SOC stock	
	[%]	[%]	[%]	[ha]	[t ha^{-1}]	[Mt*ha]	*[-]*	[t ha^{-1}]	[Mt*ha]	*[-]*	[t ha^{-1}]	[Mt*ha]	*[-]*	[t ha^{-1}]	[Mt*ha]
Gleyic Podzol	2.9	1.0	36.3	72954	137	10.0	*16*	60	4.4	*16*	20	1.4	19	216	15.8
Gleysol	6.9	5.8	13.6	27333	120	3.3	*6*	27	0.7	*9*	22	0.6	10	169	4.6
Podzol (Neocambic)	3.7	1.4	12.4	24921	74	1.8	*3*	26	0.6	*4*	11	0.3	5	110	2.8
Cambisol/Brunic Arenosol	3.7	1.6	11.2	22509	86	1.9	*7*	21	0.5	*12*	10	0.2	14	117	2.6
Podzol	2.6	1.3	8	16078	66	1.1	*8*	28	0.5	*13*	10	0.2	17	104	1.7
Rheic Histosol	-	-	6.1	12259	311	3.8	*5*	214	2.6	*10*	158	1.9	12	684	8.4
Ombric Histosol	-	-	3.7	7436	242	1.8	*3*	179	1.3	*6*	162	1.2	6	582	4.3
Sum			**91**	**183490**		**24**	*48*		**11**	*70*		**6**	*83*		**40**
Others			9	17485											

Table 1 ***(Continue).*** *Depth-specific soil organic carbon (SOC) stocks from 0 to 90 cm depth for the most frequent soil types with a relative area > 3 % in the different geological regions in Schleswig-Holstein. n = number of soil profiles.*

Higher “Geest“

Soil type (WRB, 2014)	Clay (Mean)	Clay (+/-)	Relative area	Absolute area	0-30 cm SOC stock		*n*	30-60 cm SOC stock		*n*	60-90 cm SOC stock		*n*	∑ 0-90 cm SOC stock	
	[%]	[%]	[%]	[ha]	[t ha^{-1}]	[Mt*ha]	*[-]*	[t ha^{-1}]	[Mt*ha]	*[-]*	[t ha^{-1}]	[Mt*ha]	*[-]*	[t ha^{-1}]	[Mt*ha]
Cambisol/Brunic Arenosol	4.5	2.0	18.2	68535	79	5.4	*33*	19	1.3	*34*	8	0.5	35	106	7.3
Stagnosol	15.5	8.8	11.9	44811	93	4.2	*51*	26	1.2	*49*	11	0.5	54	130	5.8
Gleyic Podzol	3.7	1.4	10	37657	138	5.2	*16*	66	2.5	*15*	18	0.7	19	223	8.4
Stagnic Cambisol/Arenosol (Stagnic)	6.1	2.4	8.8	33138	63	2.1	*8*	20	0.7	*6*	12	0.4	8	96	3.2
Podzol (Neocambic)	4.5	1.9	8.7	32761	96	3.1	*7*	23	0.7	*11*	9	0.3	11	127	4.2
Gleysol	9.2	5.6	6.7	25230	108	2.7	*10*	31	0.8	*10*	18	0.4	14	157	4.0
Anthrosol ("Colluvic")	7.9	1.5	6.2	23347	65	1.5	*4*	31	0.7	*4*	14	0.3	3	111	2.6
Rheic Histosol	-	-	4.8	18075	307	5.6	*11*	204	3.7	*14*	173	3.1	18	684	12.4
Stagnic Podzol	7.3	2.6	4.7	17699	154	2.7	*10*	49	0.9	*7*	11	0.2	11	214	3.8
Podzol	3.8	2.0	4.5	16945	97	1.6	*24*	37	0.6	*24*	14	0.2	27	148	2.5
Plaggic Anthrosol	7.5	-	4.3	16192	92	1.5	*1*	65	1.1	*1*	21	0.3	1	178	2.9
Luvisol	11.8	0.3	3.4	12803	61	0.8	*2*	23	0.3	*2*	11	0.1	2	94	1.2
Sum			**92**	**347193**		**36**	*177*		**14**	*177*		**7**	*203*		**58**
Others			8	29372											

Table 1 ***(Continue).*** *Depth-specific soil organic carbon (SOC) stocks from 0 to 90 cm depth for the most frequent soil types with a relative area > 3 % in the different geological regions in Schleswig-Holstein. n = number of soil profiles.*

Marshland

					0-30 cm			**30-60 cm**			**60-90 cm**			**∑ 0-90 cm**	
Soil type (WRB, 2014)	**Clay (Mean)**	**Clay (+/-)**	**Relative area**	**Absolute area**	**SOC stock**		***n***	**SOC stock**		***n***	**SOC stock**		***n***	**SOC stock**	
	[%]	**[%]**	**[%]**	**[ha]**	**[t ha^{-1}]**	**[Mt*ha]**	***[-]***	**[t ha^{-1}]**	**[Mt*ha]**	***[-]***	**[t ha^{-1}]**	**[Mt*ha]**	***[-]***	**[t ha^{-1}]**	**[Mt*ha]**
Eutric Fluvic Gleysol (Drainic)	25.8	7.7	27.0	77048	69	5.3	*20*	32	2.4	*40*	23	1.8	43	124	9.5
Fluvic Gleysol (Drainic)	36.8	7.7	17.6	50224	70	3.5	*19*	38	1.9	*39*	31	1.5	45	138	7.0
Calcaric Fluvic Gleysol (Drainic)	15.8	7.2	16.8	47941	51	2.5	*36*	25	1.2	*47*	20	0.9	50	96	4.6
Fluvic Gleysol (Clayic. Drainic)	42.5	8.6	8.2	23400	100	2.3	*4*	53	1.2	*5*	39	0.9	7	192	4.5
Rheic Histosol	-	-	6.7	19119	259	5.0	*1*	223	4.3	*2*	192	3.7	2	674	12.9
Calcaric Fluvic Gleysol (Salic)	18.6	11.0	4.5	12841	58	0.7	*7*	34	0.4	*9*	36	0.5	14	128	1.6
Ombric Histosol	-	-	4.0	11415	285	3.3	*6*	177	2.0	*6*	230	2.6	5	692	7.9
Fluvic Thionic Gleysol (Hyperhumic)	37.5	16.5	3.0	8276	198	1.6	*3*	207	1.7	*6*	88	0.7	7	493	4.1
Sum			**88**	**250264**		**24**	*96*		**15**	*154*		**13**	*173*		**52**
Others			12	35100											

- Effect of SOC on soil structure formation and strength

The link between the SOC and clay content may allow one to indirectly define soil strength based on the clay mineral associations, expressed as the SOC:clay ratio. Because Illites dominate the clay fraction in Schleswig-Holstein, no further mineral specific interactions need to be considered.

Irrespective of soil management, a weak positive relationship between SOC and clay content arises first for soils containing > 12 % clay, indicating the lowest threshold at which clay-carbon-associations play an important role for SOC storage processes (Figure 4). The relationship becomes closer for soils with higher clay content, i.e., > 20 %. Based on this, SOC:clay ratios are calculated only for soils with a clay content > 12% and are differentiated for the three land use systems (Figure 5).

A management specific differentiation, however, results in the data, which also show the varying sensitivity of soils and sites. In particular, the forest sites have the greatest ratio followed by the grassland sites, while the arable soils have the smallest value in the top 30 cm depth. The SOC:clay ratios are also attributed to structure quality classes according to Johannes et al. (2016). The smaller the ratio the less structured is the soil. SOC:clay ratios vary from < 1:13 (only for arable sites) to over 1:10 (predominantly for grassland sites) to > 1:8 (predominantly for forest sites) (Figure 5).

An additional classification for soil structural quality (based on our own results) of the arable, grassland, and forest sites for the clay classes is as follows: > 12 % and > 20 % in good (> 1:8), medium (1:10 up to 1:8), bad (1:13 – 1:10) and insufficient (< 1:13) soil structural quality. These classifications show a detailed differentiation among the 3 management systems (Table 2).

Table 2. *Classification of the structural strength expressed as SOC:clay ratio in dependence of the clay content > 12 % (a) and > 20 % (b) for the 3 main land use management systems: arable land, grassland and forest. The smaller the value of the SOC:clay ratio the less structured are the soils.*

a) **Clay content > 12 %**

Land use type	**SOC:clay > 1:8** [%]	**1:10 < SOC:clay < 1:8** [%]	**1:13 < SOC:clay < 1:10** [%]	**SOC:clay< 1:13** [%]
Arable land (A)	10	14	16	60
Grassland (G)	37	15	14	34
Forest (F)	81	19	0	0

b) **Clay content > 20 %**

Land use type	**SOC:clay > 1:8** [%]	**1:10 < SOC:clay < 1:8** [%]	**1:13 < SOC:clay < 1:10** [%]	**SOC:clay < 1:13** [%]
Arable land (A)	8	10	8	73
Grassland (G)	21	19	14	47
Forest (F)	0	0	0	0

When focusing on coarser textured soils, the forest sites are mostly well-structured due to the higher SOC content in forest topsoils compared to those under arable or grassland management. However, arable soils in the top 30 cm are mostly insufficiently structured and only 10 % are classified as good. Grassland soils have a medium position, as both very good, but also not appropriate, structural conditions can be found in them (Table 2a).

The results for the soils with clay contents > 20 % underline the higher sensitivity of arable soils and grassland sites for a worse structure (Table 2b). These soils become more sensitive to structure collapse, as can be seen from the increasing proportion of the sites with ratios < 1:13.

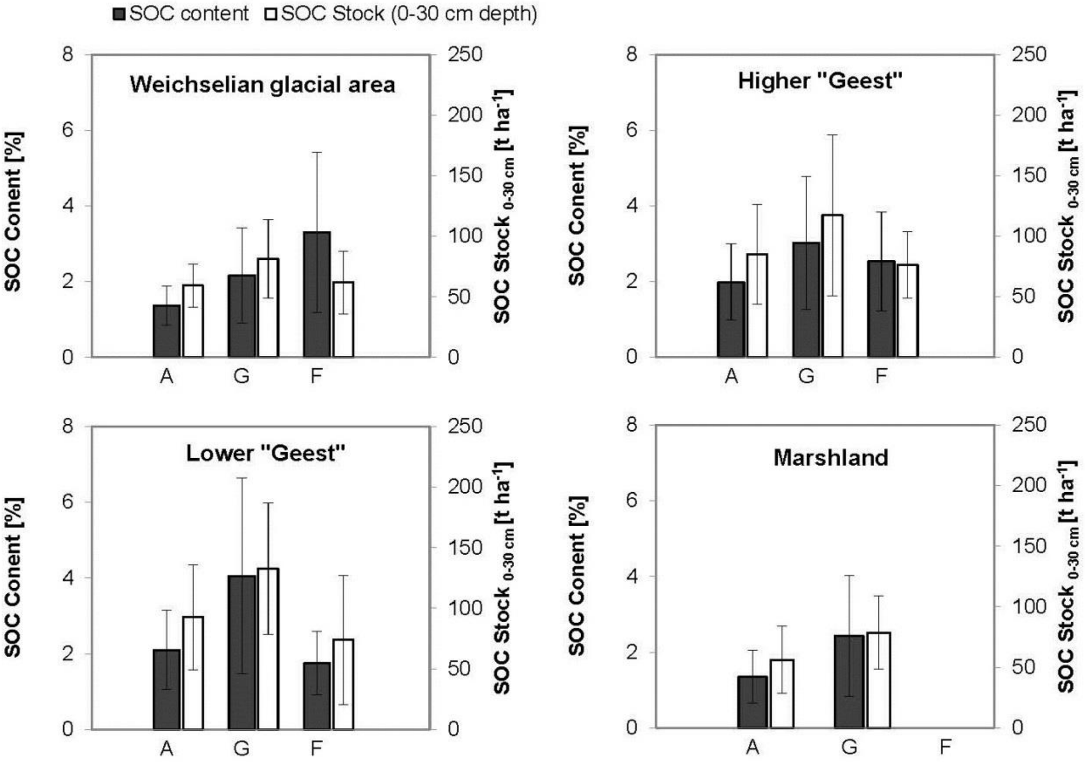

Figure 3. *Effect of land use management (A = Arable land, G = Grassland, F = Forest) on mean soil organic carbon (SOC) content of mineral A-horizons and SOC stock within 0–30 cm depths for the region-specific soil types in Schleswig-Holstein. Representative soil types for each geological region and corresponding number of soil profiles are given in Table 1. Organic soils are excluded.*

Discussion

Soil strength and soil functions depend on site-specific physical and chemical properties as well as on the biological activity, which can improve soil structure and soil functions but also worsen them. There are links among internal soil parameters, physical and chemical functions, and externally applied chemical, physical, and anthropogenic stresses.

They are responsible for soil degradation and may finally result in a reduced soil resilience, food production security, and groundwater recharge (Janzen, 2004). The enhanced sensitivity of soils due to soil slaking, erosion, reduced filtering, and buffering can be linked to soil structure strength changes and affected pore continuity (Gliński et al. 2011). Soil structure formation is, therefore, of main importance for soil processes all over the world and requires special attention. Aggregate formation always starts from coherent structure with swell-shrink and shear induced formation of prisms, blocky, and subangular blocky structure. Biological activity, as well as physicochemical processes, often additionally strengthens the formed aggregates (Blume et al., 2016). In this context, the formation of organo-mineral-bondings is of central importance, as the rigidity of these linkages between soil particles and organic components is well proven (Six et al., 2002), and may also prevent enhanced swelling because of hydrophobic coatings on the particle surfaces coinciding with a reduced accessibility for water.

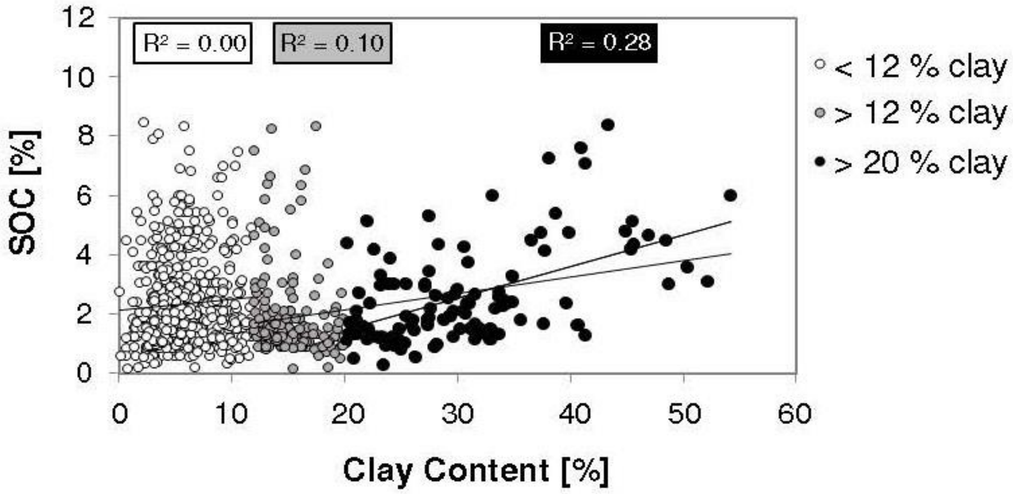

Figure 4. *Relation between soil organic carbon (SOC) and clay content for mineral A-horizons for the clay content classes: 0 – 12 % (“< 12 % clay”), 12 – 60 % (“> 12% clay”), 20 –60 % (“> 20 % clay”) (n = 807).*

Obalum et al. (2017) state that, rather than the temporal change and potential amount of SOM, the absolute amount is most important when evaluating soil degradation. Lal (2018) stated that based on various further publications, the global magnitude (Pg) of soil organic carbon (SOC) is 677 to 0.3 m, 993 to 0.5 m, and 1,505 to 1 m depth. Thus, ~55% of SOC to 1 m lies below 0.3 m depth. Soils of agroecosystems are depleted of their SOC stock and have a low use efficiency of inputs of agronomic yield. He furthermore states that the temporal change in global land use since pre-agricultural understanding natural ecosystems to 2015 can be related to changes in land management because the land areas under croplands and pasturelands have increased while that under forest, savanna, and shrubland have decreased.

This, however, causes a dilemma, because sufficient detailed datasets, either for large areas or for small areas, are only seldom available which also makes the comparison and the quantification of scenarios difficult. If soil type specific variations at the state level in Germany are included, the actually calculated SOC stock in Schleswig Holstein is slightly higher than those in the state Saxonia Anhalt but slightly smaller in Baden Württemberg (LAGB, 2014; Waldmann and Weinzierl, 2014). The latter has a greater area. The main reasons for such differences are the presence of peat and marsh soils because marsh soils contain already initially a certain SOC stock as parent material. Wiesmeier et al. (2012, 2013) prepared datasets and maps for Bavaria based on nearly 1500 soil profile datasets. They concluded that in general grassland soils stored the highest amount of SOC down to 1 m, with a median value of 11.8 kg/m^2, whereas considerably lower stocks of 9.8 and 9.0 kg/m^2 were found for forest and cropland soils, respectively. These data are in an identical range as the presented data for Schleswig-Holstein, if we consider the whole soil profiles down to 90 cm (compared to 1 m in Wiesmeier et al., 2012). Most of the SOC stocks are stored in the topsoils, irrespective of the management type. If we also include the ploughing effects on the deeper distribution of SOC in the whole profile, our datasets and calculations are also in agreement with those for Bavaria. The deeper ploughing may be one of the main reasons for the 25 % organic carbon in 30 – 60 cm depth. Due to the anthropogenically enhanced soil changes with time, „Colluvic“ Anthrosols and Plaggic Podzols (or colluvic, plaggic material) show a higher SOC stock and a more even distribution, while in the sandy outwash area (lower "Geest") only the Gleysols with a higher proportion of histic properties show high values.

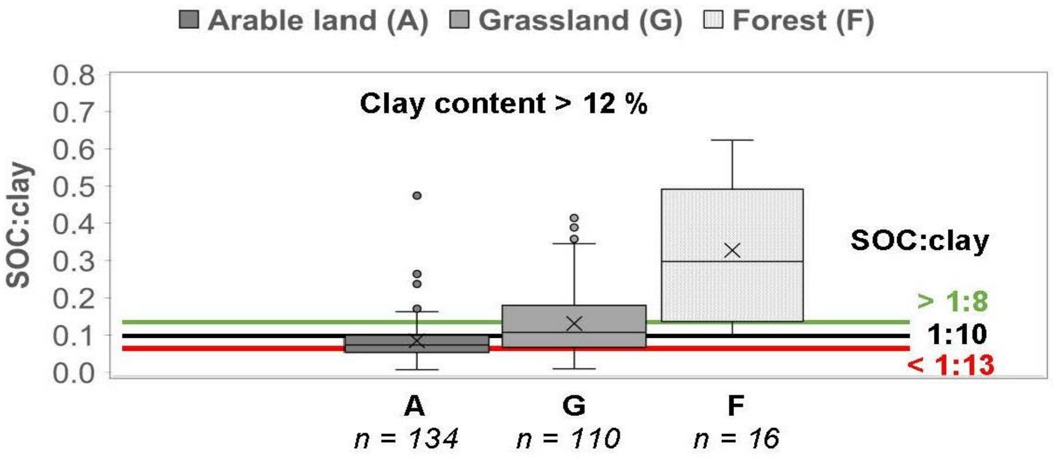

Figure 5. *Effect of land use management system on the soil organic carbon (SOC):clay ratio for the A- horizons of soils with clay contents > 12 % in the four representative geological regions of Schleswig-Holstein. The smaller the ratio the less structured are the soils.*

The ratio between SOC and clay content has often been mentioned in connection with the application of SOC stock datasets for the quantification of soil structure strength. Dexter et al. (2008) as well as Czyz et al. (2017) discussed the ratio between these parameters and concluded that, on average, the ratio should be about 1:10 in order to provide a sufficient coverage of the mineral surfaces with organic material to provide strong bondings among the particles. Johannes et al. (2017) furthermore differentiated the classification in order to get a better insight into soil physical and environmental processes. According to their findings, they concluded that, the smaller the ratio, the worse are the structural strength conditions. Comparing our results with their findings, we must conclude that the arable soils in Schleswig Holstein have a less favorable structure than the grassland and the forest sites in the top 30 cm; the latter ones seem to have the most favorable structural strength conditions based on this approach. Higher clay contents coincide with decreased SOC:clay ratios (<1:13) representing an insufficient soil structural quality, and define these soils as more sensitive to soil deformation. In particular, arable soils are throughout the year exposed to repeated wheeling and tillage operations even under less favorable soil moisture conditions.

Consequently, these soils are more intensely sheared and kneaded than grassland and forest soils, which cause an increased sensitivity to soil deformation (Hartge and Horn, 2016). However, grassland sites with less stress application throughout the year are not only stronger aggregated but also have a better linkage between the clay and organic carbon components and are, therefore, less susceptible to soil deformation. The conversion of arable into grassland soils, therefore, helps to gain more strength even if such changes take a long time. Ajayi and Horn (2016) showed these strength increases with time in stagnic Luvisols and Cambisols; but, even nearly 20 years after the conversion, there was still an ongoing strength gaining process.

How far these correlations define increases in strength must, however, be discussed in view of the composition of the organic carbon pool (Stockmann et al., 2013). Wiesmeier et al. (2014) stated that for the Bavarian soils around 90 % of total SOC stocks can be assigned to the intermediate and passive SOC pool in cropland and grassland soils. They also stated that high SOC stocks in grassland soils would be partly related to a higher degree of soil aggregation compared to cropland soils, and that forest soils were characterized by distinctly lower proportions of intermediate and passive SOC and a high amount of active SOC in form of litter and particulate organic matter. Thus, not only the total SOC amount but also its composition is relevant for the regaining of strength or its preservation. However, such information is not available for our soil profiles, although it would certainly help to further elucidate the interactions among aggregate formation, changes in accessible particle surfaces, and the coinciding strength changes. Also, we have not yet described the in situ soil conditions, because the detailed, high-tech conditions for the analysis would require undisturbed, i.e., structured, soil samples, which are impossible to obtain at the present time. Kögel-Knabner and Amelung (2013) described the interactions between mineral and organic components and pointed out that analyses of them would be feasible in order to get detailed information concerning the composition on various scales. But there are still many unsolved questions. One of the major open topics is the scale dependency and the necessity to extrapolate strength conditions from the small to the landscape scale. Babel et al. (1995) defined the interactions of mineral particle arrangements and organic matter amount on the functioning of aggregates at various scales. They also stated that surface accessibility and availability need to be linked to physicochemical processes, in view of the question of how far we can define the SOM properties and amount in structured soils, in order to predict sustainable soil properties and functions on all scales.

Conclusion

SOC stocks in Schleswig-Holstein differ depending on the land use management system and the clay content of the soil type.

Arable soils are most sensitive to soil deformation, and the higher the clay content is the less rigid they are, if the SOC:clay ratio is used as an index.

Grassland topsoils showed the highest SOC stocks and a mediate structural quality. The latter was highest for forest soils, which, however, have a higher SOC content, but, at the same time, less fertile SOC composition (litter with high C: N ratio).

Further research on the carbon composition (labile, active, intermediate, or passive pools) would help to get a better insight into the role of SOC on soil strength and soil functions.

Acknowledgement

The authors acknowledge with thanks the accessibility of these datasets from the state Institute LLUR, Schleswig-Holstein as well as the perfect proof reading and discussion of Prof. Dr. M. B. Kirkham, USA.

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