Peat and other organic soils under agricultural use in Germany: Properties and challenges for classification

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SUMMARY

Under natural conditions, peatlands store large amounts of soil organic carbon (SOC). However, they are under threat due to drainage which leads to mineralisation of soil organic matter to carbon dioxide (CO_2). This situation is especially severe in Germany, where more than 70 % of peat and other organic soils are used for agriculture. This study assessed the properties of these soils within the framework of the first German Agricultural Soil Inventory. In a nationwide 8 × 8 km grid, soils from a total of 3104 sites were sampled to depths of up to one metre or down to the peat base. Of these sites, 146 were on peat and other organic soils; and 31 % of the 146 sites were being affected not only by drainage but also by changes in horizonation (e.g. mineral covers, deep ploughing). The classification of heavily disturbed sites is limited within the German Manual of Soil Mapping, which has led to the development of an adapted classification scheme for peat and other organic soils under agricultural use in Germany. The respective peat classes showed distinct patterns of SOC and total nitrogen (N_t) contents and stocks, bulk density (BD) and C:N ratios. Overall, a SOC stock of 529 ± 201 t ha^{-1} and a N_t stock of 29.3 ± 13.9 t ha^{-1} were found within a depth of 0–100 cm. However, in deeper profiles, 48 % of the total SOC was stored below 100 cm depth down to the peat base. High SOC stocks were also found in peat-derived, mineral-covered and deep-ploughed organic soils, which might be classified as mineral soils depending on the classification system used but are still prone to mineralisation and need to be considered in terms of emissions reporting and mitigation. Logarithmic and quadratic pedotransfer functions were developed to estimate BD and SOC density, respectively, from SOC contents. This is necessary for the calculation of SOC stocks when analyses of BD are absent. The quadratic relationship between SOC content and SOC density clearly showed that heavily degraded organic soils store as much SOC in a defined volume as more natural ones, and that any estimates of differences in potential CO_2 emissions should not be based on SOC content, but on SOC density instead.

KEY WORDS: bulk density, mineral soil cover, nitrogen, SOC density, soil organic carbon

INTRODUCTION

Peatlands store large amounts of soil organic carbon (SOC), even though they cover only 2.2–3 % of the global land surface (Yu *et al.* 2010, Tubiello *et al.* 2016, Leifeld & Menichetti 2018). These are the only ecosystems that accumulate carbon as peat over millennia but the peat is highly vulnerable to anthropogenic disturbance, principally by drainage. Drainage for agriculture and forestry has turned these greenhouse gas (GHG) sinks into large sources of GHGs (Leifeld *et al*. 2019), particularly carbon dioxide (CO_2) and, especially when fertilised, nitrous oxide (N_2O) as well (Maljanen *et al*. 2010, Frolking *et al*. 2011, Tiemeyer *et al*. 2016). In addition, drainage leads to the shrinkage and subsidence of peatland, inducing changes in the peat structure and promoting a distinctive process of soil development (Okruszko 1993, Ilnicki & Zeitz 2003). Cultivation techniques, such as sand addition or deep ploughing, also have a considerable effect on the appearance and properties of the soil (Kuntze 1987, Göttlich 1990, Richardson *et al*. 1991). Worldwide, Tubiello *et al*. (2016) estimated that about 8 % of all peatlands are drained for agriculture, mainly (60 %) in boreal and cool temperate areas. Including drainage for forestry, Leifeld & Menichetti (2018) calculated the fraction of drained peatlands at about 11 %, of which 52 % are located in the boreal and temperate zones. In Europe as a whole, 25–44 % of organic soils are under agricultural use (Leppelt *et al*. 2014), while in Germany agriculture affects more than 70 % of all organic soils (Tiemeyer *et al*. 2020).

Knowledge about the soil properties of managed peatlands is essential in order to estimate GHG emissions and assess the potential effects of mitigation measures, especially when applying models at different scales. SOC contents and stocks have already been reported in numerous studies (Gorham 1991, Yu 2012, Loisel *et al*. 2014, Roßkopf *et al*. 2015), while data on nitrogen (N) and the C:N ratio are less commonly available, particularly for drained peatlands. Loisel *et al*. (2014) summarise the N contents and C:N ratios of mainly undisturbed northern peatlands, while Leifeld & Menichetti (2018) complement these data with new findings from tropical areas. However, both N stocks and the C:N ratio could be crucial factors for determining N_2O (Leppelt *et al*. 2014) and CO_2 emissions (Tiemeyer *et al*. 2016).

In the calculation of stocks, bulk density (BD) is the most important factor, but obtaining these samples is laborious. Where data are missing, pedotransfer functions (PTFs) can help estimate BD from SOC contents (Sonneveld & van den Akker 2011). The PTFs would preferably be parameterised specifically for organic soils (Hiederer & Köchy 2011). Data on SOC stocks are mostly restricted to the upper one or two metres of the soil (Batjes 1996, Hiederer & Köchy 2011, Roßkopf *et al*. 2015). This might be sufficient for mineral soils, where most of the SOC is stored in the topsoil (Batjes 1996, Poeplau *et al*. 2020), but not for organic soils, which have a potential thickness of several metres.

Unfortunately, comparability of information on soil properties and the extent of certain land-use classes is restricted not only by a lack of data but also by differences in classification systems and definitions of ‘peat’ and ‘organic soils’ (Joosten *et al*. 2017). This issue is also encountered internationally as several European countries carry out inventories in order to determine SOC stocks, all using different classification systems (e.g. Bellamy *et al.* 2005, Chapman *et al.* 2013, Heikkinen *et al.* 2013, Taghizadeh-Toosi *et al.* 2014). The aim of the first German Agricultural Soil Inventory, of which this study is a part, was to improve GHG emissions reporting. Thus, the basic definition of ‘organic soils’ comes from the guidelines of the Intergovernmental Panel on Climate Change (IPCC 2006, 2014). These follow the first version of the World Reference Base for Soil Resources (WRB; FAO 1998), which defines soils as ‘organic’ if they satisfy requirements (1) and (2) or (1) and (3) below:

(1) thickness 10 cm or more; a horizon less than 20 cm thick must have 12 % or more organic carbon when mixed to a depth of 20 cm;
(2) the soil is never saturated with water for more than a few days and contains more than 20 % (by weight) organic carbon (about 35 % organic matter);
(3) the soil is subject to water saturation episodes and has either:
    (i) at least 12 % (by weight) organic carbon (about 20 % organic matter) if it has no clay, or
    (ii) at least 18 % (by weight) organic carbon (about 30 % organic matter) if it has ≥ 60 % clay, or
    (iii) an intermediate, proportional amount of organic carbon for intermediate amounts of clay.

It is important to note that a ‘Histosol’ (FAO 1998) is not the same as an ‘organic soil’, according to IPCC (2006, 2014), since the IPCC definition omits the thickness criterion and the occurrence of andic or vitric horizons included in the FAO definition. Furthermore, the terms ‘peat’ and ‘peatland’ were deliberately not defined by the IPCC’s guidelines to leave room for country-specific definitions and classification systems. Therefore, it is not necessary to translate soil units exactly in order to comply with emissions reporting guidelines. In any case, a translation of this kind is often impossible within existing systems. Instead, it is crucial to identify the soil types that behave like ‘organic soils’ in terms of their GHG emissions.

In Germany, soils are classified using the Manual of Soil Mapping (Ad-hoc-AG Boden 2005). Peat soils are defined as soils consisting of peat containing at least 30 % soil organic matter (SOM) with a minimum thickness of 30 cm starting within the upper 20 cm of the soil. Using SOM instead of SOC is the first major difference compared with the WRB/IPCC definitions, and requires a conversion factor to be used. Mineral covers of 20–40 cm are mentioned as a soil type overlying the peat soil, whereas peat covered with ≥ 40 cm mineral horizons is classified as mineral soil. Generally, peat soils are subdivided into near-natural and degraded classes. Within these classes, a differentiation is made between rain-fed bogs and groundwater-fed fens. The general approach of the German classification system is that soil horizons should reflect soil development processes. In the case of peat soils, horizon designation could therefore indicate ‘earthification’ or ‘permanent water saturation’, for example.

However, the classification of heavily disturbed or anthropogenically modified sites is challenging in the German nomenclature. Many soils have heavily degraded topsoils or even completely degraded profiles with SOM contents of between 15 and 30 %. Depending on their texture, which is not relevant for the German nomenclature in this case, and the conversion factor between SOC and SOM, these soils may or may not be ‘organic’ according to the IPCC definition. A conversion factor of 1.72 is given for mineral substrate and 2.00 for peat (Ad-hoc-AG

Boden 2005), but it is unclear how to treat samples with SOC contents at the boundary between mineral soils and peat. Furthermore, soil types cannot be assigned for several specific combinations of horizons (e.g. mineral covers without profile development as topsoil, shallow peat above gley soils with redoximorphic features pointing to a deep groundwater table, or topsoils with SOM contents between 15 and 30 % above a thin peat horizon). Additionally, shallow peat or transitory horizons are assumed to develop towards peatland, but not to lose SOC and thus to develop towards mineral soil. Cultivation techniques such as sand-covering or deep ploughing cannot be mapped clearly either, as there are no distinct soil types for such sites. In summary, the mapping guidelines are too inflexible for mapping heavily disturbed organic soils. These issues are relevant not only for the soil data of the present study, but also for sampling in other projects and for the depiction of soils in maps.

Classification issues of this kind may lead to misunderstandings when talking about 'organic soils'. Therefore it is crucial to clarify that, in this article, the term 'organic soil' does not exactly match the IPCC definition. As with the German emissions inventory (UBA 2019), we included sites with horizons of transitory SOM content (15–30 %) irrespective of texture, as they were found to emit as much CO_2 as typical peat soils (Leiber-Sauheitl *et al*. 2014, Tiemeyer *et al*. 2016). All the soils included in the present study are referred to as 'peat and other organic soils'.

This study is part of the German Agricultural Soil Inventory, the objective of which is to improve the GHG inventory and acquire knowledge about the current status of SOC stocks and other basic soil properties. Besides providing data for modelling or upscaling, the aims of this article are:

(i) to propose a simple classification scheme for drained and heavily disturbed peat and other organic soils;
(ii) to evaluate the properties of agriculturally used peat and other organic soils in Germany;
(iii) to derive pedotransfer functions using SOC content as an explanatory variable; and
(iv) to propose steps towards fully parameterised profiles of peat and other organic soils.

METHODS

Study area and field sampling

The objective of the first German Agricultural Soil Inventory was to validate, improve and develop Germany's greenhouse gas inventory reporting in the sector of 'Land Use, Land Use Change and Forestry' (LULUCF). In line with the German Forest Soil Inventory (Grüneberg *et al*. 2014), it was carried out nationwide in a fixed 8 × 8 km grid, where the first grid point was a LUCAS site (Land Use / Land Cover Area Frame Survey, Tóth *et al.* 2013). Wherever a grid point coincided with an agricultural field (cropland, grassland, permanent crops) the site was chosen for sampling. Landowners were contacted and asked for their cooperation by completing a questionnaire about their field management in the past decade. This resulted in a total of 3104 agricultural field sites, of which 146 were found to be on peat and other organic soils. At each site, a soil pit of about 1 m^2 was dug down to 1 m depth. The soils were described following the German Manual of Soil Mapping (Ad-hoc-AG Boden 2005). Between a depth of 1 and 2 m, horizon description and sampling were conducted using soil cores and the total peat depth was determined using a Russian peat corer.

Disturbed samples were collected for soil chemical analysis and texture, while three sample rings (100 cm^3) were taken as undisturbed samples to determine BD. Sampling was conducted in five fixed depth increments of 0–10, 10–30, 30–50, 50–70 and 70–100 cm (Figure 1). When a depth increment comprised more than one soil horizon and when the horizon or parts of it comprised > 4 cm of that depth increment, the increment was subdivided accordingly (in the example given in Figure 1, the 10–30 cm increment is subdivided into Samples S2 and S3). Conversely, single thick horizons may have been sampled across several depth increments (Horizon 3 comprises Samples S5 and S6). Therefore, unambiguous soil properties are not necessarily identified for each horizon. In this article, 0–30 cm is designated as 'topsoil' and 30–100 cm as 'subsoil'. Even though there may be subsoil horizons within 0–30 cm, this term is used following the nomenclature of the German Agricultural Soil Inventory. Data were either analysed for depth increments or for individual samples.

For present purposes, 'profile depth' is defined as the thickness of the whole soil profile, including overlaying or interlaying mineral soil horizons and underlying organic or calcareous sediment ('gyttja'). In contrast, 'peat thickness' is the total thickness of organic horizons only (≥ 15 % SOM or 8.7 % SOC, respectively).

In order to evaluate the spatial variability of SOC stocks, additional one-metre-long driving hammer samples were taken in all eight main and auxiliary cardinal points 10 m from the soil pit. These cores were divided into the same depth increments without consideration being given to divergent horizon

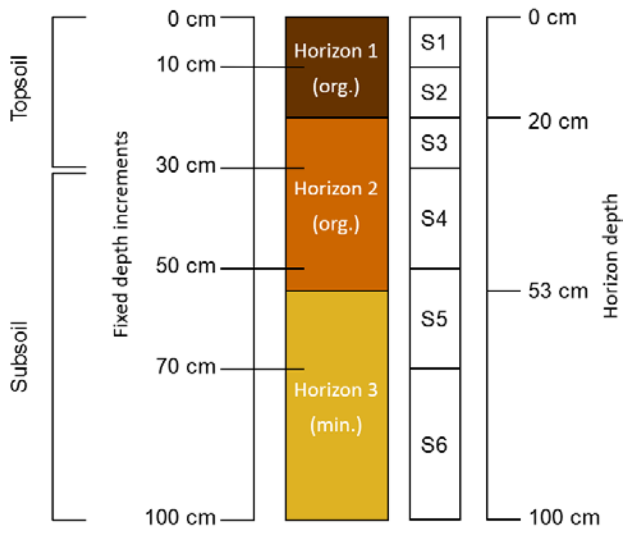

Figure 1. Sampling scheme of a hypothetical profile with two organic (org., Horizons 1 and 2) and one mineral (min., Horizon 3) horizons in the upper metre. Profiles were sampled in fixed depth increments (left) subdivided by horizon boundaries (right) unless the contribution of a horizon to a depth increment was less than 4 cm (the depth increment here is 50–70 cm). One horizon may have been sampled by more than one depth increment (here: Horizon 3). Samples from depths between 0 and 30 cm are defined as topsoil samples, samples from depths between > 30 and 100 cm are defined as subsoil samples. S1–S6: samples.

thicknesses. Compaction and stretching during the drilling procedure were captured by comparing borehole depths and total core lengths. Still in the field, each core was cut bearing in mind the necessary correction for compaction and stretching. Here, only the cores of deep-ploughed organic soils were evaluated. For more details, see Jacobs *et al*. (2018) and Poeplau *et al*. (2020).

Sample preparation and laboratory analyses

All sample preparation and analyses were carried out in the same laboratory following standardised protocols (Jacobs *et al*. 2018). To minimise drying effects on soil chemical analysis, disturbed samples and soil cores were dried at 40 °C and SOC-rich samples (estimated from field mapping) at 60 °C with reference to the methods of the German Forest Soil Inventory (Grüneberg *et al.* 2014) that are based on the expert committee on Forest Analysis (HFA 2006). Undisturbed samples were dried to constant weight at 105 °C in order to remove all water for subsequent determination of BD. Dried samples were sieved to 2 mm and rock fragments and roots were separated and weighed.

Bulk density (BD) was calculated as the mass of dry soil minus coarse soil and roots per unit volume. For samples with SOC contents < 17.4 % (corresponding to a SOM content of < 30 %), texture was determined after aggregate destruction and the removal of salts and organic matter using H_2O_2 (DIN ISO 11277). Sand fractions were determined by wet sieving, and silt and clay fractions by the pipette method using a semi-automatic device (Sedimat 4-12, UGT, Müncheberg, Germany).

Contents of total carbon (C_t) and total nitrogen (N_t) were measured by dry combustion (TRUMAC, LECO, Saint Joseph, USA), as % of dry mass. If the pH_{CaCl2} was < 6.2 it was assumed that no inorganic C (SIC) was present and thus C_t equalled SOC. Otherwise, fractionation of SIC and SOC was determined by combustion at 550 °C for SOC and 1000 °C for SIC. In the case of core samples, N_t was measured in only four of the eight cores due to the laboratory's capacity limits (only relevant for deep-ploughed organic soils). The C:N ratio was evaluated as the quotient of SOC (%) and N_t (%).

Classification approach

The mapping of diverse and anthropogenically disturbed peat and other organic soils presented a challenge due to the shortcomings of the German Manual of Soil Mapping mentioned above. Therefore, we developed an adapted but simplified classification scheme explicitly for the German Agricultural Soil Inventory (Figure 2). It was designed as a flow chart with yes/no decisions and thickness criteria for mineral covers and peat or organic horizons respectively. The definition of 'peat' followed the approach of the German Manual of Soil Mapping, setting the boundary between mineral and organic material at 30 % SOM. Here, 'organic' also includes the transitional section between 15 and 30 % SOM. For a consistent conversion of all samples within the inventory, SOM was derived from the SOC content using the factor of 1.72 (Ad-hoc-AG Boden 2005). Based on profile descriptions and laboratory data, the following six 'peat classes' were distinguished: fen peat soil, bog peat soil, peat-derived organic soil, shallowly covered organic soil, thickly covered organic soil, and deep-ploughed organic soil. Although further subdivisions might be appropriate in future, we required at least ten sites in each class.

The first decision criterion was the existence of a *mineral soil cover*, which is defined by a SOM content < 15 % or by being marsh sediment with a high SOM content not resulting from peatland genesis. However, this definition does not imply that

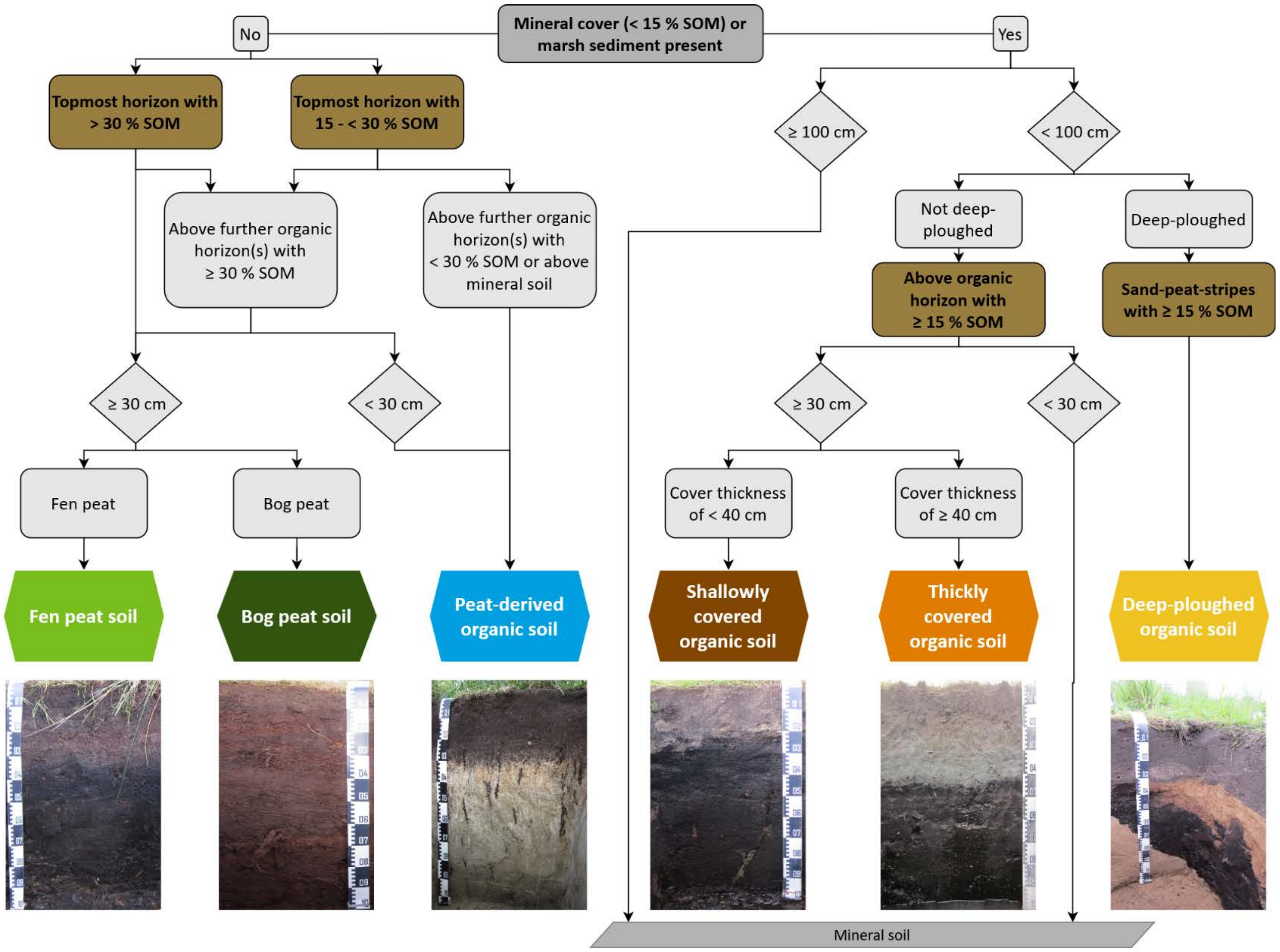

Figure 2. Classification scheme for disturbed peat and other organic soils of the German Agricultural Soil Inventory with exemplary pictures. SOM: soil organic matter.

other topsoils do not contain mineral soil material.

Fen and bog peat soils are 'typical' peat soils following the German Manual of Soil Mapping and feature peat horizons with ≥ 30 % SOM content and ≥ 30 cm peat thickness. However, they may have heavily degraded topsoil horizons with SOM contents between 15 and 30 % above further peat horizons.

The category of *peat-derived organic soils* includes a rather wide variety of organic soils. The term 'peat-derived' appears in literature but is not found in the official German Manual of Soil Mapping. Regionally different definitions might encompass shallow and ploughed sites (Schlichting *et al*. 2002), those with a peat thickness of < 30 cm or SOM contents of < 30 % (Schleier & Behrendt 2000), or sites with highly degraded topsoils with SOM contents of < 15 % above peat (LBGR 2020). In this study we use the term for soils with organic topsoil horizons ≥ 10 cm, including sites with shallow (< 30 cm) peat topsoil horizons. The typical subsoil of these sites comprises sandy or loamy gleyic horizons. As all the sites were drained and under agricultural use, it can safely be assumed that they are not currently accumulating carbon, hence the use here of the term 'peat-derived'.

Covered organic soils feature a mineral cover with < 15 % SOM, although marsh horizons without any peat formation history may exceed this value. The mineral covers differ in thickness with *shallow covers* being < 40 cm and *thick covers* ≥ 40 cm (Ad-hoc-AG Boden 2005). Underlying organic horizons have at least 15 % SOM and are ≥ 30 cm thick. Within the German classification, soils having a thick cover of ≥ 40 cm would be classified as mineral soil, but this is extended up to a cover of < 100 cm in this study.

Deep-ploughed organic soils are a special form of cultivated peat soils (e.g. 'German sand-mixing culture'). In northwest Germany, mainly bogs were ploughed to depths of 1.8 to 2.5 m to improve aeration, drainage and trafficability, e.g. to enable cultivation of degraded peatlands or former peat extraction sites. Thus, these soils show distinct tilted sand-peat stripes underneath a homogenised ploughing horizon of thickness ~ 30 cm (Figure 2). A similar technique has been applied on usually rather shallow fen peat soils in northeast Germany. The sites have been deep-ploughed and tilted and additional sand from underneath has been deposited on top ('Deep-ploughing sand cover culture', Schindler & Müller 2001, Zeitz 2014). Here, all deep-ploughed soils with organic depth increments containing ≥ 15 % SOM were included.

Typical horizon sequences based on the German Manual of Soil Mapping are presented in Table A1 (Appendix), to support the verbal description of each 'peat class' above.

Data analysis

All data analyses were performed with the R software environment (version R-3.6.0, R Core Team 2019) mainly using the packages data.table (Dowle & Srinivasan 2019) and dplyr (Wickham *et al*. 2020). Figures were created with ggplot2 (Wickham 2016).

Stocks of SOC and N_t (in t ha^{-1}) were calculated by multiplying the respective contents by the fine soil stock, according to Poeplau *et al*. (2017). The fine soil stock is the product of BD and the thickness of the depth increment corrected for coarse fragments. SOC density (g cm^{-3}) was calculated as the product of SOC content and BD for each organic sample, i.e. the stock normalised to a specific depth.

Mean and median values of all measured soil properties were calculated for the five depth increments. When a depth increment comprised more than one sample (e.g. S2 and S3 for 10–30 cm in Figure 1), weighted means using the fine soil stock of the relevant depth increment as the weighting factor were applied. SOC and N_t stocks were then totalled for a) topsoil (0–30 cm) and subsoil (30–100 cm), b) the whole upper metre, and c) the entire profile of sites with peat depth > 1 m. As samples were only available up to a maximum of 2 m, stocks were extrapolated from the last sampled horizon to the peat base. Differences in SOC and N_t stocks between the peat classes at each depth were determined by a generalised least squares model using the R package nlme (Pinheiro *et al*. 2018). *P*-values of pair-wise comparisons were then calculated using Tukey's honest significant difference test (α = 0.05) and adjusted with the Bonferroni correction using the R package multcomp (Hothorn *et al*. 2008).

A distinction was made between organic (≥ 8.7 % SOC, S1–S4 in the example in Figure 1) and mineral (< 8.7 % SOC, S5 and S6) samples and depth increments. Thus, the results were aggregated by peat class twice, first using all the increments and second using organic increments only. The first approach had the advantage of delivering full profile data without leaving 'blanks' in the topsoil of covered organic soils or in the subsoil of shallow organic soils. The second approach avoided misinterpretation of, for example, typical depth distributions of soil properties due to organic and mineral horizons being combined.

For deep-ploughed organic soils, analyses were based on the soil cores. Due to the typical tilting structure of these soils and the cores being cut into depth increments, it was not possible to distinguish between mineral and organic depth increments.

Therefore, most samples were a mixture of organic and mineral material.

To determine the relationship between SOC content and BD as well as between SOC content and SOC density, bootstrapped data (n = 1000) of all organic samples (in contrast to depth increments) were used. Data for deep-ploughed organic soils were omitted. For SOC content 8.7–56.8 %, the relationship between SOC content (SOC_c, %) and BD is described using a logarithmic equation (Equation 1) and between SOC_c and SOC density (SOC_d, g cm^{-3}) using a quadratic equation (Equation 2).

$$\mathrm{BD} = -a * \ln(SOC_c) + b \qquad [1]$$

$$SOC_\mathrm{d} = -c * (SOC_c)^2 + d * (SOC_c) + e \qquad [2]$$

The parameters *a*, *b*, *c*, *d* and *e* (all in g cm^{-3}) were estimated by minimising the sum of squared residuals with the ‘shuffled complex evolution’ (SCE-UA) algorithm of Duan *et al*. (1992) implemented in the R package SoilHyP (Dettmann 2019). For both correlations, a distinction was made between all samples, topsoil samples and subsoil samples. The scope for SOC contents was similar for all subsets, i.e. 8.7–56.0 % for topsoil samples and 9.1–56.8 % for subsoil samples.

RESULTS

Stocks of soil organic carbon and total nitrogen

The data for individual sites, along with the mean and median values for the five depth increments, are provided in Tables S1–S4 in the Supplementary Material (MS Excel file). Of the 146 sites identified as peat and other organic soils, only 47 % could be classified as ‘typical’ fen (n = 53) or bog peat soil (n = 16), 22 % are classified as peat-derived organic soils (n = 32), nearly one-fifth of all sites have either a shallow (n = 12) or thick (n = 16) mineral cover, and 12 % are deep-ploughed (n = 17).

In the upper metre of German peat and other organic soils under agriculture, the SOC store is 529 ± 201 t ha^{-1} (mean ± standard deviation). Stratified by peat class, the highest SOC stocks are in fen peat soils (66 ± 135 t ha^{-1}, Figure 3a, Table S1), followed by bog peat and shallowly covered organic soils (628 ± 118 t ha^{-1} and 618 ± 97 t ha^{-1}, respectively). The SOC stocks of thickly covered, peat-derived and deep-ploughed organic soils are significantly lower than those of the other classes (490 ± 128 t ha^{-1}, 343 ± 187 t ha^{-1} and 332 ± 112 t ha^{-1}, respectively).

In topsoils, SOC stocks are naturally higher at sites with peat on top (fen peat, bog peat and peat-derived organic soils). Thus, in classes with mineral topsoils SOC stocks are lower, although the stocks of the respective subsoils are slightly higher than in fen and bog peat subsoils (Figure 3a, Table S1). The predominantly mineral subsoils of peat-derived and deep-ploughed organic soils store significantly lower amounts of SOC. On average, about 45 % of SOC in the upper metre is stored within the topsoil and 55 % in the subsoil.

Considering stocks down to the peat base is extremely important in terms of the total SOC stocks (Figure 3a). Peat thickness may be > 400 cm, and SOC storage in the respective sites is > 1000 t ha^{-1} (Table S2). Corresponding to the highest mean peat thickness, the highest SOC stocks below 100 cm are found in fen peat soils. Excluding peat-derived organic soils, only about half (52 %) of the total SOC is stored in the upper metre and 48 % in the deep subsoil between 100 cm and the peat base. Unsurprisingly, we found a linear correlation between SOC stocks and peat thickness (not shown). Stocks of N_t show a similar pattern to SOC stocks (Figure 3b). The average N_t stock in the upper metre is 29.3 ± 13.9 t ha^{-1} with the highest stocks in fen peat soils as well as in shallowly and thickly covered organic soils (40.3 ± 10.7 t ha^{-1}, 33.8 ± 8.7 t ha^{-1} and 30.6 ± 6.2 t ha^{-1}, respectively; Figure 3b, Table S1). In bog peat soils, peat-derived and deep-ploughed organic soils, N_t stocks are significantly lower (19.4 ± 6.6 t ha^{-1}, 22.8 ± 12.7 t ha^{-1} and 12.3 ± 4.1 t ha^{-1}, respectively). In topsoils, the highest N_t stocks are observed in fen peat soils, whereas all other soils have significantly lower stocks. The lowest stocks are in deep-ploughed organic soils. In the subsoil, higher amounts of N_t are stored in covered and fen peat soils than in other classes.

Analogous to the SOC stocks, high amounts of N_t are stored in the peat below 100 cm depth (31 % of the total N_t stock) with the highest N_t stocks in the fen peat soils.

All the numbers given here (and in Figure 3, Table S1) include all the horizons, i.e. both mineral covers and subsoils. Slight differences in the numbers are due to rounding.

Soil properties

Soil organic carbon content

Figures 4–7 summarise the major soil properties in the upper metre of the six different peat classes. The properties are shown for organic increments (‘org’) and for all increments (‘all’). The description focuses on organic increments only with the exception of deep-ploughed organic soils.

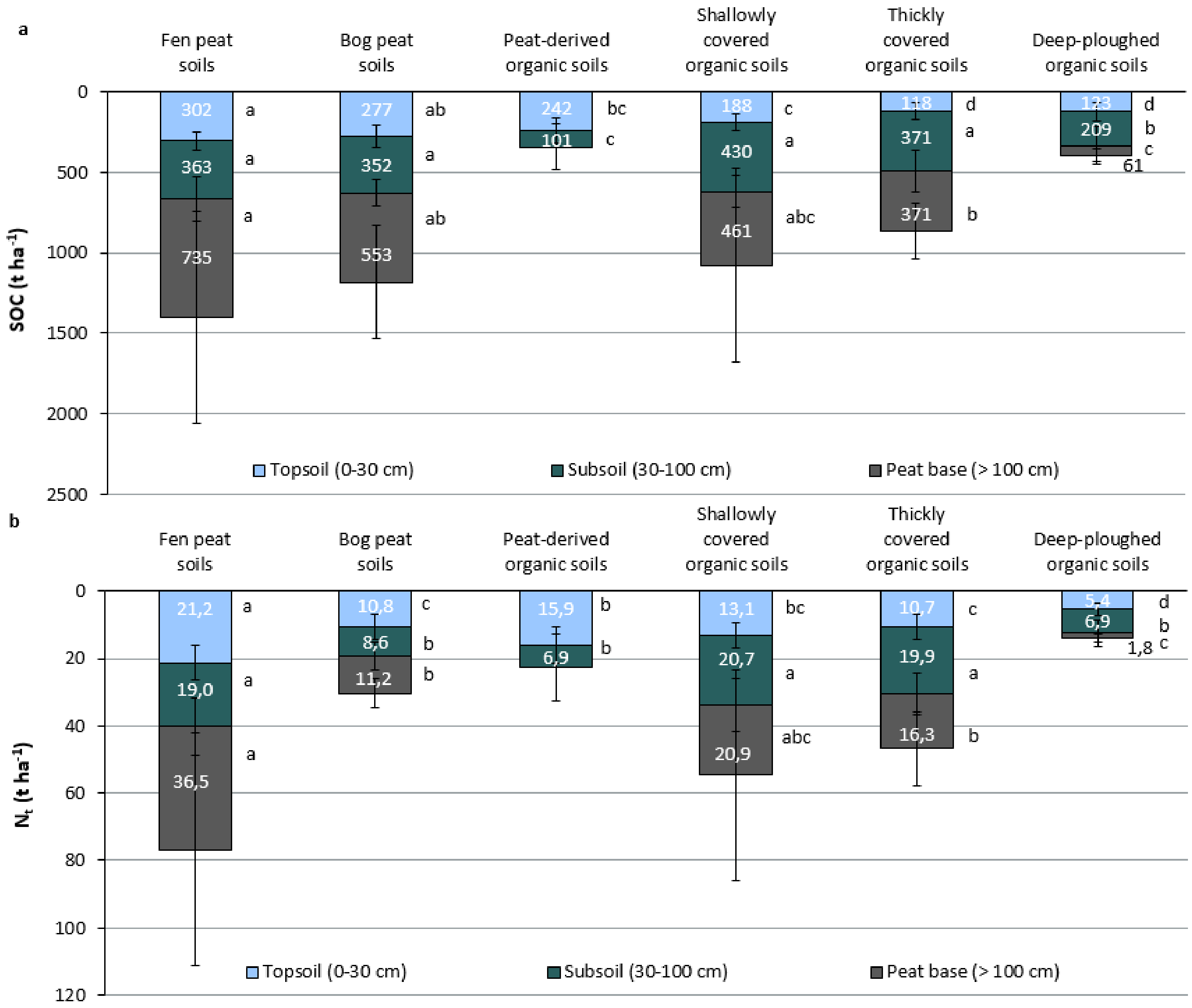

Figure 3. Stocks of (a) soil organic carbon (SOC) and (b) total nitrogen (N_t) of each peat class in topsoil (0–30 cm), subsoil (30–100 cm) and to the peat base (> 100 cm). Means and standard deviation, white numbers: mean stocks per depth, letters: significant differences ($p \leq 0.05$) between peat classes in the same depth.

The SOC contents of fen and bog peat soils increase with depth (Figure 4). Peat-derived organic soils have lower SOC contents per definition (mainly between 14 and 11 %). As expected, covered organic soils are characterised by divergent SOC contents of topsoils and subsoils. Beneath shallow covers, the SOC contents of organic increments are similar to fen peat soils, while they are lower beneath thick covers, where they also increase with depth. SOC contents of deep-ploughed organic soils are mostly around 3 %, reflecting the mixed material in the core samples.

Total nitrogen content and C:N ratio

In contrast to SOC contents, N_t contents do not vary with depth in fen peat soils, but clearly decrease as depth increases in bog peat soils (Figure 5). Peat-derived soils have low N_t contents similar to those in bog peat soils. While N_t contents in the covers are low, they are generally comparable with those in the organic increments of fen peat soils. With increasing depth, N_t contents decrease slightly in shallowly covered organic soils and increase slightly in thickly covered organic soils, reaching similar values at a

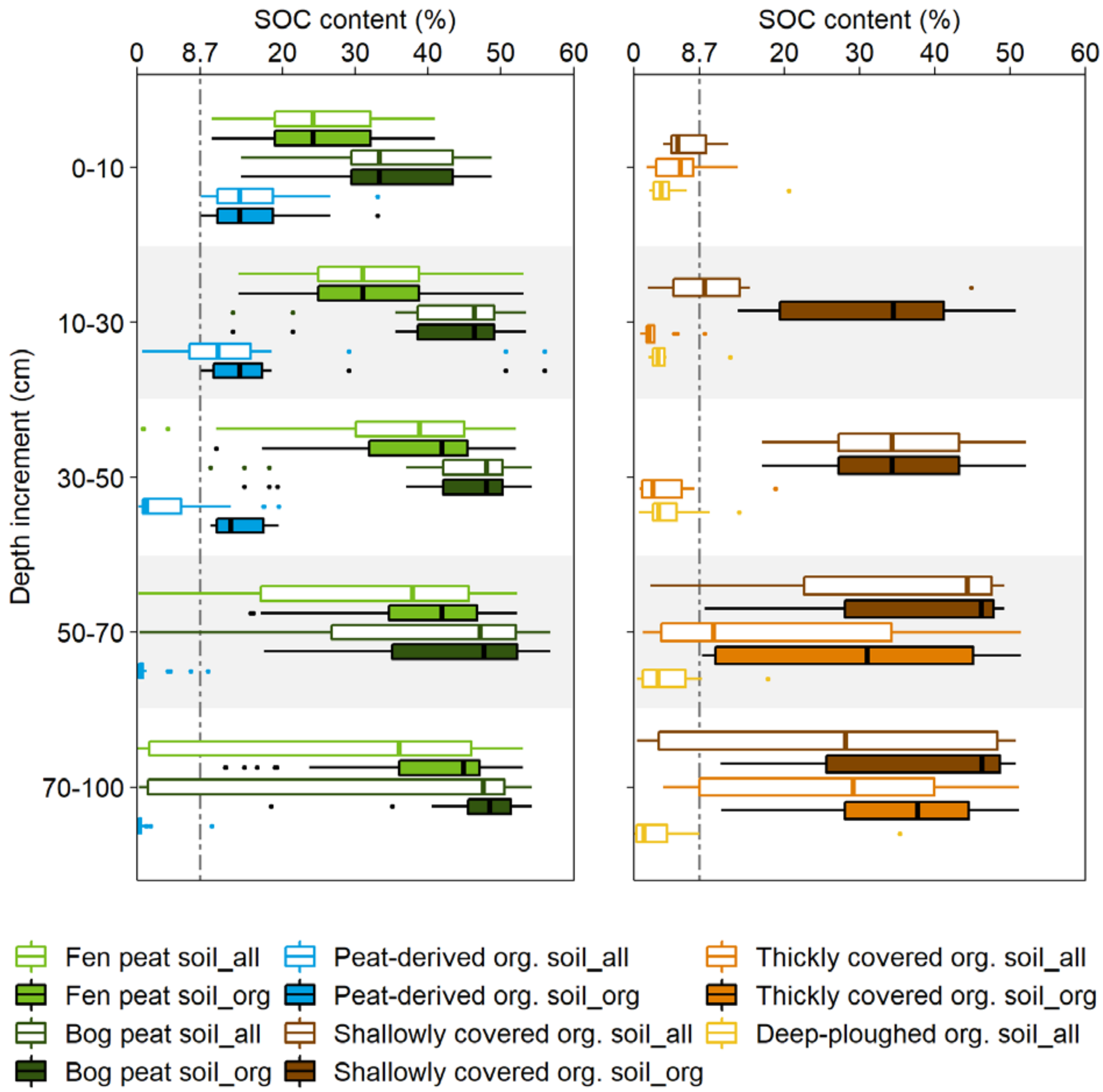

Figure 4. Soil organic carbon (SOC) content (%) of peat classes in different depth increments. ‘*_all’ comprises all depth increments, while ‘*_org’ refers to organic depth increments (SOC ≥ 8.7 %, marked by dashed line) only. Boxes: median (bold line) and quartiles, whiskers: 1.5 times the interquartile range below the first quartile or above the third quartile, outliers (dots): ≥ 1.5 times the interquartile range. Org.: organic.

depth of 70–100 cm. Compared with those of other organic soils, the N_t contents of deep-ploughed organic soils are low throughout the profile.

The C:N ratios of fen peat and peat-derived organic soils are on a similar level and increase with depth (Figure 6). Bog peat soils show the highest C:N ratios in all depth increments and a very distinct pattern: the C:N ratios of the upper increment (0–10 cm) are markedly lower than at greater depths. Patterns in covered organic soils resemble those of fen peat soils, while C:N ratios in deep-ploughed organic soils also increase with depth and lie between those for bog peat soils and all other classes.

Bulk density and its relationship to soil organic carbon

Fen and bog peat soils show decreasing BD with depth and BD is slightly lower in bog peat soils (Figure 7). In peat-derived organic soils BD is higher than in fen and bog peat soils, even in the organic increments. The BD of covered organic soils decreases with depth, but remains at slightly higher levels than in fen and bog peat soils. In deep-ploughed organic soils, BD does not show a clear pattern of variation with depth; the values are higher than for other classes, but lower than for mineral subsoils of peat-derived organic soils.

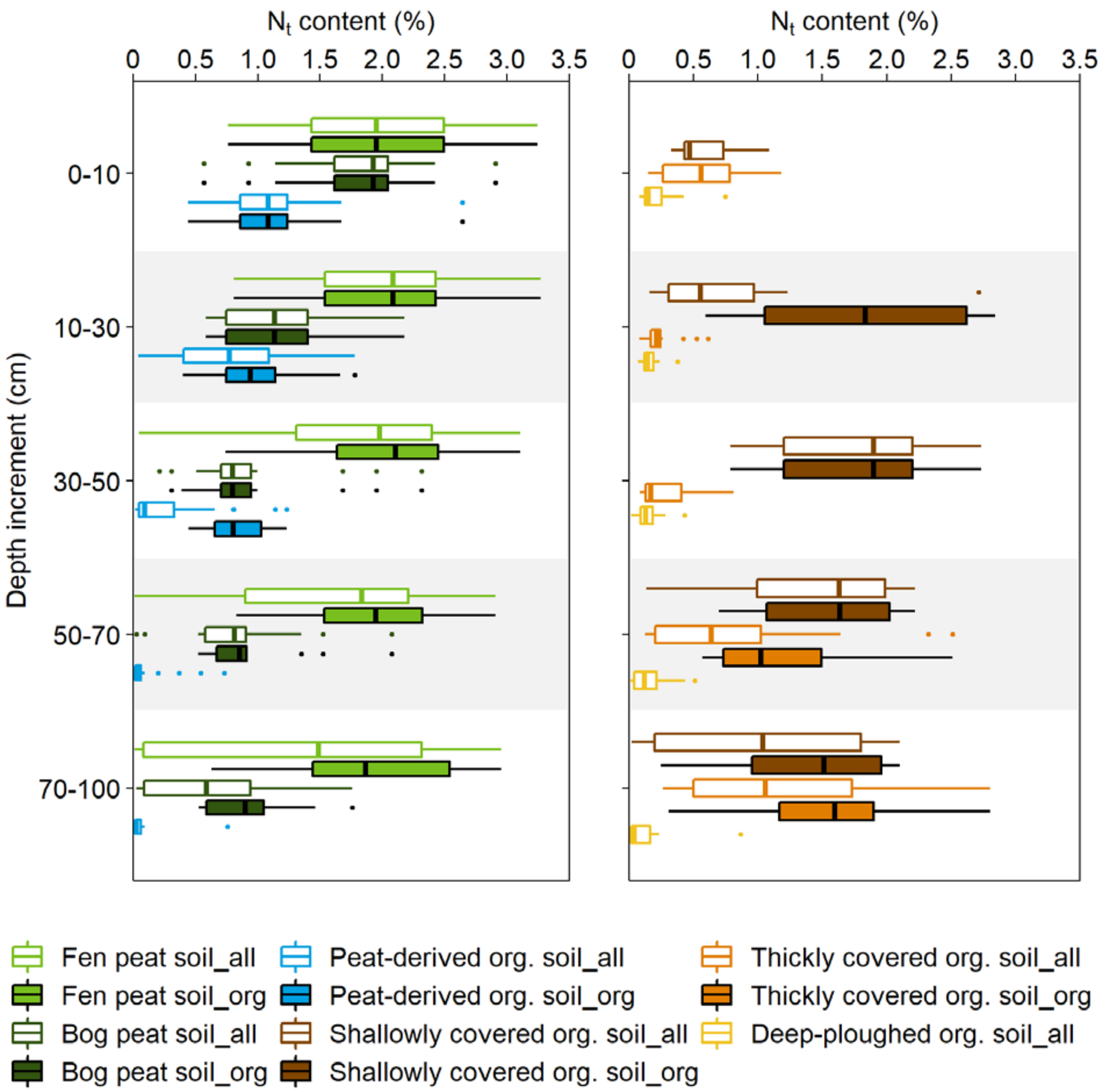

Figure 5. Total nitrogen (N_t) content (%) of peat classes in different depth increments. '*_all' comprises all depth increments, while '*_org' refers to organic depth increments (SOC ≥ 8.7 %, marked by dashed line in Figure 4) only. Boxes: median (bold line) and quartiles, whiskers: 1.5 times the interquartile range below the first quartile or above the third quartile, outliers (dots): ≥ 1.5 times the interquartile range. Org.: organic.

Bulk density strongly correlates with the SOC content (Figure 8a, Table 1, Table S3). Considering all organic samples (except samples from deep-ploughed sites), a decrease of BD with increasing SOC content was found, following a logarithmic correlation. There is a clear difference in functions between topsoil samples and subsoil samples over the whole observed range of SOC contents. As the relationship between SOC and BD is well known, the respective pedotransfer functions (PTFs) from other studies are also shown (Figure 8a, Table 1). Zauft *et al*. (2010) investigated peatlands in north-eastern Germany and found a logarithmic fit which nearly follows the same line as our function for all samples. Tiemeyer *et al*. (2017) used a logarithmic fit for data on organic samples from several studies with a range of SOC contents similar to that in the present study, den Akker (2011) are valid for Dutch grassland topsoils encompassing not only peat (mean SOC content 16 %) but also sandy and clayey soils with higher BD. Liu *et al*. (2019) found a linear relationship for their data for peat soils, which does not fit here. Finally, Ruehlmann & Körschens (2009) calculated PTFs for a wide range of mainly mineral

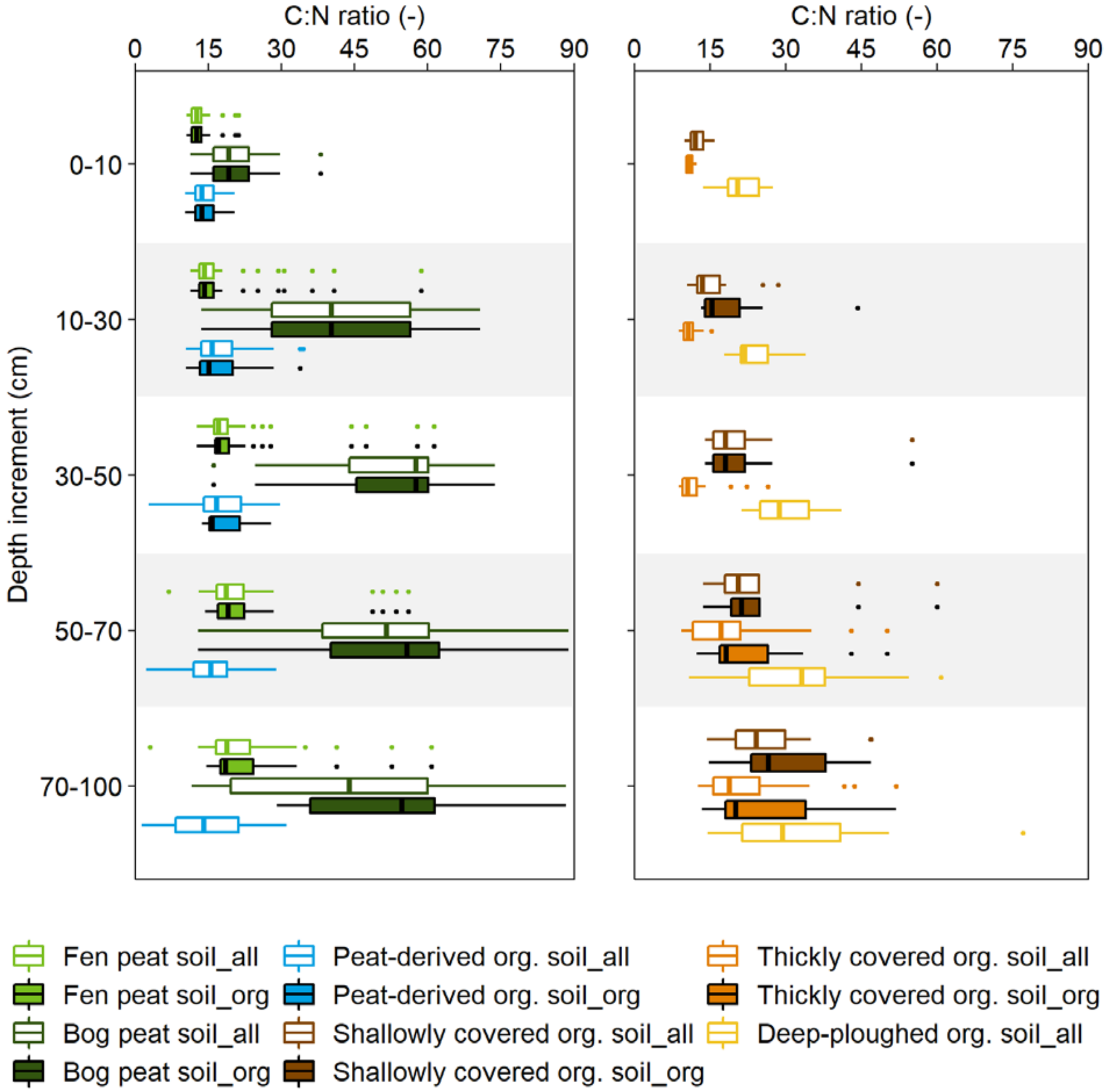

Figure 6. C:N ratio (-) of peat classes in different depth increments. ‘*_all’ comprises all depth increments, while ‘*_org’ refers to organic depth increments (SOC ≥ 8.7 %, marked by dashed line in Figure 4) only. Boxes: median (bold line) and quartiles, whiskers: 1.5 times the interquartile range below the first quartile or above the third quartile, outliers (dots): ≥ 1.5 times the interquartile range. Org.: organic.

soils and defined an exponential correlation, but even though the appropriate parameters for wetland soils and their results resemble our function for topsoils. The two logarithmic functions of Sonneveld & van that include peatlands were used here, this function does not match our data.

The correlation of SOC density with SOC content is depicted by a quadratic function (Figure 8b, Table 2, Table S3). At the same SOC content, topsoil samples show higher SOC densities than subsoil samples. Overall, data are scattered and the correlation is not as conclusive as the correlation between SOC content and BD.

Mineral covers

The textures of the mineral covers on the organic soils are heterogeneous (Figure 9). Shallow covers (thickness < 40 cm) are mainly sandy, while most of the thick covers are silty or loamy. Considering samples from covers only (instead of depth increments as in Figure 4), the mean SOC content in shallow covers is slightly higher (6.6 ± 3.6 %) than in thick covers (4.0 ± 3.1 %, Table S4). Although mean BD is slightly lower in shallow covers than in thick covers, SOC density in shallow covers is 0.05 ± 0.02 g cm^{-3}, while in thick covers it is 0.04 ± 0.02 g cm^{-3} (Table S4).

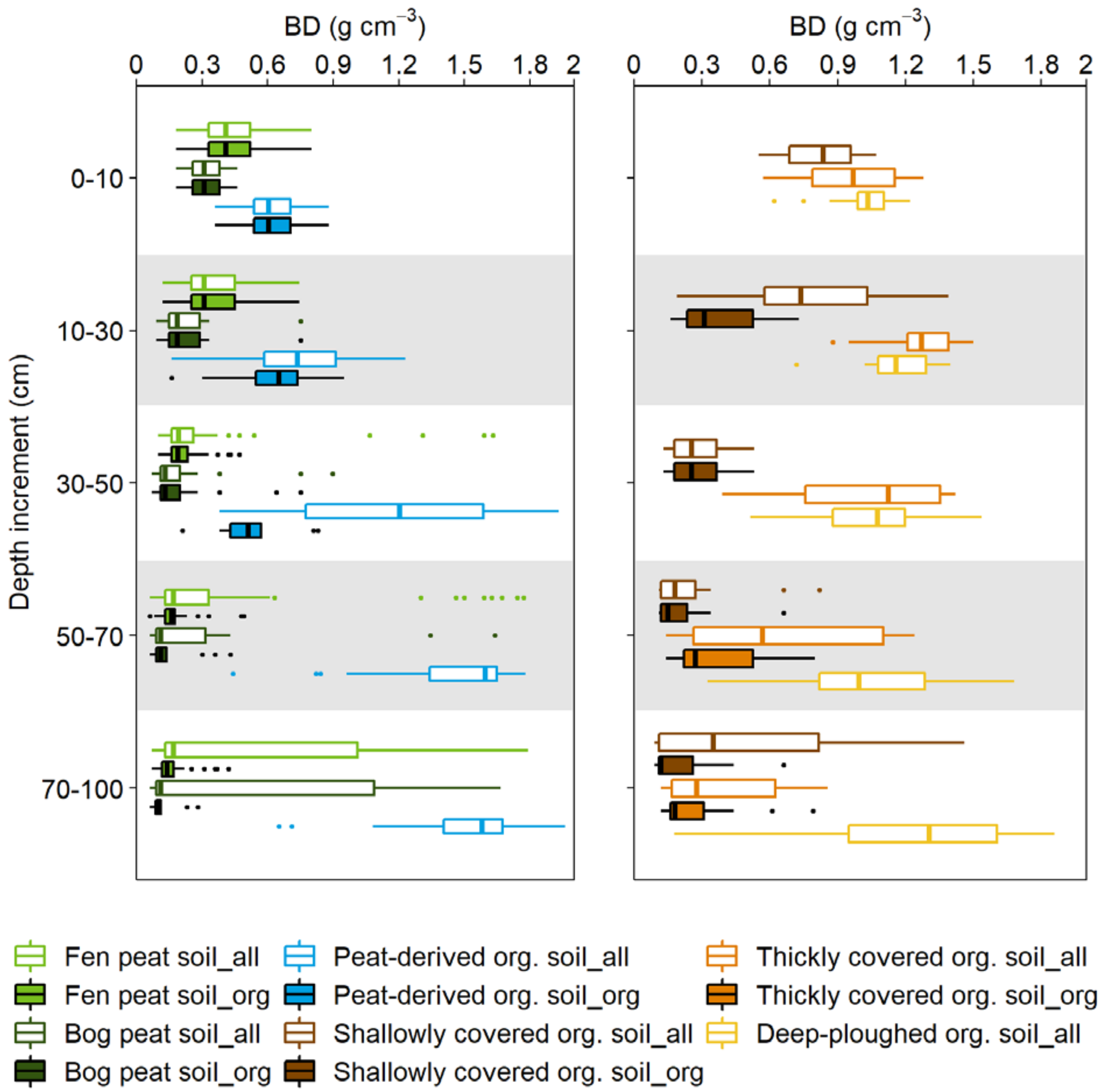

Figure 7. Bulk density (BD, g cm^{-3}) of peat classes in different depth increments. '*_all' comprises all depth increments, while '*_org' refers to organic depth increments (SOC ≥ 8.7 %, marked by dashed line in Figure 4) only. Boxes: median (bold line) and quartiles, whiskers: 1.5 times the interquartile range below the first quartile or above the third quartile, outliers (dots): ≥ 1.5 times the interquartile range. Org.: organic.

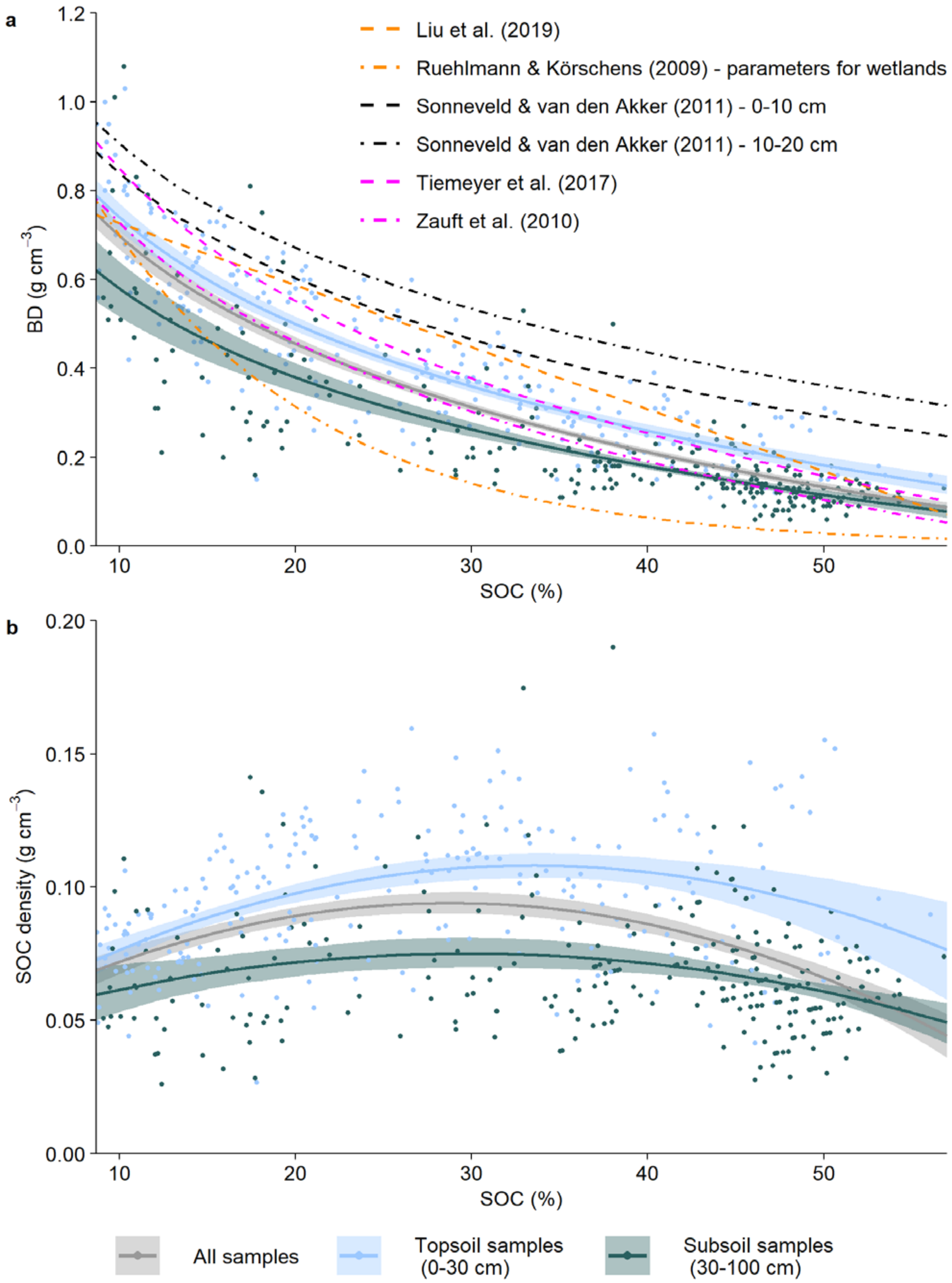

Figure 8. a) Dependence of bulk density (BD) on soil organic carbon (SOC) content with logarithmic fits and additional functions of other studies, b) dependence of SOC density on SOC content with quadratic fits for topsoil (0–30 cm), subsoil (30–100 cm) and all samples (SOC content ≥ 8.7 %). Ribbons depict the 2.5–97.5 % percentiles.

Table 1. Parameters of Equation 1 ($\mathrm{BD} = -a * \ln(\mathrm{SOC\ content}) + b$) for dependence of bulk density (BD) on soil organic carbon (SOC) content including literature values, the respective root mean square error (RMSE) and number of samples (n). For parameters and RMSE, the median and 2.5–97.5 % percentiles (in brackets) are given. Uncertainties are not fully available for literature data; Sonneveld & van den Akker (2011) report the 95 % percentile.

	a **(g cm^{-3})**	***b*** **(g cm^{-3})**	**RMSE (g cm^{-3})**	**n**
All samples	0.35 (0.33–0.37)	1.51 (1.42–1.58)	0.11 (0.01–0.12)	487
Topsoil samples (0–30 cm)	0.35 (0.32–0.37)	1.54 (1.45–1.63)	0.10 (0.09–0.11)	232
Subsoil samples (30–100 cm)	0.29 (0.25–0.33)	1.24 (1.08–1.40)	0.09 (0.08–0.11)	255
Sonneveld & van den Akker (2011) Dutch peat, sandy and clayey soils, 0–10 cm	0.340 (0.292–0.388)	1.622 (1.524–1.719)	no data	54
Sonneveld & van den Akker (2011) Dutch peat, sandy and clayey soils, 10–20 cm	0.339 (0.301–0.378)	1.687 (1.617–1.757)	no data	54
Tiemeyer *et al.* (2017) Different peat types and depths, data from different countries	0.43 (no data)	1.84 (no data)	no data	no data
Zauft *et al.* (2010) Fen peat soils from north-east Germany, data for different depths	0.3881 (no data)	1.6219 (no data)	no data	393

Table 2. Parameters of Equation 2 ($SOC\ \mathrm{density} = -c * (SOC\ \mathrm{content})^2 + d * (SOC\ \mathrm{content}) + e$) for dependence of soil organic carbon (SOC) density on SOC content, the respective root mean square error (RMSE) and number of samples (n). For parameters and RMSE, the median and 2.5–97.5 % percentiles are given (in brackets).

	c **(g cm^{-3} × 10^{-5})**	***d*** **(g cm^{-3} × 10^{-3})**	***e*** **(g cm^{-3} × 10^{-2})**	**RMSE (g cm^{-3} × 10^{-2})**	**n**
All samples	6.2 (4.8–7.8)	3.6 (2.7–4.5)	4.2 (3.0–5.4)	2.6 (2.4–2.8)	487
Topsoil samples (0–30 cm)	5.8 (3.6–7.7)	3.9 (2.7–5.0)	4.3 (3.1–5.7)	2.3 (2.1–2.5)	232
Subsoil samples (30–100 cm)	3.5 (1.7–5.5)	2.1 (0.86–3.5)	4.5 (2.5–6.3)	2.2 (1.9–2.5)	255

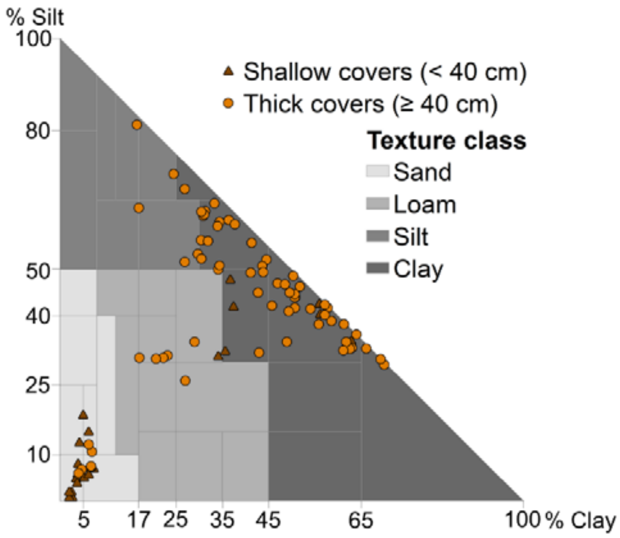

Figure 9. Texture composition of mineral covers (shallow and thick) in the investigated organic soils. Texture triangle after the German Mapping Guidelines (Ad-hoc-AG Boden 2005).

DISCUSSION

German peat and other organic soils under agricultural use: disturbance beyond drainage

The results of the first German Agricultural Soil Inventory show that only 47 % of peat and other organic soils under agricultural use could be classified as 'typical' fen or bog peat soils. The remainder are either shallow or low in SOC (< 17.4 %) (22 %), covered with mineral soil (19 %) or deep-ploughed (12 %). While an extrapolation of these percentages to all German peatlands would be inappropriate and some of the covers might be of natural origin, these values nonetheless indicate a dramatic loss of soils with 'typical' fen or bog peat horizonation. This finding is supported by Fell *et al.* (2015), who calculated a decrease in peatland area of about 40 % in the federal state of Brandenburg between the start of the 20th century and the year 2013. As Roßkopf *et al.* (2015) estimated a share of only 18 % of 'non-peat organic soils', the results of the present study are surprising. However, there are several issues that limit comparability with their study. First, there is a difference in classification because it was not possible for them to evaluate covered peatlands in all federal states, so they describe fen, bog and non-peat organic soils only. Furthermore, it should be noted that data availability and quality differ between the federal states. Nevertheless, Roßkopf *et al.* (2015) provide the key reference in terms of the extent and properties of organic soils at national scale.

Generally, another issue is that the data included in meta-studies often come from project sites (e.g. Bechtold *et al*. 2014, Liu *et al*. 2019), which are frequently typical or well-preserved sites. This might also influence scientists' perception of the status of organic soils in general. Thus, we believe that the grid sampling approach avoided a bias towards sites presumed 'typical', and that the high number of non-typical organic soils is indeed relevant.

Despite being disturbed, peat and other organic soils under agricultural use still store on average 529 ± 201 t ha^{-1} of SOC and 29.3 ± 13.9 t ha^{-1} of N_t, considering the upper metre only. To quantify complete stocks, such soils need to be sampled down to the peat base. Even the two classes with the lowest SOC stocks, the peat-derived and deep-ploughed organic soils, store at least twice as much SOC (343 ± 118 and 332 ± 112 t ha^{-1}) as typical mineral soils under agricultural use, for which the German Agricultural Soil Inventory found average SOC stocks of 96 ± 48 t ha^{-1} and 135 ± 70 t ha^{-1} under cropland and grassland respectively (Poeplau *et al.* 2020). Thus, peat-derived, covered and deep-ploughed organic soils, which might be classified as mineral soils depending on the classification system, also need to be considered in terms of emissions reporting and GHG mitigation efforts.

The well-known and the hidden: properties of different classes of peat and other organic soils

In *fen and bog peat soils*, the well-known 'typical' organic soils, the SOC contents follow a characteristic, increasing trend with depth, as observed by Zauft *et al.* (2010). As was also found by Roßkopf *et al.* (2015), SOC content is generally lower and BD higher in fen peat than in bog peat soils. This can be explained by differences in vegetation and development conditions, e.g. the addition of mineral material during peatland development (e.g. occasional flooding). Furthermore, statistical analysis of > 1000 dipwells showed that some fen peatland types tend to be drier than bog peatlands (Bechtold *et al*. 2014), which might cause stronger degradation and thus higher BD and lower SOC contents in fen peat soils. With a few exceptions, the BD even of most subsoils is higher than in natural peatlands (about 0.1 g cm^{-3}, Loisel *et al*. 2014).

Roßkopf *et al*. (2015) estimated SOC stocks for different peatland types in Germany. Their values for the upper metre in fens (669 t ha^{-1}, area-weighted mean of all fen types under arable and grassland use) and bogs (693 t ha^{-1}, area-weighted mean of both bog types under arable and grassland use) exceed our results of 665 and 628 t ha^{-1}. This discrepancy might be due to the inclusion of non-agricultural sites and older data (i.e. sites will have lost C since sampling) in their derivation of idealised profiles, and the relatively small number of sites in our dataset. In addition, samples from bog peat are under-represented in Roßkopf *et al*. (2015) and did not reflect the distribution of bogs across the whole of Germany.

Both N_t contents and C:N ratios show an enrichment of N in the topsoil, which is especially evident for bog peat soils (Figures 5 and 6). The low C:N ratios of fen peat soils are typical for drained sites (Müller *et al*. 2007), while there are limited data for drained bog peat soils beyond single-site studies. However, even in deeper horizons, the C:N ratios of drained bog peat soils are lower than in natural sites (81 ± 49.2 for *Sphagnum* peat, Loisel *et al*. 2014). While the relevance of peat and other organic soils as SOC pools is well known, their importance for the N cycle is less acknowledged. Fen peat and covered organic soils in particular store large amounts of N_t (Figure 3b). Although carbon in particular is lost following drainage-induced mineralisation (Okruszko 1993), N_t is also mineralised and might be leached into surface waters (Tiemeyer & Kahle 2014) or transformed into N_2O (Leppelt *et al*. 2014). Overall, the present dataset is the first comprehensive dataset on N_t contents and stocks as well as on C:N ratios of agriculturally used peat and other organic soils (Table S2). Thus, the results offer a first step towards regionalisation and parameterisation of GHG models or simple transfer functions, for which N_t stocks and C:N ratios have been shown to be of major importance (Leifeld 2018, Tiemeyer *et al*. 2016).

Peat-derived organic soils reflect the transitory state of peat soils caused by advanced degradation processes. In addition, there are sites where remaining peat has been mixed with the underlying mineral soil e.g. after peat extraction (Leiber-Sauheitl *et al*. 2014). According to their C:N ratios (14–16 in the organic increments; Figure 6) the sites in the present dataset are, however, fairly comparable with fen peat soils. The high BD resulted in high SOC and N_t stocks in the upper metre (343 ± 187 and 22.8 ± 12.7 t ha^{-1}, Figure 3). These might previously have been under-estimated - Roßkopf *et al*. (2015) indicate only about one-third of our value for SOC stock (123 t ha^{-1}, area-weighted mean of both types of ‘non-peat organic soils’ under arable and grassland use). Besides classification issues, another reason for this might be their assumption of zero SOC stocks below a depth of 30 cm. In addition to the high stocks, such sites usually have low groundwater levels (Bechtold *et al*. 2014, Tiemeyer *et al.* 2016) which, in combination with the high stocks, may be a reason for high CO_2 emissions in the same range as ‘typical’ peat soils (Leiber-Sauheitl *et al*. 2014, Eickenscheidt *et al*. 2015). If drainage-based agriculture continues, such organic soils are likely to maintain or increase these emission levels in future.

Another relevant proportion comprises *covered organic soils*. Shallow covers are mainly sandy (Figure 9), which points to an aeolian or anthropogenic origin. However, there are also cases of either alluvial or anthropogenic addition of loamy or clayey material (‘Spittkultur’). In contrast, most of the thick covers are silty or loamy, which might indicate tidal or riverine deposition. Those sites are located in coastal regions, where they make up a considerable proportion of organic soils (Schulz & Waldeck 2015, LLUR 2016). SOC and N_t stocks in the upper metre are comparable with fen peat soils but might be overlooked, as sites with a thick cover could be classified as mineral soils. A general similarity between covered organic soils and fen peat soils in the present dataset was expected as the subsoils mainly comprise fen peat (92 %). These high “hidden” stocks are vulnerable to degradation as it is not yet clear whether there are conditions under which mineral soil covers protect the underlying peat. Zaidelman & Shvarov (2000) identified increased biochemical depletion of peat beneath sand covers, while Höper (2015) found that a covered site under grassland had lower CO_2 emissions than a corresponding site without cover, but no differences under cropland. In a laboratory study comparing degraded topsoils with organo-mineral covers (SOC contents between 4.9 and 21.4 %), Säurich *et al*. (2019a) found no differences in specific CO_2 fluxes of the two types of topsoil, indicating a low stability of SOM even in the covers themselves. As in Säurich *et al*. (2019a), the relatively high SOC contents especially in shallow covers (6.6 ± 3.6 %) in the present study point to frequent ploughing of peat into the covers. There is an absence of field studies on GHG emissions from thickly covered organic soils, but while the peat itself is being subjected to drainage, there is little reason to assume protection from mineralisation.

Originating from a special cultivation technique, *deep-ploughed organic soils* are a regional phenomenon mainly in the north-west of Germany, but nevertheless account for 12 % of all sites in this study. It is assumed that the study sites, which are all located in the federal state of Lower Saxony with one exception in North Rhine-Westphalia, were formerly bogs due to the high C:N ratios and the general land use history of the region. Deep ploughing was intended to provide an enhancement in terms of agricultural use and the conservation of peat in the subsoil (Kuntze 1987, Göttlich 1990, Bambalov 1999). Actual measurements of long-term SOC dynamics are rare, however, and restricted to topsoils, for which Höper (2015) estimated a SOC loss of 1.8 t ha^{-1} yr^{-1}. Some studies on deep-ploughed mineral soils (Alcántara *et al*. 2016, Schiedung *et al*. 2019) found that deep ploughing leads to higher SOC stability of the buried former topsoils and generally higher SOC stocks. However, the stabilisation mechanism from mineral soils may not be transferred to (former) peat soils. Therefore, while there is a lack of actual data on the SOC dynamics of deep-ploughed organic soils, they should be treated like other degraded former peat soils due to precautionary principles and because of their high SOC stocks. In this study, the SOC stocks of deep-ploughed organic soils are similar to those of peat-derived organic soils, which have been shown to emit large quantities of CO_2 (Leiber-Sauheitl *et al*. 2014, Tiemeyer *et al*. 2016). However, the stock estimates presented here are likely to be highly uncertain as they are based on only eight (SOC, BD) or even four (N_t) soil cores, which is well below the number of 20 cores used in the study on deep-ploughed mineral soils by Alcántara *et al*. (2016).

SOC density matters

When data on BD are absent, PTFs relying on SOC content are useful for calculating BD or SOC stocks. As in previous studies (Zauft *et al*. 2010, Sonneveld & van den Akker 2011, Tiemeyer *et al*. 2017), we found a negative logarithmic relationship between SOC content and BD (Figure 8a). For the drained peat and other organic soils studied here, the data could not be described by the exponential function of Ruehlmann & Körschens (2009) or the linear function of Liu *et al*. (2019). As a result of drainage, the BD of managed peat and other organic soils increases due to physical and biological processes, but only the latter influences SOC content (Ilnicki & Zeitz 2003). There are clear differences between topsoils and subsoils (Table 1), with topsoil showing higher BD at the same SOC content due to greater compaction. In future, more data on moisture (Chapman *et al*. 2017) or pedogenetic features, for example, are needed to enhance the ability of PTFs to parameterise specific horizons also with additional properties (e.g. N_t).

Furthermore, a quadratic relationship was found between SOC content and SOC density (Figure 8b). Due to the relationship between BD and SOC content discussed above, the SOC density of topsoils is also higher than that of subsoils at the same SOC content. Overall, organic soils with low SOC contents show SOC densities similar to natural peat soils, with SOC contents of around 50 %. These results have important implications. The line between peat and mineral soils is frequently drawn at 12–18 % SOC (FAO 1998, Ad-hoc AG Boden 2005). However, the high SOC densities of heavily degraded sites below this limit show that these soils are prone to mineralisation when drained (which is usually the case, see the discussion above on peat-derived organic soils). Indeed, Säurich *et al*. (2019b) demonstrated that soils with SOC contents at the boundary between mineral and organic soils show high and variable basal respiration rates. There is no indication that respiration decreases with decreasing SOC content, but instead specific respiration rates may *increase* with degradation. In terms of the CO_2 emission potentials of organic soils, SOC content is not an appropriate variable and the distinction between “peat” and “other organic soils” seems superfluous in this context. Therefore, SOC (and N_t) densities (or stocks) should be used when upscaling CO_2 emissions or when developing mitigation measures.

Towards fully parameterised profiles of peat and other organic soils

We developed a simplified classification scheme that is applicable for drained and disturbed peat and other organic soils. The classification is based on basic soil properties (i.e. SOC content, thickness of the organic layers, peat type, or anthropogenic measures), which require only basic knowledge about peatland genesis. This is helpful in order to homogenise rather heterogeneous soil data. However, besides the limited number of sites in this study, several issues need to be highlighted in order to be able to progress towards fully parameterised profiles and eventually to maps of peat and other organic soils. These issues are discussed below.

Conversion factor and boundary between mineral and organic soils

One uncertainty is the conversion factor between SOC and SOM content. Here, the factor 1.72 was used for peat instead of 2.00 (Ad-hoc-AG Boden, 2005), but the German Manual is not clear on how to deal with substrates at the boundary between mineral and organic substrate. Depending on peat substrates, the conversion factor may vary between 1.73 and 2.41 (Klingenfuß *et al*. 2014). Pribyl (2010) has shown that, for soils in general, a factor of 1.9 or 2.0 would be more accurate. Apart from this rather technical question, the real challenge lies in defining an appropriate classificatory boundary between organic and mineral soils. As highlighted above, SOC content is not necessarily suitable for all purposes. Therefore, further work should focus on identifying (former) peatland sites where the organic matter is mainly derived from peat and thus is not stabilised in the same way as in mineral soils. Such work would comprise both experimental work and analyses of land cover and land use history.

Refinement according to pedogenetic processes and peatland genesis

In a first step, peat-derived, covered or deep-ploughed organic soils might be differentiated by peat substrate or, in the case of covers, by texture. A further distinction according to a profile development in terms of pedogenetic features (e.g. earthification, formation of aggregates or moorsh) has not yet been included as this was considered to be of minor importance - at least compared with strong changes in horizonation - for the soil properties evaluated here. However, especially when aiming at adding soil-hydrological properties to the parameterisation, a differentiation by horizons will become necessary since pedogenetic features of this kind do not only influence bulk density (as approximated by topsoil and subsoil here), but hydraulic conductivity, water retention characteristics and hydrophobicity as well (Schwärzel *et al*. 2002, Wallor *et al*. 2018). Peatland genesis results in a distinct combination of horizons and peat substrates with specific properties (Okruszko 1993, Roßkopf *et al*. 2015). Thus, for example, hydrogenetic mire types have been shown to affect typical peat thickness and hence total SOC storage (Zauft *et al*. 2010, Roßkopf *et al*. 2015), and to be valuable for the regionalisation of groundwater levels (Bechtold *et al*. 2014). Therefore, an ideal classification for peat and other organic soils should combine pedogenetic and anthropogenic features with peatland genesis.

Adding missing types of peat and other organic soils

Due to the limited number of sampling sites, it was not possible to include rarer types of organic soils, such as organic marshes or organic gyttja soils. The latter develop when (nearly) all peat has been mineralised and former sediment forms the upper part of the profile (Chmieleski & Zeitz 2006). Furthermore, no near-natural peatlands have yet been considered because they are rare in Germany and have not been examined in the Agricultural Soil Inventory. Finally, successfully rewetted peatlands develop distinct soil profiles with either fresh organic sediment or even newly-formed peat on top of a degraded peat profile. If climate mitigation efforts accelerate rewetting, it is hoped that such soils will become more common in the future.

ACKNOWLEDGEMENTS

This study was funded by the German Federal Ministry of Food and Agriculture within the framework of the German Agricultural Soil Inventory. We gratefully acknowledge the field and laboratory teams of the German Agricultural Soil Inventory coordinated by Roland Prietz, Arne Heidkamp and Anna Jacobs; and the work of Rayk Hopfstock on database management. We also thank Tina Asmuß, Stefan Frank, Sebastian Heller, Wiltrut Koppensteiner, Jan Oestmann, Laura Panitz, Arndt Piayda, Christopher Poeplau and Liv Sokolowsky for valuable discussions on previous versions of this manuscript; and Sabine Jordan as Article Editor and the anonymous reviewers for their helpful comments.

AUTHOR CONTRIBUTIONS

MW, BT and UD conceived and designed the study. MW and BT developed the classification scheme. MW performed the analyses with assistance of UD. MW wrote the first draft with contributions from BT, while all the authors discussed the results and revised the manuscript.

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Submitted 01 Jul 2020, final revision 27 May 2021
Editor: Sabine Jordan

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Supplementary material: MS-Excel file containing:
Table S1: SOC and N_t stocks, significant differences, and number of sites of each peat class and depth.
Table S2: Soil properties and stocks of all investigated sites of all depth increments.
Table S3: SOC and N_t content, BD and SOC density of all organic samples.
Table S4: Texture, SOC and N_t content and SOC density of all samples from shallow and thick covers.

Appendix

Table A1. Typical horizons and horizon sequences according to the German Manual of Soil Mapping (Ad-hoc-AG Boden 2005) of the 'peat classes' defined in this study. SOM: soil organic matter.

Typical sequences (examples)	**Description**
nHm/nHw/nHr	**Fen peat soil**; moorshyfied topsoil, fluctuating water table below, water saturation in the subsoil; all horizons have a SOM content of ≥ 30 % and in total ≥ 30 cm thickness (German: '*Mulmniedermoor*')
hHv/hHw/hHr	**Bog peat soil**; earthified topsoil, fluctuating water table below, water saturation in the subsoil; all horizons have a SOM content of ≥ 30 % and in total ≥ 30 cm thickness (German: '*Erdhochmoor*')
nHv/fFw/IIGro/IIGr	**Peat-derived organic soil**; shallow (< 30 cm) earthified fen peat horizon (SOM content ≥ 30%) above a fossil subhydric horizon and further mineral groundwater influenced subsoil horizons (German: '*Moorgley*')
rnHv/rnHw/IIGo/IIGr	**Peat-derived organic soil**; relict fen peat horizons (< 30 % SOM), earthified, above mineral groundwater influenced subsoil horizons (*not defined as an independent soil type*)
jAh/IIhHv/IIhHw/IIIGor	**Shallowly covered organic soil**; shallow (< 40 cm) mineral topsoil horizon of anthropogenically applied natural material above earthified and temporarily waterlogged bog peat horizons (≥ 30 cm) and a mineral groundwater influenced horizon (*not defined as an independent soil type*)
tbAh/tbGo/tbGro/IIfnHw/IInHr	**Thickly covered organic soil**; thick (≥ 40 cm) mineral topsoil horizons of naturally sedimented material (tidal-brackish environment) with pedogenetic features (groundwater influence), above fossil fen peat horizons (≥ 30 cm), as well in water table fluctuation range (German: *'mächtige Kleimarsch über Niedermoor'*)
R-Ap/R+hH+Go/Gr	**Deep-ploughed organic soil**; mixed and ploughed (homogenised) mineral topsoil horizon above a deep-ploughed layer of a bog peat horizon and mineral subsoil horizon next to each other (indicated by R and '+', as the materials were not homogenised; distinct 'sand-peat-stripes'), the mineral groundwater influenced subsoil horizon lies below (German: *'Treposol aus Hochmoor'*)
Organic soil horizons (≥ 30 % SOM)	
Hv, *Hm*	Topsoil horizons of moderately to heavily drained sites; plant residuals not recognisable anymore
	Hv: earthified; crumbly structure
	Hm: 'moorshyfied'; black, highly degraded, hydrophobic peat substrate with dusty powdery structure when dry or smeary when moist
Hw	Soil horizon with alternate saturated and unsaturated conditions und thus, temporarily subjected to aerobic conditions, showing oxidative features; peat structure not yet altered by secondary pedogenetic processes
Hr	Subsoil horizon with permanently saturated and anoxic conditions, peat structure not altered by secondary pedogenetic processes

Mineral soil horizons (< 30 % SOM)	
Ah, Ap	Topsoil horizons with accumulation of SOM
	Ah: minimum SOM content between 0.6 and 1.2 %
	Ap: ploughed
Go, Gro, Gr	Semiterrestrial soil horizons with groundwater influence
	Go: predominantly oxidizing conditions throughout the year
	Gro: approximately similar shares of oxidizing and reducing conditions
	Gr: predominantly reducing conditions throughout the year
R	Anthropogenically mixed horizon by melioration measures (e.g. deep ploughing)
(Semi-) Subhydric horizon	
F	Horizon at the bottom of a waterbody; may be the starting point or intermediate stage of fen development (‘*gyttja*’, German: ‘*Mudde*’)
Prefixed attributes	
h or n (for H-horizons only)	h: bog substrate (German: ‘*Hochmoor*’)
	n: fen substrate (German: ‘*Niedermoor*’)
f	Fossil, buried horizon; not developing further
j	Anthropogenically relocated natural material, e.g. mineral material brought to another site as part of a melioration technique
r	Relict in terms of diagnostic features
tb	Tidal-brackish sedimented material (in coastal regions with tidal influence)
II, III	Roman numeral, indicating a change of layers (difference in geological genesis, e.g. mineral sediment above peat)