

Stocks of organic carbon in German agricultural soils—Key results of the first comprehensive inventory

Christopher Poeplau^{1*}, Anna Jacobs^{1,2}, Axel Don¹, Cora Vos¹, Florian Schneider¹, Mareille Wittnebel¹, Bärbel Tiemeyer¹, Arne Heidkamp¹, Roland Prietz¹, and Heinz Flessa¹

¹ Thünen Institute of Climate-Smart Agriculture, Bundesallee 65, 38116 Braunschweig, Germany

² Coordination Unit Soil of Thünen Institute, Bundesallee 49, 38116 Braunschweig, Germany

Abstract

Background: There is considerable uncertainty about the actual size of the global soil organic carbon (SOC) pool and its spatial distribution due to insufficient and heterogeneous data coverage.

Aims: We aimed to assess the size of the German agricultural SOC stock and develop a stratification approach that could be used in national greenhouse gas reporting.

Methods: Soils from a total of 3104 sites, comprising 2234 croplands, 820 permanent grasslands and 50 sites with permanent crops (vineyards, orchards) were sampled in a grid of 8 × 8 km to a depth of 100 cm in fixed depth increments. In addition, a decade of management data was recorded in a questionnaire completed by farmers. Two different approaches were used to stratify cropland and grassland mineral soils and derive homogeneous groups: stratification *via* soil type (pedogenesis) and *via* SOC-relevant soil properties.

Results: A total of 146 soils were identified as organic soils, which stored by far the highest average SOC stock of $528 \pm 201 \text{ Mg ha}^{-1}$ in 0–100 cm depth. Of the mineral soils, croplands and permanent crops stored on average 61 ± 25 and $62 \pm 25 \text{ Mg ha}^{-1}$ in 0–30 cm (topsoil) and 35 ± 30 and $44 \pm 28 \text{ Mg ha}^{-1}$ in 30–100 cm (subsoil), while permanent grasslands stored significantly more SOC (88 ± 32 and $47 \pm 50 \text{ Mg ha}^{-1}$ in topsoil and subsoil). Overall, topsoils stored $67 \pm 14\%$ and subsoils $33 \pm 14\%$ of total SOC stocks. Soil C:N ratio, clay content and ground-water level were major factors that explained the spatial variability of SOC stocks in mineral soils. Accordingly, Podzols, Gleysols and Vertisols were found to have the highest SOC stocks.

Conclusions: Stratification *via* soil properties yielded the most comparable cropland and grassland strata and is thus preferable for estimating land-use change effects, e.g., for greenhouse gas inventories.

In total, 2.5 Pg C are stored in the upper 100 cm of German agricultural soils, making them the largest organic carbon pool in terrestrial ecosystems of Germany. This bares a large responsibility for the agricultural sector and society as a whole to maintain and, if possible, enhance this pool.

Key words: agriculture / agricultural soil inventory / soil organic matter / soil survey / stratification / terrestrial carbon

Accepted September 04, 2020

1 Introduction

The level of soil organic matter (SOM), consisting of more than 50% soil organic carbon (SOC), is a key ecosystem feature (Johnston et al., 2009). This is due to the strong positive impacts of SOM on almost all major soil functions, including the retention and release of nutrients, retention of water, structural stability, and the habitat function for soil micro- and macrofauna. Furthermore, SOC is the largest carbon pool in terrestrial ecosystems and stores more carbon than vegetation and the atmosphere combined (Stocker et al., 2013). Consequently, even small changes in that pool in either direction may be climate-relevant and are to be reported as such within national greenhouse gas reporting under the United

Nations Framework Convention on Climate Change (UNFCCC). Also, the FAO considers loss of SOC as an indicator of land degradation that is to be reported within the context of the Sustainable Development Goals (*Global Soil Partnership*, 2017).

Agricultural soils are subject to diverse management interventions such as tillage, fertilization, liming, harvest, irrigation, drainage, and grazing, all of which have an impact on SOC stocks to some extent (Freibauer et al., 2004; Kätker et al., 2012; Paradelo et al., 2015). Furthermore, the global area of soils under agricultural production is huge and expected to



Supporting Information
available online

* Correspondence: C. Poeplau;
e-mail: Christopher.poeplau@thuenen.de

increase (Ramankutty and Foley, 1999). The sheer size of that area and the fact that SOC stocks are strongly influenced by anthropogenic management support the intention of considering SOC sequestration as potential negative emission technology to achieve climate mitigation (Smith, 2016). For improved scientific understanding of SOC stabilization mechanisms and temporal dynamics, systematic and representative soil inventories are needed (Prechtel et al., 2009) and can also serve to validate measures implemented to increase SOC stocks. High-quality sampling and analysis are crucial here since changes in SOC occur slowly and in small magnitudes relative to total SOC stocks and their variability in space (Schrumpf et al., 2011). It has been demonstrated that the effects of environmental or management changes on SOC and related key soil parameters can be observed in comprehensive soil monitoring schemes. For example, Bellamy et al. (2005) reported losses of SOC in soils of Wales and England between 1978 and 2003 and related them to enhanced mineralization of SOC. While the reasons for this decline in SOC have been debated (Hopkins et al., 2009; Smith et al., 2007), the study was an early example of highlighting the value of high-quality repeated inventories. In other European countries too, comparable soil inventories have indicated losses of SOC from agricultural soils (Sleutel et al., 2007; Heikkinen et al., 2013). However, the opposite has also been observed: in the past three decades, SOC in Swedish agricultural soils increased by 7%, which has been explained by the increased proportion of leys and green fallow in crop rotations (Poeplau et al., 2015).

In 2008, the German Federal Ministry of Food and Agriculture commissioned the Thünen Institute of Climate-Smart Agriculture to conduct the first agricultural soil inventory at national scale to meet the increased requirements of greenhouse gas reporting. The unique features of this inventory were the sampling depth of 100 cm and the collection of management data for each of the sampled sites. Subsoils were found to be of high relevance for SOC storage (Lorenz and Lal, 2005). This is especially true for agricultural soils, which are often characterized by SOC-depleted topsoils and by tillage operations that exceed the standard reporting depth of 0–30 cm. It was thus expected that a considerable proportion of total SOC is stored in subsoils. Furthermore, SOC stocks and dynamics are driven by agricultural management. Only the knowledge of the management and yields of the sampled fields enables an in-depth analysis of the drivers and causes of detected SOC stocks and their dynamics. For dynamic modelling purposes too, precise management data of each sampling point are advantageous. For these reasons, one decade of management data prior to sampling was evaluated by means of a questionnaire completed by farmers. The dataset generated by this provides rare first-hand insights into organic fertilization, residue management and other key variables related to SOC stocks (Jacobs et al., 2020, in press).

An initial report on the results of this inventory (in German) was based on an interim dataset (Jacobs et al., 2018). Several case studies using the inventory dataset have also been published. For example, Vos et al. (2019) used a machine learning algorithm to explain the country-scale variability in SOC stocks with a wide range of pedoclimatic and manage-

ment variables, while Vos et al. (2018) used a combination of near infrared spectroscopy and SOC fractionation at selected sites to identify hot regions of labile SOC. The degree of severe soil compaction and the potential for alleviating root-restricting layers in German agricultural soils have also been investigated (Schneider and Don, 2019a; 2019b). Wittnebel et al. (submitted) summarized the properties of peat and other organic soils, while Säurich et al. (2019) determined aerobic respiration rates of a large variety of organic soil samples. However, there has been no concise or complete presentation of the key outcomes of the first German Agricultural Soil Inventory so far, and the question of how soils in Germany should be stratified to derive groups with distinct SOC stocks remains unresolved. This is of specific importance for greenhouse gas reporting on mineral soils, where the effects of land-use change from cropland to grassland and *vice versa* are estimated from average SOC stock differences between grassland and cropland soils. However, a simple comparison of the average SOC stocks of croplands and grasslands might give a biased estimate for the effect of land use, since the two land-use types are not necessarily equally distributed on similar soils. Thus, the aims of this study were: (1) to assess the overall size of German agricultural SOC stocks, (2) to develop a meaningful stratification for advanced understanding of SOC stock drivers, and (3) to develop improved predictions of potential land-use change effects, e.g., for greenhouse gas reporting.

2 Material and methods

2.1 Inventory design and management survey

In line with the German Forest Soil Inventory (Grüneberg et al., 2014), German agricultural soils were sampled in a fixed grid of 8 × 8 km. In total, the grid comprised 3104 sampling points, of which 2234 were located on croplands, 820 on permanent grasslands and 50 on fields with permanent crops, i.e., vineyards and orchards. Permanent grassland was defined as a site with more than five consecutive years of grassland use, and is referred to below as 'grassland'. The proportions of 72%, 26.4%, and 1.6% for cropland, grassland and permanent crops respectively were well in line with official German land-use statistics (Jacobs et al., 2018). After identification of sampling points and the respective landowners and tenants, farmers were contacted directly and asked for their cooperation. At the same time, the identified sampling points were checked for potential warfare material or cable tracks in the ground. If sampling of the exact grid point was not possible for one of the given reasons, a new sampling point of the same land-use type was identified within a radius of 400 m.

Where they agreed, farmers were sent a questionnaire to record general information on the type and size of their farm, as well as ten years of management data for the specific sampling site, including the type and yield of the main crop, the type and usage of cover crop, residue management, liming, the type and amount of organic and mineral fertilizer application, soil tillage, soil melioration measures (drainage, deep ploughing, grassland renewal), and the number of cuts. The

type and number of animals were evaluated for the farm as a whole.

2.2 Soil sampling and *in situ* soil profile descriptions

The sampling points were visited by a three-person team consisting of one experienced soil scientist and two technicians. The soil scientists had been trained beforehand to ensure comparability of results of the *in situ* soil description (Vos et al., 2016). Croplands were mainly sampled in spring and winter to minimize crop damage and sampling on freshly ploughed fields was widely avoided, due to the strong effect of tillage on bulk density and thus SOC stock estimates. Grasslands and permanent crops were sampled year-round. A profile pit of approximately 1 m³ (100 cm depth) was dug and the soil profile described to a depth of 200 cm (if possible, using a 3-cm diameter auger for the 100–200 cm depth) according to the German Soil Survey Guidelines KA5 (*Ad-Hoc-AG Boden*, 2005). The profile walls were always plumb-vertical. A complete list of soil parameters evaluated *in situ* can be found in Jacobs et al. (2018). Soil sampling was performed at fixed depth increments: 0–10 cm, 10–30 cm, 30–50 cm, 50–70 cm, and 70–100 cm. If a diagnostic horizon boundary was more than 4 cm away from a border between two depth increments, an extra depth increment was sampled to ensure that the soil properties could be investigated based on either fixed depth increments or diagnostic horizons. A total of 228 soil profiles were shallower than 100 cm. If the organic layer in peat soils exceeded 100 cm or mineral soils appeared particularly SOC-rich at depth, a machine-driven auger (6 cm diameter) was used to sample the subsoil in increments of 100–150 cm and 150–200 cm (133 sites, data not shown). In this study, the presentation of SOC stocks was mainly restricted to two depth increments, *i.e.*, topsoil (0–30 cm) and subsoil (30–100 cm). For the chemical and textural analysis, a disturbed composite sample of about 1 kg was taken from each depth increment using a shovel. For bulk density and rock fragment fraction estimation, two to ten undisturbed samples were taken from each depth increment using cylindrical soil cores. The number of cylindrical soil cores depended on their size, which in turn depended on the rock fragment fraction. The smallest cylinders used were 5 cm³ ($n = 10$) and the largest 250 cm³ ($n = 2$). If the visually estimated rock fragment fraction exceeded 5% in a specific depth increment, an additional spade sample was taken for a more accurate estimation of it. In the case of very large rocks, the volumetric rock fragment fraction was estimated in the field. If it was suspected that the density of the rock fragment fraction deviated from the common density of 2.65 g cm⁻³, a particle density determination kit was used in the laboratory (YDK01, Sartorius, Göttingen, Germany). In addition to the soil profile, eight satellite soil cores to a depth of 1 m and a diameter of 6 cm were taken at a distance of 10 m from the soil pit, as described by Grüneberg et al. (2014). This was done to evaluate the small-scale heterogeneity of SOC and other soil parameters. These satellite samples are still being processed, therefore the results presented in this study are based on soil profile sampling only. A total of 146 sampling points (4.7%) were located on peat and other organic soils, which were defined by either an organic (SOC

content ≥ 87 g kg⁻¹) horizon at the top of the profile, or an organic layer of ≥ 30 cm thickness within the first meter (Witnebel et al., submitted). These soils will be referred to as organic soils in the following and comprise peat soils (drained fens or bogs), but also a large variety of highly disturbed and degraded soils that used to be peatland, including deep ploughed organic soils. The wide definition of organic soils is in line with the German emission inventory (Tiemeyer et al., 2016; German Environment Agency, 2019) and the high CO₂ emissions measured from shallow and relatively SOC-poor organic soils (Tiemeyer et al., 2016).

2.3 Sample analysis and calculation of soil organic carbon stocks

Soils were either directly oven-dried at 40°C (or at 105°C for bulk density determination) or stored at -15°C until further processing. Soils with high clay or carbonate contents were freeze-dried to improve the workability of dried soil material. Subsequently, dried samples were sieved to 2 mm and coarse fragments manually separated into roots and rock fragments, and weighed. The chemical parameters measured were organic and inorganic carbon and total nitrogen *via* dry combustion using an elemental analyzer (LECO TRUMAC and RC612, St Joseph, MI, USA) and soil pH in H₂O and CaCl₂. Soils with a pH > 6.2 were assumed to contain carbonates. In these soils, organic carbon (combustion at 550°C) and inorganic carbon (subsequent combustion at 1000°C) were determined by ramped combustion (LECO RC612). The physical parameters measured were soil texture (DIN ISO 11277, clay < 2 µm, silt 2–63 µm, sand > 63 µm and < 2000 µm), bulk density, root mass and rock fragment fraction. The latter parameters were used to calculate soil organic carbon stocks (SOCstock, Mg ha⁻¹), in brief according to Poeplau et al. (2017):

$$\text{SOCstock}_i = \text{SOCcon}_i \times \text{BD}_{\text{finesoil}_i} \times \text{depth}_i \times (1 - \text{rock fragment fraction}_i - \text{root fraction}_i), \quad (1)$$

where SOCcon_i is the SOC content in the soil < 2 mm (%) of the individual depth increment i , $\text{BD}_{\text{finesoil}_i}$ is the bulk density of the fine soil (g cm⁻³), depth_i is the depth of the individual depth increment, and rock fragments and root fraction refers to the volumetric fraction of particles > 2 mm in the respective depth increment (vol%/100). The distribution of general soil parameters in topsoils and subsoils is displayed in Fig. 1. Continuous variables as measured for the different depth increments were averaged for topsoil and subsoil increments using weighted means, with the fine soil stock of the individual depth increments (Mg fine soil ha⁻¹) as a weighting factor. For soil pH, averaging was performed with antilog values. All the soils were processed and analyzed in the same laboratory.

2.4 Stratification and statistics

Organic soils were excluded from the stratification because they were considered a separate stratum due to distinct pedogenesis and SOC stabilization mechanisms. An in-depth

analysis of the sampled organic soils can be found in Wittnebel et al. (submitted). For mineral soils, two different stratification approaches were adopted to derive groups of soils (strata) with distinct SOC stocks and comparable soils between land-use types within each stratum. The first approach was based on the notion that pedogenesis is a major driving factor for SOC stocks (Rodríguez-Murillo, 2001; Wiesmeier et al., 2012). The major soil type, as evaluated by the soil scientist in the field, was therefore translated into the reference soil group of the World Reference Base (WRB; FAO, 2015), as suggested by the German Soil Survey Guidelines KA5 (*Ad-Hoc-AG Boden*, 2005). These major soil types were subsequently used to stratify the soils. Within each stratum, cropland and grassland soils were evaluated separately.

In the second approach, soils were divided along SOC-relevant pedoclimatic site properties. To determine the most important predictors for SOC stocks, in the first instance a conditional inference forest algorithm (R package *cforest*) was applied (Hothorn et al., 2006). Vos et al. (2019) also adopted this approach with a previous version of the dataset (2350 sampling points) using a total of 200 potential predictors, consisting of measured and described soil parameters, geological and geomorphological parameters, climatic as well as management variables. The number of predictor variables was reduced to 39 (Tab. S1) in four steps. First, we only considered predictors that appeared somewhat meaningful as explanatory variables for SOC from a mechanistic point of view. Second, a correlation matrix was used to identify and remove redundant predictors. Of the remaining predictors, we selected only those, which had, according to the *cforest* algo-

rithm, a higher relative importance than in a theoretical model in which all predictors had the same importance (Hobley et al., 2015; Vos et al., 2019). Finally, we removed certain variables, which had high predictive power but were not meaningful for stratification (such as electric conductivity). The C:N ratio of the soil, which was excluded by Vos et al. (2019), was included in the present study as a key variable describing SOC quality. Vos et al. (2019) excluded this parameter, because their focus was on deriving predictors for SOC that can be used without knowing SOC. Cropland and grassland soils were separated before running the statistical model in order to determine SOC stock differences between croplands and grasslands within certain strata, *i.e.*, between comparable soils. The *cforest* algorithm was thus run for six different datasets: the topsoils and subsoils of croplands, of grasslands and of both land-use types combined (Fig. S1).

Both stratification approaches were conducted for topsoils and subsoils. To compare the two approaches, three simple statistical indices were used: (1) the mean interquartile range, with stratification aiming to isolate homogeneous groups, in this case with respect to SOC stocks. This homogeneity is expressed by within-group variability. As an indicator of variability, the interquartile range of each stratum per stratification method was averaged, with a low value indicating successful clustering; (2) goodness of fit. Another aim of stratification is to derive groups that differ strongly from one other. Analyses of variance (ANOVA) were conducted for each stratification approach. The Akaike information criterion (AIC) was used to identify the model (stratification approach) with the best fit (lowest AIC), *i.e.*, the approach with the greatest differ-

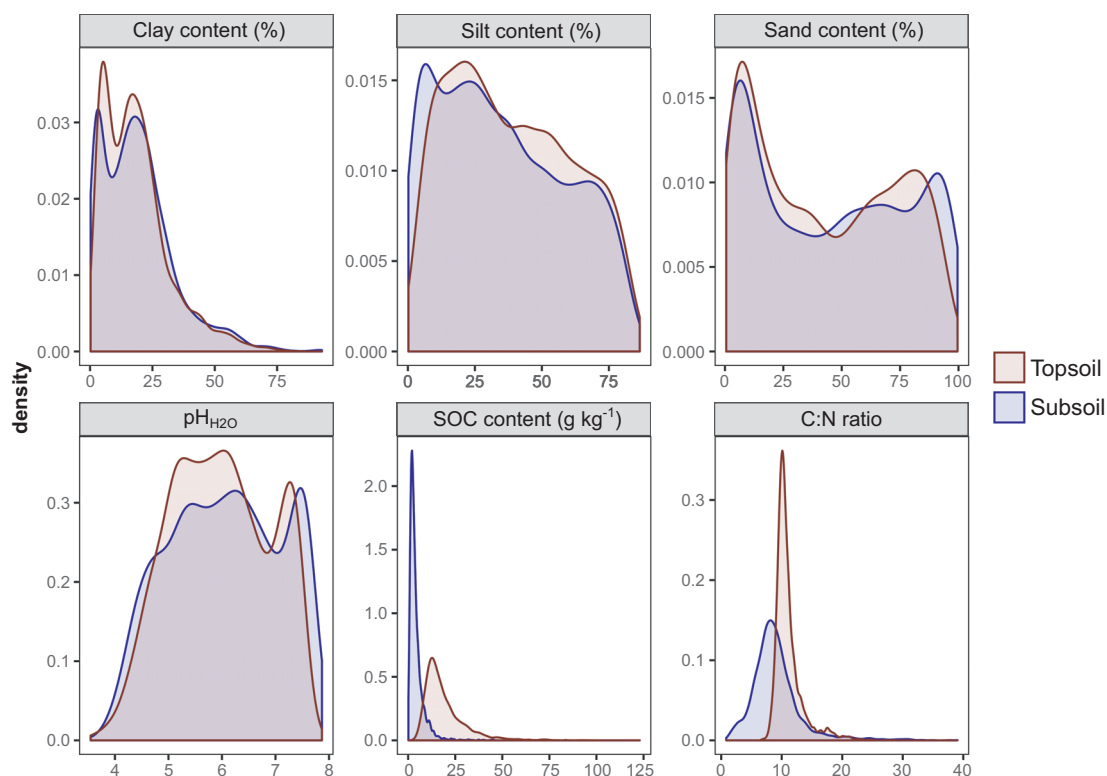


Figure 1: Density distribution of general soil chemical parameters for German agricultural mineral topsoils (0–30 cm) and subsoils (30–100 cm), $n = 2958$. SOC = soil organic carbon.

ences between strata; and finally (3) comparability of cropland and grassland soils. Another important aspect of stratification is that soils with similar properties are grouped together for unbiased comparisons. Here, the most SOC-relevant soil parameters (C:N ratio, clay content, groundwater level) were averaged for cropland and grassland soils within each stratum to evaluate their comparability.

To test whether the difference between cropland and grassland was influenced by stratum, an analysis of variance (ANOVA) was conducted with an interaction term 'stratum×landuse'. Before each ANOVA, the data were checked for normal distribution (histograms) and homogeneity of variance (Levene-Test). Data were log-transformed where needed and Tukey HSD was used as a post-hoc test. Significance was assessed at $p \leq 0.05$. Errors given in the text along with mean values are standard deviations. All statistical analyses were conducted in R version 3.5.2 (R Development Core Team, 2010).

3 Results

3.1 Average SOC stocks and their spatial distribution

On average, German agricultural soils stored $125 \pm 113 \text{ Mg SOC ha}^{-1}$. The highest SOC stocks were detected in organic soils with average values of 239 ± 92 and $289 \pm 172 \text{ Mg ha}^{-1}$ in topsoils and subsoils, respectively (Fig. 2). Organic soils were mostly used as grassland (81%) and mainly located in the far north and south of Germany, with a regional cluster in northwest Germany (Fig. 3). Average SOC contents in those soils ranged from $18.4 \pm 12.1\%$ to $22.2 \pm 19.4\%$ (Tab. 1). In accordance with high SOC contents, bulk densities were lower than or equal to 0.8 g cm^{-3} in all depth increments of the organic soils. In mineral soils, croplands with $96 \pm 48 \text{ Mg ha}^{-1}$ and permanent crops with $107 \pm 46 \text{ Mg ha}^{-1}$ stored similar average SOC stocks, while grasslands stored significantly higher SOC stocks at $135 \pm 70 \text{ Mg ha}^{-1}$ (Fig. 2; $p < 0.001$). On average, grasslands had 44% (27 Mg ha^{-1}) and 37% (12 Mg ha^{-1}) higher SOC stocks than croplands in topsoil and subsoil respectively. The depth profile of average SOC contents in croplands reflected the effects of soil tillage, with a relatively uniform SOC content in the upper 30 cm and a steep decline in SOC content below the maximum tillage depth of 30 cm on average (Tab. 1). For grasslands and permanent crops, a more gradual but exponential decline in SOC content with depth was observed. Furthermore, cropland soils had the highest bulk density values of all land-use types in all depth increments. As expected, rock fragment fractions tended to increase with depth and grassland mineral soils had higher rock fragment fractions than cropland mineral soils (Tab. 1).

For croplands, a clear regional pattern of SOC stocks was found, being particularly high in the northwest, southeast and northern central part of Germany (Fig. 3). In contrast, the lowest cropland SOC stocks were detected in northeast Germany. In particular, subsoils in that region were characterized by very low SOC stocks, with the majority of sampling points

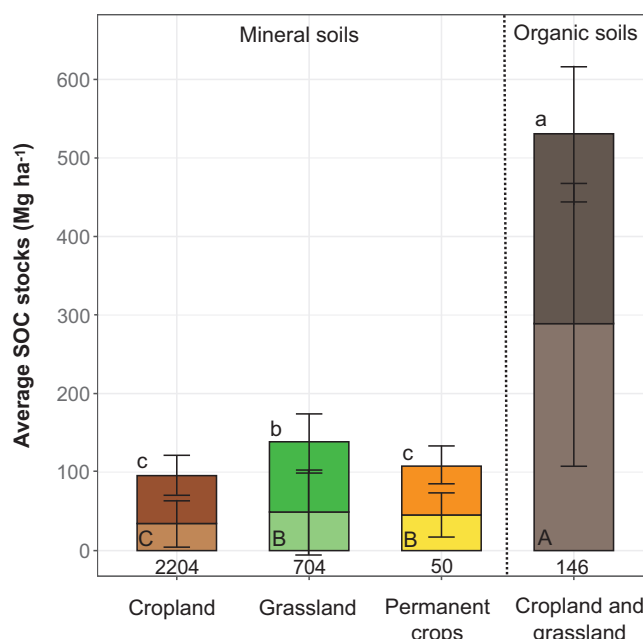


Figure 2: Average soil organic carbon (SOC) stocks in 0–100 cm for all land-use types in mineral soils and all organic soils under cropland and grassland use with standard deviations for topsoils (0–30 cm, darker colours), and subsoils (30–100 cm, lighter colours) in Germany. Letters indicate significant differences ($p \leq 0.05$) between the four classes in the topsoil (lowercase letters) and subsoil (capital letters). Numbers below each bar indicate the number of observations (n).

having less than 19 Mg ha^{-1} stored in 30–100 cm soil depth. A similar, yet less pronounced pattern was also detected for grassland soils. permanent crops (vineyards and orchards), comprising just 50 sites and mainly located southwest Germany, are not depicted in Fig. 3.

3.2 Stratification

The stratification *via* soil types derived strata with significantly different SOC stocks in cropland and grassland soils ($p < 0.001$; Tab. 2). In topsoils, Podzols and Gleysols followed by Anthrosols and Chernozems had the highest SOC stocks, while Luvisols and Cambisols were found to be at the lower end. This was also true for croplands and grasslands (Fig. 4A), while subsoils did not entirely follow that order (Fig. 4B). Shallow Regosols had the lowest subsoil SOC stocks, while Fluvisols, Anthrosols and Chernozems tended to have the highest.

The *cforest* models were able to explain 34–55% of the total variability in SOC stocks across German agricultural mineral soils (Fig. S1). The most important explanatory variable for SOC stocks in mineral soils was the C:N ratio of the soil. This was true for all models considered, *i.e.*, for croplands, grasslands, croplands and grasslands combined, as well as in topsoils and subsoils (Fig. S1). The second most important explanatory variable for SOC stocks was clay content in topsoils and chronostratigraphy (classification based on the age of deposits or rocks) in subsoils. However, also in subsoils, both clay content and sand content played an important role

Table 1: Average soil organic carbon (SOC) contents (g kg^{-1}), fine soil bulk density (g cm^{-3}), rock fragment fractions (vol%) and SOC stocks (Mg ha^{-1}) for all sampled depth increments (cm) per land-use type with standard deviation (SD). Organic soils are listed as their own class.

Class	Depth	SOC content		Bulk density _{fine soil}		Rock fraction		SOC stock	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Cropland (<i>n</i> = 2204)	0–10	17.6	8.9	1.27	0.17	3.4	5.5	20.7	8.5
	10–30	15.5	8.2	1.42	0.16	3.9	6.8	40.5	17.7
	30–50	6.2	6.1	1.51	0.17	6.8	14.1	16.3	14.3
	50–70	3.5	4.3	1.52	0.18	7.8	16.5	9.1	10.0
	70–100	2.4	3.1	1.55	0.18	7.6	16.7	8.9	11.1
Grassland (<i>n</i> = 704)	0–10	44.6	19.6	1.04	0.20	2.9	6.1	41.9	13.0
	10–30	21.1	13.7	1.29	0.21	7.7	13.1	46.3	24.4
	30–50	10.7	26.2	1.38	0.24	11.6	19.9	20.9	23.5
	50–70	6.1	14.0	1.43	0.24	12.6	21.0	12.5	15.5
	70–100	4.7	13.2	1.47	0.23	13.0	21.2	13.6	26.2
Permanent crops (<i>n</i> = 50)	0–10	25.6	10.3	1.20	0.20	5.6	2.6	27.9	10.6
	10–30	13.7	7.2	1.38	0.19	6.1	9.5	34.3	17.3
	30–50	7.3	5.2	1.45	0.19	6.4	10.5	18.2	12.3
	50–70	4.7	3.3	1.46	0.19	4.9	7.6	12.6	8.3
	70–100	3.8	4.2	1.47	0.23	5.5	9.2	13.9	13.3
Organic soils (grassland and cropland) (<i>n</i> = 146)	0–10	183.8	120.9	0.63	0.30	0.6	10.9	84.1	32.5
	10–30	210.1	162.3	0.67	0.43	0.9	3.4	155.0	69.4
	30–50	221.6	193.6	0.67	0.56	2.3	10.7	107.4	66.2
	50–70	215.7	205.8	0.71	0.63	2.8	11.1	83.8	61.1
	70–100	187.1	210.4	0.79	0.63	3.8	12.5	98.1	83.7

for SOC stocks. In the topsoil model combining croplands and grasslands, C:N ratio and clay content were even more important than land use. In subsoils, land use was not among the important explanatory variables (Fig. S1). Due to the fact that (1) the C:N ratio was the most important explanatory vari-

able of SOC stocks and (2) soils with wide C:N ratios were restricted to very sandy soils (Fig. 5A), the dataset was first split along the C:N ratio. Pre-tests, including density plots and regression analysis, revealed that a C:N ratio of 13 was the most meaningful threshold for cropland and grassland soils.

Figure 5A indicates that those two groups, *i.e.*, topsoils with a C:N ratio > 13 and ≤ 13 , separated strongly along the clay to SOC relationship, while Fig. 5B depicts that those soils with C:N > 13 were clustered in northwest Germany. Due to the fact that clay content did not play any role in SOC storage in soils with C:N > 13 , clay content was only used to further stratify the soils with a C:N ratio ≤ 13 . To do so, three fixed classes were used to stratify the dataset in accordance with the Association of German Agricultural Analytic and Research Institutes (Kerschberger et al., 2000): $< 12\%$ clay, $12\text{--}25\%$ clay, and $> 25\%$ clay.

The third most important predictor variable for topsoil SOC was land use (Fig. S1). Land-use type is a key feature of agricultural soils and was thus investigated separately for each stratum. As a further predictor, the mean annual groundwater level,

Table 2: Summary statistics for the two applied soil stratification approaches for two different soil depth increments (cm) and land-use types with mean interquartile range of the strata (mean IQR) as well as *p* value and the Akaike information criterion (AIC) of the conducted ANOVA.

Land use	Soil depth	Stratification	Mean IQR	<i>p</i>	AIC
Cropland	0–30	Soil properties	29.78	< 0.001	907
		Soil types	27.02	< 0.001	1197
	30–100	Soil properties	34.96	< 0.001	3786
		Soil types	29.74	< 0.001	4248
Grassland	0–30	Soil properties	33.9	< 0.001	327
		Soil types	33.7	< 0.001	465
	30–100	Soil properties	47.46	< 0.001	1439
		Soil types	31.33	< 0.001	1708

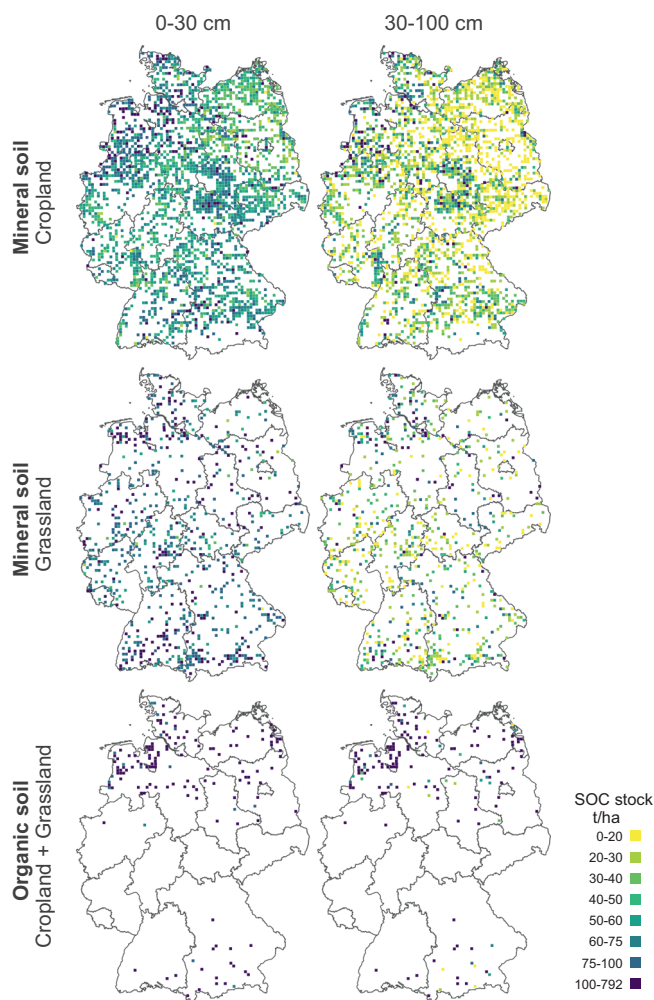


Figure 3: Spatial distribution of topsoil (0–30 cm) and subsoil (30–100 cm) soil organic carbon (SOC) stocks in Germany, divided into mineral soil croplands ($n = 2204$) and mineral soil grasslands ($n = 704$), as well as organic soils under both land-use types ($n = 146$).

influenced topsoil SOC stocks. This parameter was recorded by visual detection of oximorphic properties in gleyic soil horizons and consisted of seven classes describing a range of mean annual groundwater levels (*Ad-Hoc-AG Boden*, 2005). An analysis of variance (ANOVA) revealed the most suitable separation of the dataset to be between classes with mean annual groundwater levels above or below 130 cm: across those soils that showed oximorphic properties within the upper 130 cm of the soil profile, no significant difference in SOC stocks was found between groups. Only when the mean groundwater level was lower than 130 cm were SOC stocks significantly lower (Fig. 6). Furthermore, the classes differed greatly in size: 2174 sites were not influenced by groundwater at all. The soils of each previously derived stratum were therefore split into two groundwater level classes. Within each of the eight strata, the soils were divided into cropland and grassland soils (Fig. 7). A significant effect of stratum on the relative difference was detected between cropland and grassland topsoil SOC stocks ($p = 0.021$), with the smallest relative difference between cropland and grassland (23%) in

soils with a high clay content and a groundwater level higher than 130 cm (Tab. 3). Interestingly, the greatest average difference between cropland and grassland was found in soils with a high clay content and groundwater level below 130 cm (38%). The difference in topsoil SOC stocks between cropland and grassland within each stratum was considerably lower than the difference between the overall, non-stratified average cropland and grassland topsoil SOC stocks (Tab. 3). This can be explained by the uneven distribution of the most SOC-relevant soil parameters within cropland and grassland soils: grasslands tended to be on slightly more groundwater-influenced and fine-textured soils, while no difference was found for the C:N ratio (Fig. 8). For subsoils, the difference between cropland and grassland SOC stocks was mostly small (Fig. 7B, –9% to +40%), while C:N ratio, soil texture and groundwater level were as important as in the topsoil (Fig. S1). For a better comparability, the topsoil stratification was therefore applied equally to the subsoil. The strong influence of geological stratigraphy on SOC stocks is particularly driven by the SOC-rich soils of north Germany, which developed on quaternary glacial sediments, as well as by Holocene fluvial and tidal sediments.

A comparison of the two stratification approaches revealed that both approaches were valid, i.e., they derived strata that significantly differed in SOC stocks (Tab. 2). Stratification *via* soil types isolated slightly more homogeneous strata, as indicated by the lower average IQR compared with the stratification *via* soil properties. This can partly be explained by the larger number of strata. However, the AIC revealed that the difference between strata was greater in the second approach. This was true for croplands and grasslands, as well as for topsoils and subsoils. More importantly, for the purposes of deriving comparable cropland and grassland soils, the first approach was not suitable. For example, grassland Podzols had an average C:N ratio of 18.6 while for cropland Podzols it was 16.6. Furthermore, grassland Vertisols had on average 52% clay and cropland Vertisols 41% clay (Tab. 3). In all strata, grasslands had a higher clay content than croplands. This resulted in SOC stock differences between land-use types that in part were larger than average (Tab. 4). In contrast, in the second stratification approach the differences between cropland and grassland soils were negligible.

4 Discussion

4.1 Size of the German agricultural soil carbon stock

The German Agricultural Soil Inventory is among the first national inventories to investigate SOC stocks to a depth of 100 cm, with actual site-specific measurements of bulk density and rock fragment fraction throughout the soil profile. Similar SOC stocks were observed in regional assessments across Germany (*Neufeldt*, 2005; *Mordhorst et al.*, 2018). Other national or international soil inventories or surveys within Europe have restricted their investigation to topsoil SOC content (*Jones et al.*, 2005; *Reijneveld et al.*, 2009; *Poeplau et al.*, 2015), topsoil SOC stocks (*Martin et al.*, 2011; *Heikkinen et al.*, 2013) or extrapolated topsoil SOC stocks to

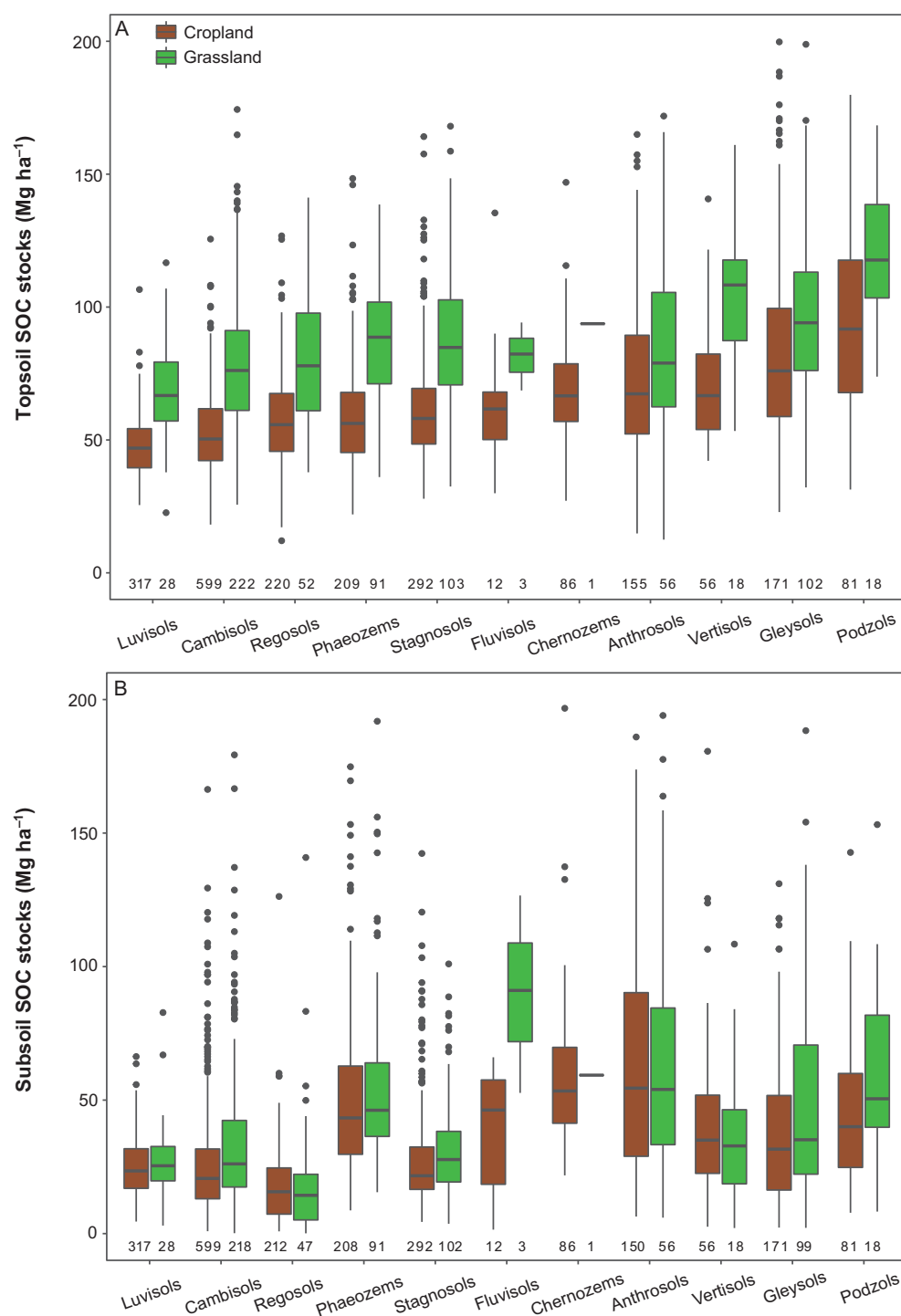


Figure 4: (A) Topsoil (0–30 cm) and (B) subsoil (30–100 cm) soil organic carbon (SOC) stocks of mineral soils by soil type for cropland and grassland soils. Numbers below each boxplot indicate the number of observations (n). The reference soil groups were derived by translating the German soil systematic units into World Reference Base reference soil groups in accordance with KA5: *Lessivés* = Luvisols; *Braunerden* = Cambisols; *A/C-Böden* = Regosols; parts of *terrestrische anthropogene Böden* (YK) and parts of *Auenböden* (AT) = Phaeozems; *Stauwasserböden* and partly *Marschen* (MD, MK) = Stagnosols; *Auenböden* (AQ, AZ) = Fluvisols; *Schwarzerden* = Chernozems; *terrestrische anthropogene Böden* (> YK, YE, YO, YY, YU) = Anthrosols; *Terrae calcis*, *Pelosoile* = Vertisols; *Gleye* and parts of *Marschen* (MC, MN, MO) = Gleysols; *Podsole* = Podzols.

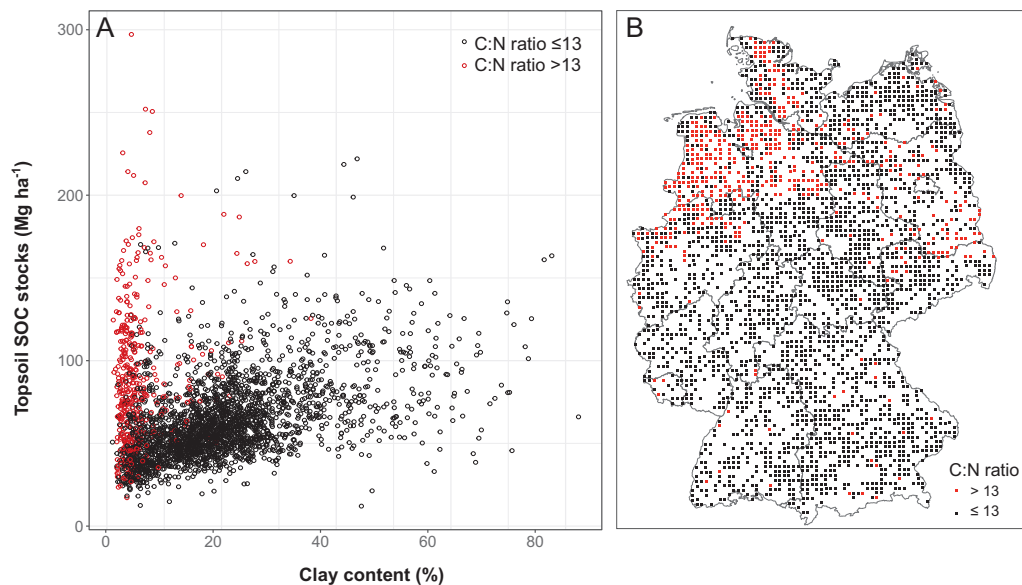


Figure 5: (A) Topsoil (0–30 cm) soil organic carbon (SOC) stocks of mineral soils as a function of clay content clustered in soils with C:N ratio ≤ 13 and > 13; (B) Spatial distribution of soils with topsoil (0–30 cm) C:N ratio > 13 and ≤ 13 across Germany.

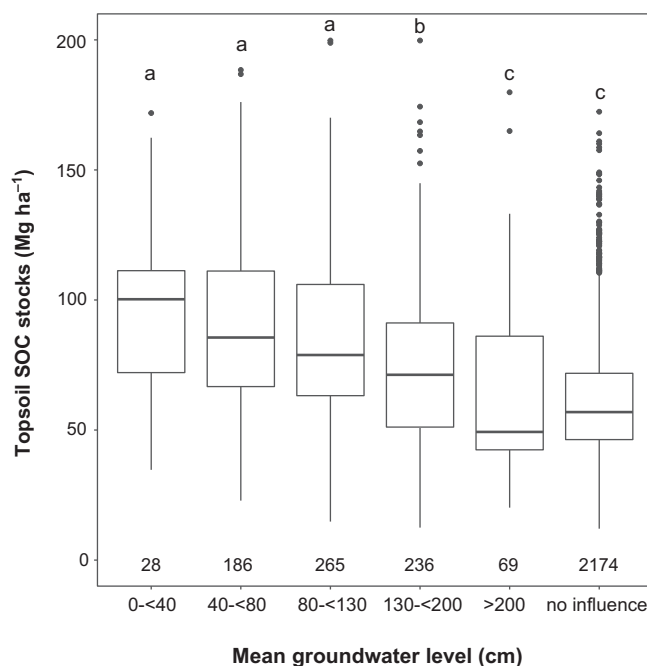


Figure 6: Topsoil (0–30 cm) soil organic carbon (SOC) stocks of mineral soils as a function of groundwater level class (adapted from the German Soil Survey Guidelines KA5), with letters indicating significant differences between classes ($p \leq 0.05$).

100 cm depth using a depth distribution model (Sleutel et al., 2003). However, several countries such as Denmark (Krogh et al., 2003; Taghizadeh-Toosi et al., 2014) and Scotland (Chapman et al., 2013) have conducted similar surveys a depth of 100 cm. In Danish agricultural mineral soils, the average SOC stock was 142 Mg ha⁻¹ and thus is comparable with the German average SOC stock of 125 ± 113 Mg ha⁻¹. In Scotland, the average country-wide SOC stock was 266 Mg ha⁻¹, owing to the fact that more than half of the sam-

pling points were located on 'woodlands', 'moorlands' or 'bogs'. In general, the huge diversity of sampling approaches, investigated depth increments, land-use types and also classification schemes, such as the cut-off between mineral and organic soils, hampers a harmonized interpretation or interpolation of measured SOC stocks beyond a national scale. In 2018, the FAO released a global SOC map, which resulted from a comprehensive data gathering approach and a harmonized spatial interpolation approach (*Global Soil Partnership*, 2017). For Germany, data from the present study and the German Forest Soil Inventory were used. Due to the great diversity of source data, abrupt changes in SOC stocks are still being observed along national borders. A harmonized methodological approach to assess SOC stocks is thus required (Hengl et al., 2017), as highlighted also by the FAO Global Soil Partnership (Pillar 5). Also country-scale estimates of SOC stocks can vary greatly, depending on data sources and methodology. Martin et al. (2011) used boosted regression trees to extrapolate results of the French soil monitoring network and derive a SOC map. They estimated a total topsoil SOC stock of 3.3 Pg C, while the European estimate for France was 5.3 Pg C (Hiederer, 2010).

On average (including organic soils), topsoils (0–30 cm) stored 67 ± 14% and subsoils (30–100 cm) 33 ± 14% of SOC stocks in German agricultural soils. This underlines the importance of assessing SOC to a greater depth than the standard national inventory reporting depth of 0–30 cm (IPCC, 2006). Additionally, the sporadic sampling to 2 m depth revealed that even below the first meter, certain soils store huge amounts of SOC and that SOC stocks are greatly underestimated when investigations are limited to the uppermost decimeters. In addition to the mere quantification of subsoil SOC and its potential contribution to ecosystem carbon cycling, deeper sampling allows the correct capture of certain management effects on SOC stocks. For example, between 1978 and 2009, the average ploughing depth in Scottish agricultural

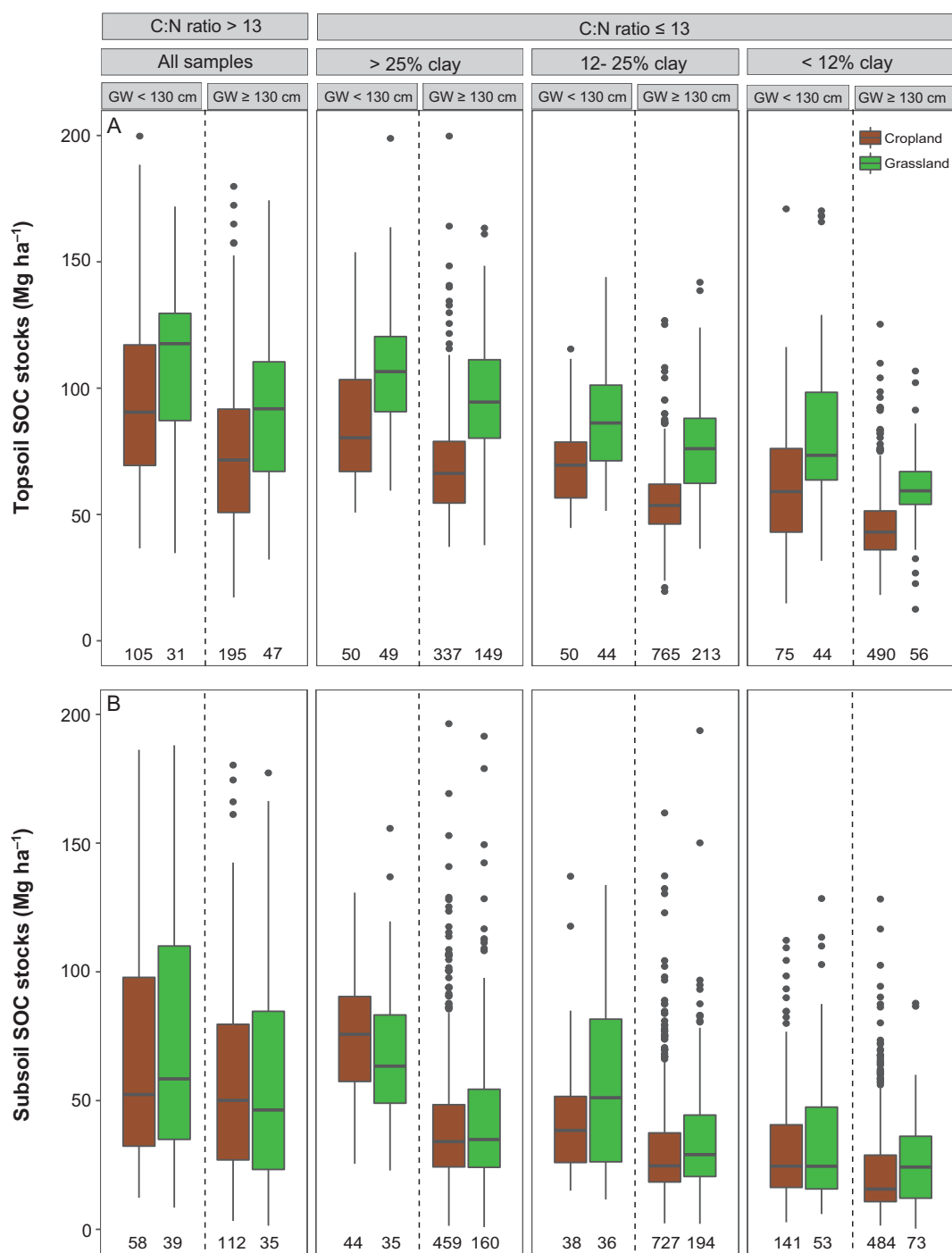


Figure 7: (A) Topsoil (0–30 cm) and (B) subsoil (30–100 cm) soil organic carbon (SOC) stocks of mineral soils by stratum for cropland and grassland soils. Numbers below each boxplot indicate the number of observations (n).

soils increased from 29 to 32 cm, leading to a redistribution of SOC along the soil profile (Chapman et al., 2013). This redistribution, which equals a dilution of the SOC-rich topsoil with less SOC-rich subsoil, would have been interpreted as mere SOC loss in the case of shallow sampling to 30 cm depth only. In the present study as well, the depth distribution of SOC was revealed to be strongly dependent on land use (Tab. 1) and in 44% of all croplands the ploughing horizon was deeper than 30 cm depth (data not shown).

Agriculture currently covers 51% of Germany's land surface (DESTATIS, 2019). With an average SOC stock of $124 \pm 111 \text{ Mg ha}^{-1}$ (including organic soils) in 0–100 cm soil depth, the total estimated size of the German agricultural SOC stock amounts to 2.5 Pg C (average stock of each land use type multiplied by respective area). This is 10.7 times the total annual anthropogenic CO_2 -C emissions in Germany (German Environment Agency, 2019) and makes agricultural soils the largest organic carbon pool in terrestrial ecosystems

Table 3: Average topsoil (0–30 cm) properties for cropland and grassland soils in each stratum of two stratification approaches; GW = mean annual groundwater level. The reference soil groups were derived by translating the German soil systematic units into World Reference Base reference soil groups in accordance with KA5: *Lessivés* = Luvisols; *Braunerden* = Cambisols; *A/C-Böden* = Regosols; parts of *terrestrische anthropogene Böden* (YK) and parts of *Auenböden* (AT) = Phaeozems; *Stauwasserböden* and partly *Marschen* (MD, MK) = Stagnosols; *Auenböden* (AQ, AZ) = Fluvisols; *Schwarzerden* = Chernozems; *terrestrische anthropogene Böden* (> YK, YE, YO, YY, YU) = Anthrosols; *Terrae calcis*, *Pelosole* = Vertisols; *Gleye* and parts of *Marschen* (MC, MN, MO) = Gleysols; *Podsole* = Podzols.

Approach	Stratum	C:N ratio		Clay content (%)		Proportion of soils with GW < 130 cm (%)	
		Cropland	Grassland	Cropland	Grassland	Cropland	Grassland
Soil types	Luvisols	10.4	10.3	14.7	16.5	0.9	0
	Cambisols	10.8	10.7	14.5	20.5	6.2	7.2
	Regosols	10	10.3	29.1	36.4	0.9	3.8
	Phaeozems	10.1	10.1	20.9	26.8	3.8	8.8
	Stagnosols	10.9	10.8	16.2	24.4	5.5	19.4
	Fluvisols	9.7	10	23.8	25.7	41.7	66.6
	Chernozems	10.5	9.7	23.7	32	2.3	0
	Anthrosols	13.6	13.2	9.7	11.9	32.5	45
	Vertisols	9.8	10.3	40.6	51.8	0	0
	Gleysols	11.9	11.1	15.6	19.1	77.6	91.5
	Podzols	16.7	18.6	3.5	3.9	40.2	55
Soil properties	C:N > 13, GW < 130 cm	16.9	17.5	4.5	6.3	100	100
	C:N > 13, GW ≥ 130 cm	15.2	15.7	5.2	9.2	0	0
	C:N ≤ 13, > 25% clay, GW < 130 cm	9.9	9.9	37.2	37	100	100
	C:N ≤ 13, > 25% clay, GW ≥ 130 cm	9.7	9.9	36.1	39.2	0	0
	C:N ≤ 13, 12–25% clay, GW < 130 cm	10.1	10.5	19	19.3	100	100
	C:N ≤ 13, 12–25% clay, GW ≥ 130 cm	10.1	10.4	18.1	18.9	0	0
	C:N ≤ 13, < 12% clay, GW < 130 cm	11.3	11.1	6.2	6	100	100
	C:N ≤ 13, < 12% clay, GW ≥ 130 cm	11.1	10.8	7.3	8.1	0	0
All soils		11.1	11.1	17.2	22.3	13.2	25.9

of Germany. Forest soils, which cover 29.8% of the land surface and have an average SOC stock of 117.1 Mg ha⁻¹, store 1.3 Pg C to a depth of 90 cm (Wellbrock et al., 2016). The slightly lower average SOC stock in forests as compared with agricultural soils can be explained by: (1) a high proportion of shallow and stony soils under forests, and (2) more agricultural than forest soils on organic soils. With an average SOC stock of 528 ± 201 Mg ha⁻¹, German organic soils are hot spots of SOC stocks and of SOC losses (German Environment Agency, 2019). Under agricultural land use, they are drained, which promotes rapid mineralization (Tiemeyer et al., 2020). Although a relatively low proportion of agriculture is taking place on organic soils in Germany, these soils constitute a considerable carbon source emitting more than

35 million tons of CO₂ per year (German Environment Agency, 2019) and thus around one third of the total agricultural greenhouse gas emissions. This underlines the important role played by these soils in agriculture-related CO₂ emissions and the urgent need to rewet drained organic soils to minimize their emissions (Günther et al., 2020).

4.2 Spatial distribution of SOC stocks

The variability of SOC stocks on a national scale was great, ranging from 9 to 419 Mg ha⁻¹ in the topsoil and from 0.3 to 792 Mg ha⁻¹ in the subsoil. The highest SOC stocks were found in organic soils, where climatic and soil hydrological

Table 4: Average topsoil (0–30 cm) soil organic carbon (SOC) stocks (Mg ha^{-1}) in mineral soils for cropland and grassland soils within each stratum and all soils combined with standard deviation (SD) and relative (%) and absolute (Mg SOC ha^{-1}) difference between cropland and grassland. GW = mean annual groundwater level. The reference soil groups were derived by translating the German soil systematic units into World Reference Base reference soil groups in accordance with KA5: *Lessivés* = Luvisols; *Braunerden* = Cambisols; *A/C-Böden* = Regosols; parts of *terrestrische anthropogene Böden* (YK) and parts of *Auenböden* (AT) = Phaeozems; *Stauwasserböden* and partly *Marschen* (MD, MK) = Stagnosols; *Auenböden* (AQ, AZ) = Fluvisols; *Schwarzerden* = Chernozems; *terrestrische anthropogene Böden* (> YK, YE, YO, YY, YU) = Anthrosols; *Terrae calcis*, *Pelosole* = Vertisols; *Gleye* and parts of *Marschen* (MC, MN, MO) = Gleysols; *Podsole* = Podzols.

Approach	Stratum	Cropland SOC stocks		Grassland SOC stocks		ΔSOC	
		Mean	SD	Mean	SD	Absolute	Relative
Soil types	Luvisols	47.3	11.2	69.1	20.5	45.9	21.7
	Cambisols	52.5	15.6	78.6	25.4	49.6	26
	Regosols	57.6	18.6	81.7	24.5	41.9	24.1
	Phaeozems	59.8	19.2	87.3	20.3	46.1	27.5
	Stagnosols	61.9	20.8	88.2	26.4	42.5	26.3
	Fluvisols	65.5	26.5	81.7	12.8	24.8	16.2
	Chernozems	68.4	18.4	93.7	NA	37.1	25.4
	Anthrosols	72.3	31.2	93.8	47.1	29.8	21.6
	Vertisols	71.5	21	103.4	26.7	44.5	31.9
	Gleysols	85	38.9	101.9	37.8	19.8	16.9
	Podzols	97.1	37	134.8	55.2	38.8	37.7
Soil properties	C:N > 13, GW < 130 cm	101.9	42	132.2	56.7	30.3	29.7
	C:N > 13, GW \geq 130 cm	74.7	31.9	93.4	35.4	18.7	25.1
	C:N \leq 13, > 25% clay, GW < 130 cm	90.3	32.4	111.1	30.5	20.8	23
	C:N \leq 13, > 25% clay, GW \geq 130 cm	69	20.9	95.3	23.9	26.3	38.2
	C:N \leq 13, 12–25% clay, GW < 130 cm	70.4	18	96.8	35.8	26.4	37.5
	C:N \leq 13, 12–25% clay, GW \geq 130 cm	55	12.9	75.3	19.3	20.3	37
	C:N \leq 13, < 12% clay, GW < 130 cm	62.3	27.5	84.6	34.6	22.2	35.6
	C:N \leq 13, < 12% clay, GW \geq 130 cm	45.3	14.3	59.8	17.2	14.5	32
All soils		61	25.1	88	32.6	27	44.3

conditions favored growth of peatlands during the Holocene (Kaiser et al., 2012). Consequently, the most important driver of SOC stocks in German agricultural soils overall was the occurrence of strong hydromorphic conditions, or more specifically the historic or current abundance of a high groundwater table. In organic soils, the lack of oxygen is the controlling factor hampering microbial breakdown of organic matter (Blodau, 2002). Also in mineral soils, the mean annual groundwater level affected SOC stocks (Fig. 6). In soils that are mostly drained, it appears unlikely however that current oxygen limitation strongly influences SOC dynamics, especially in topsoils. For example, only 28 soils had a mean annual groundwater level < 40 cm, and even those soils are probably not water-saturated in the topsoil for long periods. It

is more likely that fluvial or tidal sedimentation, as well as past *in-situ* hydrological conditions, led to strong accumulations of SOC that were still detectable. In this case, it is likely that these soils constitute potential hot spots of SOC losses.

For mineral soils, other factors were more important than groundwater level. A considerable proportion of soils had an unusually high C:N ratio for agricultural soils. C:N ratios were observed of up to 28 in the topsoil and 39 in the subsoil, while those of agricultural soils are usually around 10 (Jenkinson, 1988). The soils with a wide C:N ratio were almost exclusively located in northwest Germany (Fig. 4B), had an average sand content of 79% as well as extraordinarily high SOC stocks (Tab. 2) and are therefore also referred to as 'Black Sands'

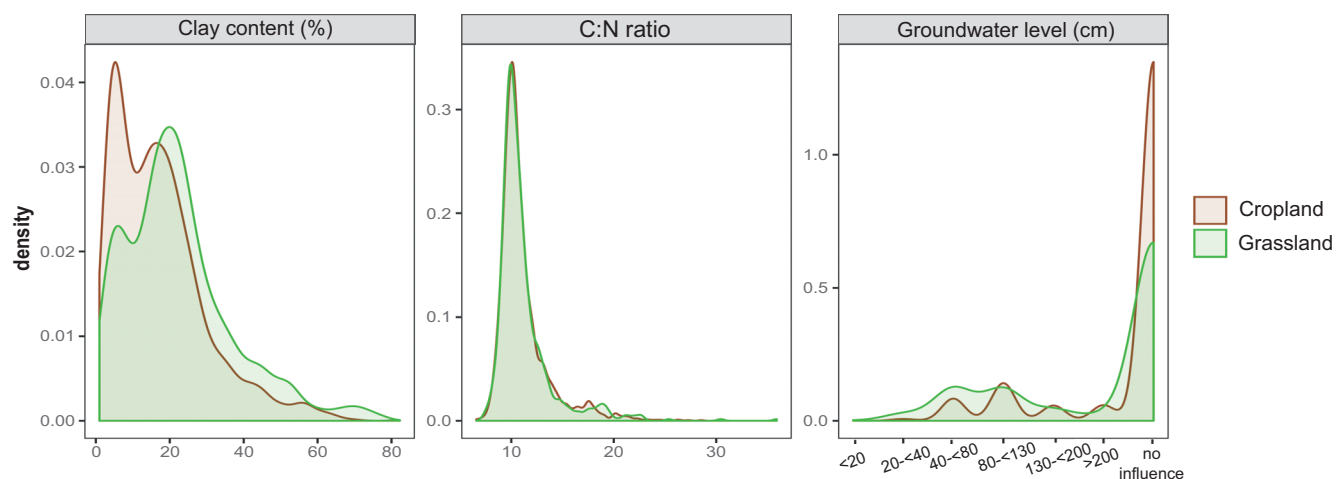


Figure 8: Distribution of the soil properties most relevant for soil organic carbon (SOC) stocks for cropland and grassland mineral topsoils (0–30 cm).

(Vos et al., 2018). Also in parts of Denmark, Belgium and The Netherlands, these ‘Black Sands’ are an acknowledged phenomenon and are mostly linked to a specific pedogenesis (podzolization) or land cover history as heathland or peatland (Thomsen et al., 2008; Sleutel et al., 2008, 2010; Vos et al., 2018). These two factors are probably interlinked, with land use influencing podzolization and *vice versa*. Accordingly, podzols were found to have the highest topsoil SOC stocks across all soil groups. A wide C:N ratio has been identified as a good indicator of a high amount of undecomposed and thus stable plant material (Springob and Kirchmann, 2003). *Calluna vulgaris*, a major heathland plant species, is acknowledged to form specifically resistant plant litter, with high amounts of polyphenolic substances (Sleutel et al., 2008). Indeed, Vos et al. (2018) found that SOC in those soils consisted of up to 85% particulate organic matter. However, some of the northern German SOC-rich sands are former peatlands, but not complying with our definition of organic soils anymore, or were formed by plaggen manuring (Vos et al., 2018). Despite the potentially high recalcitrance of organic matter in these soils, it remains unclear how SOC stocks in relictic peatlands, heathlands or plaggen soils respond to long-term agricultural management, including liming and fertilization. Indeed, Säurich et al. (2019) found that organic soil samples at the boundary to mineral soils originating from this inventory still emitted considerable amount of CO₂ and could not be considered as stable. A repeated sampling might give valuable insights in this regard. In summary, soils with a wide C:N ratio are specific to a certain region of Germany and are characterized by a unique land-use history and pedogenesis, which strongly affect SOC stabilization mechanisms. It is therefore a logical step to separate those soils from the majority of soils with a narrow C:N ratio in a stratifying approach.

For soils with a C:N ratio ≤ 13 , soil texture was the major controlling factor, explaining 22% of the total explained variance or 12% of the total variance in agricultural topsoil SOC stocks (Fig. S1). Many studies have observed a positive correlation of clay content and SOC, which can be related to: (1) sorption of SOC to mineral surfaces, and (2) aggregate formation

(Tisdall and Oades, 1982; Wagner et al., 2007). Furthermore, indirect SOC-stabilizing effects related to soil texture, such as pedogenic oxides, soil hydrology, anoxic microsites and microbial community composition, might play a certain role (Fierer and Schimel, 2002; Keiluweit et al., 2018). The positive influence of clay fits well with the fact that Vertisols are among the most SOC-rich soil types in Germany. As discussed in the previous section, the sandy soils of northwest Germany had exceptionally high SOC stocks. Other areas in Germany dominated by coarse-textured soils, especially the east and northeast of Germany, had particularly low SOC stocks. In the north-eastern part of central Germany, to the southeast of this sandy region in a similarly continental climate, the largest German Chernozem area developed on loess deposits. The most fertile agricultural soils in Germany are found in this region because of their high storage capacity of plant-available water and they are characterized by high SOC stocks, particularly in the subsoil (Fig. 3). This highlights the fact that abrupt changes in SOC stocks can be strongly driven by soil parent material.

Due to the high variability in SOC stocks at national scale, which is mainly driven by pedological, hydrological and geological site conditions, no significant effect of recent agricultural management (organic fertilization, crop rotation, tillage, etc.) on SOC stocks of mineral soils was detected. The potential absolute effect on SOC stocks in ten years of management is in single digits (Freibauer et al., 2004), while the actual variability of SOC stocks on national scale was in triple digits. However, the effect of land use, *i.e.*, if the land is cropland, grassland or under a permanent crop, had a significant influence on SOC stocks. In the stratification approaches, the dataset was therefore split into croplands and grasslands, the two major land-use types in German agriculture. It should also be noted that the soil group of Anthrosols, which consists of strongly manipulated and deeply meliorated soils, contained particularly high SOC stocks in the subsoil. This group mainly consisted of deep tilled former peatlands or plaggen soils (Alcántara et al., 2016).

4.3 Cropland vs. grassland SOC stocks

The conversion of cropland to grassland and *vice versa* is among the most relevant land-use changes in Germany with regard to area extent (Baumgarten et al., 2018) and also the magnitude of change in SOC stock (Freibauer et al., 2004) per area. It is thus important for greenhouse gas emission reporting on mineral soils to derive reliable estimates of the difference between cropland and grassland SOC stocks under steady-state conditions. In the present dataset, grasslands had on average 44% and 37% higher SOC stocks than croplands in topsoil and subsoil respectively. Grasslands can often be found in regions where cropping is barely possible or not economical, and are clustered in Germany's Prealps, the Central Uplands and the northwest of the country. This is possibly related to hydrology (too wet), soil texture (too heavy), topography (too steep) or the stone content of the soil (too stony, too shallow). Thus not only does land use influence the soil properties, but soil properties and other environmental factors also strongly influence land-use patterns. Consequently, using average SOC stock differences between land-use types to account for land-use change effects carries the risk of over or underestimating the latter. Indeed, grassland mineral soils in Germany tended to have slightly higher groundwater levels and slightly higher clay contents than cropland mineral soils. Those differences were not diminished after stratification *via* soil type. In contrast, stratification by SOC-relevant soil properties mostly decreased or diminished differences in these properties (Tab. 3). Thus, the difference in SOC stock between cropland and grassland was considerably lower within each of the derived strata as compared with the countrywide average (Fig. 7). In topsoils, the relative difference was reduced from 44% to 25–39%, which is closer to the values used in recent national inventory reports. For example, in the 2018 reports, Germany applied an average cropland SOC stock change from croplands to grasslands of 28%, Belgium used 38% and Switzerland used 16% for lowlands and 25% for midlands. The absolute differences between croplands and grasslands, *i.e.* between 14.5 and 30.3 Mg ha⁻¹, were well in the range of observed literature values for paired plot studies (5–28 Mg ha⁻¹) (Poeplau and Don, 2013) and a long-term field experiment following SOC losses and gains from grassland to cropland conversion and *vice versa* (23 Mg ha⁻¹) (Johnston et al., 2009). However, there are still certain drawbacks of a stratification approach like this to derive groups of comparable soils. Firstly, soils compared within each stratum might have been more comparable than all cropland and grassland soils in Germany were with one another, but they still differed. Tab. 3 shows that in certain strata, grasslands still had a slightly higher clay content and/or a wider C:N ratio and/or more groundwater level-influenced sites than cropland soils. Also the parameters used for stratification only explained less than half of the total variability in SOC stocks. Thus, it might be that soils differed in other properties that were not identified as being important for SOC storage in this study. Secondly, for reporting purposes it is important to know the difference between croplands and grasslands in a steady state. However, many soils in Germany have been subjected to land-use changes in the past century with contrasting effects on SOC stocks. For grasslands, the legacy effect of cropland use has had a nega-

tive effect on SOC stocks and *vice versa* (Springob et al., 2001; Mayer et al., 2019). However, the stratification approach highlighted that the application of one average absolute SOC change rate (*e.g.*, 27 Mg ha⁻¹) to account for the effects of conversion from cropland to grassland or *vice versa* on all soils will lead to overestimations for soils with high SOC stocks and underestimations for soils with low SOC stocks. An accurate SOC map combined with the strata and associated relative SOC change rates derived here (Tab. 2) could increase the accuracy of German greenhouse gas reporting in the land-use, land-use change and forestry (LULUCF) sectors.

4.4 Comparing stratification approaches

The two stratification approaches adopted here were valuable and valid. In regional-scale soil inventories, clustering by soil type is a classical approach (Rodríguez-Murillo, 2001; Wiesmeier et al., 2012), probably predominantly for practical reasons. Information on the spatial distribution of major soil types is mostly available and thus average values of SOC stock per soil type, for example, can be used to extrapolate point measurements. From a mechanistic point of view, to a certain extent it makes sense to consider pedogenesis as important for SOC storage, yet this link is often more indirect than using measured soil properties. For example, Vertisols had particularly high SOC stocks, which is most likely related to the high clay content (> 30%) in these soils. However, in soils with clay contents < 30%, clay is also among the most important predictors of SOC, which is not considered any further in the soil type approach. However, in certain aspects the soil type approach can be advantageous compared with stratification *via* selected soil properties since SOC sequestration is the result of a complex interplay of abiotic and biotic factors that can only partly be tackled by selecting a handful of soil properties. The best example might be Chernozems. These soils are characterized by higher than average SOC stocks, while their C:N ratios, clay contents and groundwater levels are in an intermediate range. This study also revealed that the difference between cropland soils and grassland soils with regard to SOC-relevant soil properties and thus also SOC stocks increased rather than decreased compared with the overall averages. Therefore, stratification *via* soil type failed to derive comparable soils that would be of value for estimating the effects of land-use change.

5 Conclusions

The first comprehensive inventory of German agricultural soils revealed that agricultural soils store the largest organic carbon pool in German terrestrial ecosystems. This pool is entirely managed for the production of food, feed, fiber and fuel for around 80 million people and partly for export. It is up to farmers, politicians and society as a whole to minimize the SOC losses from organic soils and to preserve or increase the SOC pool of mineral soils to maintain soil fertility, climate adaptation and food security, and realize climate mitigation goals. Centralized and accurate monitoring of SOC dynamics is essential for achieving those goals by keeping track of management or climate-driven alterations to SOC and key

related soil properties. The inventory also revealed that there are soils and regions with particularly high SOC stocks, mainly driven by abiotic environmental influences as well as historical land cover. These soils are, or might be, particularly prone to SOC losses due to climate and management changes. Finally, grasslands were found on slightly wetter and more fine-textured soils than croplands. The use of average SOC stocks of both land-use types to account for land-use changes, e.g., in greenhouse gas reporting, might thus lead to an overestimation of induced SOC stock changes. When targeting least biased estimates of land-use change effects, stratification via most relevant soil properties proved to be more feasible than the use of pedogenic proxies such as soil type.

Acknowledgments

The German Agricultural Soil Inventory was funded by the Federal Ministry of Food and Agriculture. Our thanks to everyone involved in the German Agricultural Soil Inventory.

Open access funding enabled and organized by Projekt DEAL.

Data Availability Statement

The data that support the findings of this study are openly available in OpenAgrar at <http://www.OpenAgrar.de>. (DOI: 10.3220/DATA20200203151139).

References

- Ad-Hoc-AG Boden (2005): Bodenkundliche Kartieranleitung. E. Schweizerbart'sche Verlagsbuchhandlung, Hannover, Germany.
- Alcántara, V., Don, A., Well, R., Nieder, R. (2016): Deep ploughing increases agricultural soil organic matter stocks. *Global Change Biol.* 22, 2939–2956.
- Baumgarten, C., Bilharz, M., Döring, U., Eisold, A., Friedrich, B., Frische, T., Gather, C., Günther, D. (2018): Daten zur Umwelt 2018: Umwelt und Landwirtschaft. Umweltbundesamt, Dessau-Roßlau, Germany.
- Bellamy, P. H., Loveland, P. J., Bradley, R. I., Lark, R. M., Kirk, G. J. (2005): Carbon losses from all soils across England and Wales 1978–2003. *Nature* 437, 245–248.
- Blodau, C. (2002): Carbon cycling in peatlands—a review of processes and controls. *Environ. Rev.* 10, 111–134.
- Chapman, S. J., Bell, J. S., Campbell, C. D., Hudson, G., Lilly, A., Nolan, A. J., Robertson, A. H. J., Potts, J. M., Towers, W. (2013): Comparison of soil carbon stocks in Scottish soils between 1978 and 2009. *Science* 64, 455–465.
- FAO (2015): World Reference Base for Soil Resources 2014. International Soil Classification System for Naming Soils And Creating Legends for Soil Maps, Update 2015. FAO, Rome, Italy.
- Fierer, N., Schimel, J. P. (2002): Effects of drying–rewetting frequency on soil carbon and nitrogen transformations. *Soil Biol. Biochem.* 34, 777–787.
- Freibauer, A., Rounsevell, M. D., Smith, P., Verhagen, J. (2004): Carbon sequestration in the agricultural soils of Europe. *Geoderma* 122, 1–23.
- German Environment Agency (2019): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2019—National Inventory Report for the German Greenhouse Gas Inventory 1990–2017. German Environment Agency, UNFCCC-Submission, Dessau-Roßlau, Germany.
- Global Soil Partnership (2017): Global Soil Organic Carbon Map—Leaflet. FAO, Rome, Italy.
- Grüneberg, E., Ziche, D., Wellbrock, N. (2014): Organic carbon stocks and sequestration rates of forest soils in Germany. *Global Change Biol.* 20, 2644–2662.
- Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebisch, F., Couwenberg, J. (2020): Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nat. Commun.* 11, 1–5.
- Heikkinen, J., Ketoja, E., Nuutinen, V., Regina, K. (2013): Declining trend of carbon in Finnish cropland soils in 1974–2009. *Global Change Biol.* 19, 1456–1469.
- Hengl, T., Mendes de Jesus, J., Heuvelink, G. B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M. N., Geng, X., Bauer-Marschallinger, B., Guevara, M. A., Vargas, R., MacMillan, R. A., Batjes, N. H., Leenaars, J. G. B., Ribeiro, E., Wheeler, I., Mantel, S., Kempen, B. (2017): Soil-Grids250m: Global gridded soil information based on machine learning. *PLoS One* 12. DOI: <https://doi.org/10.1371/journal.pone.0169748>.
- Hiederer, R. (2010): Organic carbon per country. Joint Research Centre, ESDAC, Brussels, Belgium. Available at: <http://eusoils.jrc.ec.europa.eu/ESDBArchive/octop/Resources/OCPerCountry.pdf>.
- Hobley, E., Wilson, B., Wilkie, A., Gray, J., Koen, T. (2015): Drivers of soil organic carbon storage and vertical distribution in Eastern Australia. *Plant Soil* 390, 111–127.
- Hopkins, D. W., Waite, I. S., McNicol, J. W., Poulton, P. R., Macdonald, A. J., O'Donnell, A. G. (2009): Soil organic carbon contents in long-term experimental grassland plots in the UK (Palace Leas and Park Grass) have not changed consistently in recent decades. *Global Change Biol.* 15, 1739–1754.
- Hothorn, T., Hornik, K., Zeileis, A. (2006): Unbiased recursive partitioning: A conditional inference framework. *J. Comput. Graph. Stat.* 15, 651–674.
- IPCC (2006): IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Kanagawa, Japan.
- Jacobs, A., Flessa, H., Don, A., Heidkamp, A., Prietz, R., Dechow, R., Gensior, A., Poeplau, C., Riggers, C., Schneider, F. (2018): Landwirtschaftlich genutzte Böden in Deutschland: Ergebnisse der Bodenzustandserhebung. Thünen Report No. 64. Johann Heinrich von Thünen Institute, Federal Research Institute for Rural Areas, Forestry and Fisheries, Braunschweig, Germany.
- Jacobs, A., Poeplau, C., Weiser, C., Fahrion-Nietschke, A., Don, A. (2020): Exports and inputs of organic carbon on agricultural soils in Germany. *Nutr. Cycl. Agroecosys.* DOI: <https://doi.org/10.1007/s10705-020-10087-5> (in press).
- Jenkinson, D. S. (1988): Soil Organic Matter and Its Dynamics, in Wild, A. (ed.): Russell's Soil Conditions and Plant Growth, 11th Ed. Longman, London, UK, pp. 564–607.
- Johnston, A. E., Poulton, P. R., Coleman, K. (2009): Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. *Adv. Agron.* 101, 1–57.
- Jones, R. J., Hiederer, R., Rusco, E., Montanarella, L. (2005): Estimating organic carbon in the soils of Europe for policy support. *Eur. J. Soil Sci.* 56, 655–671.
- Kaiser, K., Lorenz, S., Germer, S., Juschus, O., Küster, M., Libra, J., Bens, O., Hüttel, R. F. (2012): Late Quaternary evolution of rivers, lakes and peatlands in northeast Germany reflecting past climatic and human impact—an overview. *Quat. Sci. J.* 61, 103–132.

- Kätterer, T., Bolinder, M. A., Berglund, K., Kirchmann, H. (2012): Strategies for carbon sequestration in agricultural soils in northern Europe. *Acta Agric. Scand. Sect. A* 62, 181–198.
- Keiluweit, M., Gee, K., Denney, A., Fendorf, S. (2018): Anoxic microsites in upland soils dominantly controlled by clay content. *Soil Biol. Biochem.* 118, 42–50.
- Kerschberger, M., Deller, B., Hege, U., Kape, H. E., Krause, O., Pollehn, J., Rex, J., Severin, K. (2000): Bestimmung des Kalkbedarfs von Acker- und Grünlandböden. VDLUFA, Darmstadt, Germany.
- Krogh, L., Noergaard, A., Hermansen, M., Greve, M. H., Balstroem, T., Breuning-Madsen, H. (2003): Preliminary estimates of contemporary soil organic carbon stocks in Denmark using multiple datasets and four scaling-up methods. *Agric. Ecosyst. Environ.* 96, 19–28.
- Lorenz, K., Lal, R. (2005): The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. *Adv. Agron.* 88, 35–66.
- Martin, M., Wattenbach, M., Smith, P., Meersmans, J., Jolivet, C., Boulonne, L., Arrouays, D. (2011): Spatial distribution of soil organic carbon stocks in France. *Biogeosciences* 8, 1053–1065.
- Mayer, S., Kühnel, A., Burmeister, J., Kögel-Knabner, I., Wiesmeier, M. (2019): Controlling factors of organic carbon stocks in agricultural topsoils and subsoils of Bavaria. *Soil Tillage Res.* 192, 22–32.
- Mordhorst, A., Fleige, H., Zimmermann, I., Burbaum, B., Filipinski, M., Cordsen, E., Horn, R. (2018): Organische Kohlenstoffvorräte von Bodentypen in den Hauptnaturräumen Schleswig-Holsteins (Norddeutschland). *J. Land Manag. Food Environ.* 69, 85–95.
- Neufeldt, H. (2005): Carbon stocks and sequestration potentials of agricultural soils in the federal state of Baden-Württemberg, SW Germany. *J. Plant Nutr. Soil Sci.* 168, 202–211.
- Paradelo, R., Virto, I., Chenu, C. (2015): Net effect of liming on soil organic carbon stocks: A review. *Agric. Ecosyst. Environ.* 202, 98–107.
- Poeplau, C., Bolinder, M., Eriksson, J., Lundblad, M., Kätterer, T. (2015): Positive trends in organic carbon storage in Swedish agricultural soils due to unexpected socio-economic drivers. *Biogeosciences* 12, 3241–3251.
- Poeplau, C., Don, A. (2013): Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe. *Geoderma* 192, 189–201.
- Poeplau, C., Don, A., Flessa, H., Heidkamp, A., Jacobs, A., Prietz, R. (2020): Erste Bodenzustandserhebung Landwirtschaft—Kern Datensatz. OpenAgrar. DOI: <https://doi.org/10.3220/DATA20200203151139>.
- Poeplau, C., Vos, C., & Don, A. (2017): Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. *Soil* 3, 61–66.
- Prechtel, A., von Lützow, M., Uwe Schneider, B., Bens, O., Bannick, C. G., Kögel-Knabner, I., Hüttl, R. F. (2009): Organic carbon in soils of Germany: Status quo and the need for new data to evaluate potentials and trends of soil carbon sequestration. *J. Plant Nutr. Soil Sci.* 172, 601–614.
- R Development Core Team (2010): R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Ramankutty, N., Foley, J. A. (1999): Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochem. Cy.* 13, 997–1027.
- Reijneveld, A., van Wensem, J., Oenema, O. (2009): Soil organic carbon contents of agricultural land in the Netherlands between 1984 and 2004. *Geoderma* 152, 231–238.
- Rodríguez-Murillo, J. C. (2001): Organic carbon content under different types of land use and soil in peninsular Spain. *Biol. Fertil. Soils* 33, 53–61.
- Saurich, A., Tiemeyer, B., Don, A., Fiedler, S., Bechtold, M., Amelung, W., Freibauer, A. (2019): Drained organic soils under agriculture—The more degraded the soil the higher the specific basal respiration. *Geoderma* 355. DOI: <https://doi.org/10.1016/j.geoderma.2019.113911>.
- Schneider, F., Don, A. (2019a): Root-restricting layers in German agricultural soils. Part I: Extent and cause. *Plant Soil* 442, 433–451.
- Schneider, F., Don, A. (2019b): Root-restricting layers in German agricultural soils. Part II: Adaptation and melioration strategies. *Plant Soil* 442, 419–432.
- Schrumpf, M., Schulze, E. D., Kaiser, K., Schumacher, J. (2011): How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? *Biogeosciences* 8, 1193–1212.
- Sleutel, S., Abdul Kader, M., Ara Begum, S., De Neve, S. (2010): Soil-organic-matter stability in sandy cropland soils is related to land-use history. *J. Plant Nutr. Soil Sci.* 173, 19–29.
- Sleutel, S., De Neve, S., Hofman, G. (2007): Assessing causes of recent organic carbon losses from cropland soils by means of regional-scaled input balances for the case of Flanders (Belgium). *Nutr. Cycl. Agroecosyst.* 78, 265–278.
- Sleutel, S., De Neve, S., Hofman, G. (2003): Estimates of carbon stock changes in Belgian cropland. *Soil Use Manage.* 19, 166–171.
- Sleutel, S., Leinweber, P., Begum, S. A., Kader, M. A., Van Oostveldt, P., De Neve, S. (2008): Composition of organic matter in sandy relict and cultivated heathlands as examined by pyrolysis-field ionization MS. *Biogeochemistry* 89, 253–271.
- Smith, P. (2016): Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biol.* 22, 1315–1324.
- Smith, P., Chapman, S. J., Scott, W. A., Black, H. I. J., Wattenbach, M., Milne, R., Campbell, C. D., Lilly, A., Ostle, N., Levy, P. E., Lumsdon, D. G., Millard, P., Towers, W., Zaehle, S., Smith, J. U. (2007): Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978–2003. *Global Change Biol.* 13, 2605–2609.
- Springob, G., Brinkmann, S., Engel, N., Kirchmann, H., Böttcher, J. (2001): Organic C levels of Ap horizons in North German Pleistocene sands as influenced by climate, texture, and history of land-use. *J. Plant Nutr. Soil Sci.* 164, 681–690.
- Springob, G., Kirchmann, H. (2003): Bulk soil C to N ratio as a simple measure of net N mineralization from stabilized soil organic matter in sandy arable soils. *Soil Biol. Biochem.* 35, 629–632.
- Stocker, T., Qin, D., Plattner, G.-K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. M. (2013): Climate Change 2013: The Physical Science Basis. Cambridge University Press, New York, NY, USA.
- Taghizadeh-Toosi, A., Olesen, J. E., Kristensen, K., Elsgaard, L., Østergaard, H. S., Lægdsmand, M., Greve, M. H., Christensen, B. T. (2014): Changes in carbon stocks of Danish agricultural mineral soils between 1986 and 2009. *Eur. J. Soil Sci.* 65, 730–740.
- Thomsen, I. K., Petersen, B. M., Bruun, S., Jensen, L. S., Christensen, B. T. (2008): Estimating soil C loss potentials from the C to N ratio. *Soil Biol. Biochem.* 40, 849–852.
- Tiemeyer, B., Albiac Borraz, E., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Dröslér, M., Ebli, M., Eickenscheidt, T., Fiedler, S.,

- Förster, C., Freibauer, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Leiber-Sauheitl, K., Peichl-Brak, M., Roßkopf, N., Sommer, M., Zeitz, J. (2016): High emissions of greenhouse gases from grasslands on peat and other organic soils. *Global Change Biol.* 22, 4134–4149.
- Tiemeyer, B., Freibauer, A., Borraz, E. A., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Ebli, M., Eickenscheidt, T., Fiedler, S., Förster, C., Gensior, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Laggner, A., Leiber-Sauheitl, K., Peichl-Brak, M., Drösler, M. (2020): A new methodology for organic soils in national greenhouse gas inventories: Data synthesis, derivation and application. *Ecol. Ind.* 109. DOI: <https://doi.org/10.1016/j.ecolind.2019.105838>.
- Tisdall, J. M., Oades, J. (1982): Organic matter and water-stable aggregates in soils. *Eur. J. Soil Sci.* 33, 141–163.
- Vos, C., Don, A., Hobbey, E. U., Prietz, R., Heidkamp, A., Freibauer, A. (2019): Factors controlling the variation in organic carbon stocks in agricultural soils of Germany. *Eur. J. Soil Sci.* 70, 550–564.
- Vos, C., Don, A., Prietz, R., Heidkamp, A., Freibauer, A. (2016): Field-based soil-texture estimates could replace laboratory analysis. *Geoderma* 267, 215–219.
- Vos, C., Jaconi, A., Jacobs, A., Axel, D. (2018): Hot regions of labile and stable soil organic carbon in Germany—Spatial variability and driving factors. *Soil* 4, 153–167.
- Wagner, S., Cattle, S. R., Scholten, T. (2007): Soil-aggregate formation as influenced by clay content and organic-matter amendment. *J. Plant Nutr. Soil Sci.* 170, 173–180.
- Wellbrock, N., Bolte, A., Flessa, H. (2016): Dynamik und räumliche Muster forstlicher Standorte in Deutschland: Ergebnisse der Bodenzustandserhebung im Wald 2006 bis 2008. Thünen Report No. 43. Johann Heinrich von Thünen Institute, Federal Research Institute for Rural Areas, Forestry and Fisheries, Braunschweig, Germany.
- Wiesmeier, M., Spörlein, P., Geuß, U., Hangen, E., Haug, S., Reischl, A., Schilling, B., von Lütow, M., Kögel-Knabner, I. (2012): Soil organic carbon stocks in southeast Germany (Bavaria) as affected by land use, soil type and sampling depth. *Global Change Biol.* 18, 2233–2245.