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RESEARCH ARTICLE

# Benchmarking soil organic carbon to support agricultural carbon management: A German case study

Sophie Drexler[1] | Gabriele Broll[2] | Heinz Flessa[1] | Axel Don[1]

[1]Thünen Institute of Climate-Smart Agriculture, Braunschweig, Germany

[2]Institute of Geography, University of Osnabrück, Osnabrueck, Germany

**Correspondence**
Axel Don, Thünen Institute of Climate-Smart Agriculture, Bundesallee 65, 38116 Braunschweig, Germany.
Email: axel.don@thuenen.de

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## Abstract

**Background:** Soil organic carbon (SOC) storage is highly variable across sites and primarily depends on site properties and land use. It is therefore difficult for farmers to evaluate the actual SOC status of a site. To aid the interpretation of measured SOC contents, easy-to-use frameworks for the assessment of SOC contents are needed.

**Aims:** The aim of this study was to derive site-specific SOC benchmarks for German mineral soils under agricultural use based on the dataset of the first German Agricultural Soil Inventory.

**Methods:** The dataset was stratified into 33 strata by land use, soil texture, C/N ratio and mean annual precipitation. Lower and upper SOC benchmarks were calculated for all strata (0.125 and the 0.875 quantile).

**Results:** The SOC benchmark value ranges were lower for cropland (6.8–48.9 g kg$^{-1}$) than for grassland (14.1–76.6 g kg$^{-1}$), and increased with rising clay content and precipitation. Sandy soils with a wide C/N ratio and high SOC content due to their heathland or peatland history were divided into separate strata. The number of strata only decreased the SOC benchmark ranges slightly. Around 15–20 sites were required as a minimum to quantify SOC benchmarks for one stratum.

**Conclusions:** The presented framework is easy to use, requiring only four readily available stratification factors to perform a comparative classification of SOC contents. It allows farmers and extension services to compare where their measured SOC contents fall within the expected SOC value range for their site, and can thus help develop an initial evaluation of the SOC status of a site with regard to soil-specific differences.

KEYWORDS
best agricultural practice, Bundes-Bodenschutzgesetz, carbon farming, climate-smart agriculture, site-specific soil organic carbon content, soil health

## 1 | INTRODUCTION

Soil organic carbon (SOC) content plays a key role in many soil functions, including soil fertility and hence food security. In recent decades, SOC has attracted increasing interest in the context of climate change mitigation and adaptation (Minasny et al., 2017). Maintaining and enhancing SOC are thus crucial on multiple levels. Agricultural soils have the potential to contribute to climate change mitigation through SOC sequestration (Smith, 2016). To sequester additional SOC in agricultural soils, SOC mineralisation needs to be reduced or organic carbon (C) input increased by applying best agricultural management practices, such as cover cropping (Poeplau & Don, 2015) and agroforestry (De Stefano & Jacobson, 2018). To encourage the implementation of improved agricultural management practices for SOC sequestration and acknowledge farmers' efforts to build up SOC for climate change mitigation, C farming initiatives are on the rise worldwide. In addition to government programmes, most C farming schemes are initiated by private companies in voluntary C markets, incentivising SOC sequestration with financial rewards (Paustian et al., 2019; von Unger& Emmer, 2018). SOC certificates are awarded more generally for the implementation of C farming practices or are result-based in relation to tonnes of reduced $CO_2$ emissions or sequestered C (COWI et al., 2021). However, there are a number of limitations to consider when implementing SOC certificates for climate change mitigation, including that evidence of the increased SOC stocks is not sufficient to verify or quantify climate change mitigation effects. Steps also need to be taken to ensure that there are no negative effects of SOC accumulation, such as SOC leakage at other sites or nutrient surplus (Wiesmeier et al., 2020).

Furthermore, SOC storage is highly variable across sites depending on soil-forming factors, including time, parent material, topography, climate, organisms and impact by humans (Jenny, 1941). Inherent site properties influence both the build-up and decomposition of SOC and thus to a large extent the SOC level of a soil (Kögel-Knabner & Amelung, 2021; Wiesmeier et al., 2019). The inherent SOC level of a mineral soil can only be shifted slightly by agricultural management, that is, by so-called dynamic site properties. For example, sites with a high sand content will typically not reach the SOC levels of sites with a high clay content under common agricultural practices. This inherent variability in SOC levels must be considered when evaluating agricultural management practices in relation to SOC storage (Amelung et al., 2020). Site-specific, accurate predictions of SOC stocks, stock changes and possible SOC sequestration potential require detailed data on site properties and agricultural management, which are often not available. Therefore, in addition to these statistical and modelling approaches, easy-to-use, comprehensible frameworks are needed to help farmers assess the current SOC status of their cropland or grassland.

SOC is the most frequently proposed indicator of soil quality or health (Bünemann et al., 2018). In the last few decades, different approaches have been taken to establish reference values for interpreting measured SOC contents based on two different concepts. The first concept aims to define desirable SOC targets, also called critical limits or thresholds. These targets are intended to provide a direct interpretative framework to evaluate soil properties with respect to certain soil functions, for example, primary productivity or water regulation. Approaches have been based on (1) expert knowledge (Andrews et al., 2004), (2) empirical functional relationships between specific soil functions and soil properties (Carter, 2002) and (3) the use of values of undisturbed sites, mostly long-term pasture or other semi-natural or natural vegetation, as desirable targets (Lilburne et al., 2004; Maharjan et al., 2020). Within this concept of desirable targets, both minimum and maximum thresholds have been defined. A critical lower threshold of 2% SOC derived from aggregate stability has been widely used (Kemper & Koch, 1966). However, the setting of one strict threshold ignores site-specific differences of the SOC–aggregate relationship. Furthermore, no effects of such a strict limit on soil properties and crop yields have been quantitatively proven (Loveland & Webb, 2003). More recently, SOC/clay ratios as a proxy for soil structural quality and corresponding optimal SOC/clay levels have been proposed to help farmers evaluate the effect of soil management (Collier et al., 2020; Johannes et al., 2017; Prout et al., 2021). Upper limits or optimum target values have been proposed as the maximum capacity of a given soil to store C (Lawrence-Smith et al., 2018; H. J. Vogel et al., 2019). These are based on the concept of C saturation as a function of soil texture (Hassink, 1997; Six et al., 2002; Stockmann et al., 2013). However, the findings of C. Vogel et al. (2014) contradict the existence of an upper limit of SOC sequestration depending on inherent soil properties, especially clay content. Moreover, an upper SOC limit of this kind would not be directly associated with soil health or negative impacts on most soil functions, for example, crop yields. For SOC, 'more is better' seems more appropriate (Fine et al., 2017). Huber et al. (2008) and Hüttl et al. (2008) conclude that the evidence for critical SOC limits is weak, and critical threshold values for SOC depending on certain soil functions do not seem to be meaningful. Hence, this concept was not considered in the present study.

The second promising concept is to define a set of benchmark, reference or baseline values where SOC values are compared with a representative dataset. These benchmark values then allow an indicative comparison with measured values, but no direct evaluation with respect to specific soil functions (Verheijen et al., 2005; Wiesmeier et al., 2019). The concept has been integrated into soil quality assessments at country scale, for example, in New Zealand (Landcare Research New Zealand, 2022; Lilburne et al., 2004), Australia (Murphy et al., 2021) and parts of the United States (Fine et al., 2017; Moebius-Clune et al., 2016). These frameworks provide a direct comparative assessment without any evaluation or establish scoring functions based on the distribution of the indicator (e.g., SOC) within the dataset. Recently, Amsili et al. (2020) proposed using the 0.75 quantiles of the distribution of different soil health indicators, including SOC, as aspirational soil health goals for New York State. The dataset was therefore stratified by soil texture and cropping system. In another recent study, Nunes et al. (2021) further developed US soil health protocols based on an extensive dataset and established soil scoring curves to compare SOC contents with 'soil peer groups' defined by soil texture, suborder, mean annual air temperature and mean annual precipitation (MAP).

Benchmarks of this kind have not yet been derived at country scale for Germany. The definition of SOC benchmarks for Germany is particularly interesting since the country's Bundes-Bodenschutzgesetz (Federal Soil Protection Act) legally obliges farmers to maintain the 'site-specific soil organic matter content' and thus benchmark SOC content of agricultural soils (Bodenschutzgesetz, 1998). However, there is no clear definition of site-specific SOC contents. Several studies have derived SOC baseline values based on regional soil inventories, permanent soil monitoring sites and long-term field trials (e.g., Grabe et al., 2003; Neufeldt, 2005). Site-specific SOC contents have been defined at regional scale of Bavaria in southeast Germany, where a consistent SOC dataset is available (Capriel, 2010). At the scale of Germany, Marx and Gaul (2021) calculated SOC benchmarks based on 301 permanent field monitoring sites. Düwel et al. (2007) derived SOC baseline values at national scale, using a total of 8966 sites with different sampling dates and laboratory methods to determine SOC contents. However, the main problem in defining representative and consistent SOC benchmarks at the scale of Germany has been a lack of data (Prechtel et al., 2009; Wessolek et al., 2008). The first German Agricultural Soil Inventory, which was completed in 2018 (Poeplau et al., 2020), provides a representative and consistent dataset for the whole country, allowing us to apply a data-driven approach to define site-specific benchmarks for SOC contents.

The aims of this study were (1) to establish benchmarks for the SOC content of German mineral soils under agricultural use based on the dataset of the first German Agricultural Soil Inventory, and (2) to assess why sites have SOC contents outside the benchmarks in order to understand the possible impact of agricultural management on the classification framework. The benchmarks were defined as value ranges between a lower and an upper quantile (referred to below as 'benchmarks') in the sense of a current status of agricultural soil in Germany. The focus was to establish benchmarks intended for farmers and agricultural extension services that are easy to use, comprehensible and require minimal data input.

## 2 | MATERIALS AND METHODS

### 2.1 | Dataset

The dataset from the first German Agricultural Soil Inventory (2011–2018) contained data from 2973 sites sampled in an 8 km × 8 km grid covering all agricultural land in Germany (Jacobs et al., 2018; Poeplau et al., 2020). At each site, soil profiles were characterised according to the German Soil Classification, including the long-term average groundwater level of a site (Ad-Hoc-AG Boden, 2005). Disturbed and undisturbed soil samples were taken from a sampling depth of 1 m and analysed for texture, C and N content and bulk density. Furthermore, for each site, data on agricultural management over the past 10 years were recorded from farmer questionnaires. These included the farming system, tillage practices, organic C inputs and land-use history of the site. A detailed description of the methods used to calculate the organic C inputs can be found in Jacobs et al. (2020). Data on the land-use history of the sites were expanded through further research to fill data gaps and provide land-use information going back further. Therefore, for each site, at least one indication of land use for each of the four chosen time periods (1890–1930, 1930–1960, 1960–2000, >2000) was collected via historic maps and orthoimages, standardised and combined with the information from the farmer questionnaires.

Sites with a SOC content >8.7%, indicative of organic soils (126 sites, comprising 4.2% of sites) and sites with permanent woody crops (48 sites, comprising 1.6% of sites) were excluded, resulting in a total of 2799 considered sites. For permanent woody crops (e.g., viticulture or short rotation coppice), meaningful benchmarks could not be derived due to the small number of sampled sites. For sites with organic soils, the framework defined here is not meaningful and applicable. Soils under agricultural use and drainage exhibit large SOC losses and extremely high $CO_2$ emission rates, making current agricultural use of these soils unsustainable (Tiemeyer et al., 2020). In addition, the SOC status of organic soils cannot be assessed by determining the SOC content in the upper soil layer due to processes such as peat subsidence.

To derive the SOC benchmarks, topsoil data were used, defined to a depth of 10 cm for permanent grassland and to a depth of 30 cm for cropland and ley-arable rotation. These fixed depths allow comparability between sites and were chosen based on the usual sampling depth of agricultural sampling schemes in Germany. This allows farmers to easily compare existing measured values and commonly recorded values with the benchmarks derived in this study.

### 2.2 | Stratification approach

In order to develop benchmarks with distinct SOC contents for the sites, the dataset was stratified according to the main factors controlling the variability of SOC. Vos et al. (2019) identified land use, land-use history, clay content and electrical conductivity as the main predictors of the variability of SOC stocks in topsoil at country scale based on the dataset of the German Agricultural Soil Inventory. Other important factors controlling SOC stocks in the topsoil include MAP, soil moisture, soil structure, relief and parent material (Vos et al., 2019). Wiesmeier et al. (2014), who adopted a similar approach at a smaller scale (Bavaria), found soil type and mean annual air temperature to be important predictors of the spatial variability of SOC stocks. Also, using the dataset of the German Agricultural Soil Inventory, Poeplau et al. (2020) used either soil type or soil properties ($C_{org}/N_t$ ratio of the soil, clay content, groundwater level) in addition to land use for stratification, with the aim of developing homogenous strata with regard to SOC stocks.

The aim of this study was to establish an easy-to-use framework for users such as farmers or agricultural extension services. Therefore, it was particularly important for the stratification factors to be available to farmers. Consequently, we excluded factors that require special analytics (long-term average groundwater level) or in-depth knowledge of soil sciences (German soil types, parent material and relief). We also did not consider factors where the cause-and-effect relationship was not evident (electrical conductivity, soil moisture and soil structure). Moreover, other than land use as the most important predictor of SOC stocks (Vos et al., 2019; Wiesmeier et al., 2014), we excluded agricultural management factors and the land-use history of the sites since the benchmarks were intended to primarily reflect inherent site properties. MAP showed a stronger correlation with SOC ($rs = 0.42$, $p < 0.001$), compared to mean annual temperature ($rs = -0.18$, $p < 0.001$). Capriel (2010) did propose elevation, which combined the effects of mean annual precipitation and temperature, as stratification factor for deriving benchmarks at the scale of Bavaria. At the scale of Germany, the differences in elevation are not as pronounced as at the scale of Bavaria and thus correlation between SOC and MAP ($rs = 0.42$, $p < 0.001$) was more evident than between SOC and elevation ($rs = 0.23$, $p < 0.001$). Based on knowledge of important predictors of SOC levels and the above-defined criteria, we chose land use, texture, $C_{org}/N_t$ ratio of the soil (referred to below as 'C/N ratio') and MAP as stratification factors. The dataset was first stratified according to land use as the most important predictor of topsoil SOC variability (Vos et al., 2019). Afterwards, the correlation between the SOC content and the other stratification factors was tested at different levels, and the order of the stratification was set according to the strength of the correlations.

For each stratification factor, we defined strata thresholds with the aim of establishing (1) the narrowest possible SOC benchmark value ranges, (2) the greatest possible differences in SOC benchmarks between strata, (3) a minimum of 20 sites within each stratum to ensure sufficient statistical certainty and relevance for German agricultural soils and (4), as an overall criterion, a stratification that is easy to use for applicants, including thresholds for the strata that are as standard as possible. After the strata were defined for each factor, we checked kernel density plots and performed Kolmogorov–Smirnov tests to ensure that the distribution of SOC contents within the strata was significantly differentiated. Moreover, the correlation between SOC content and the stratification factor within each of the defined strata was tested. If there was still a significant correlation and thus the SOC variability within a stratum was still high, the stratum was split further if the other criteria were still fulfilled.

We defined three land-use strata: cropland, permanent grassland and ley-arable rotation. Permanent grassland (referred to below as 'grassland') was defined as land use with more than five consecutive years of grassland use. Ley-arable rotation was defined as a land use with alternating grassland or clover grass and cropland use, with the site being used as grassland/clover grass for at least two consecutive years. Set-aside land was also counted as ley-arable rotation. Cropland excluded permanent crops such as vineyards.

The texture strata were based on texture classes defined by the Association of German Agricultural Analytic and Research Institutes (VDLUFA), which are widely used in agricultural practice: 'coarse' with a clay content <12% and a silt content <50%, 'medium' with a clay content ≥12% and <25% or a clay content <12% and a silt content ≥ 50%, and 'fine' with a clay content ≥25% (VDLUFA, 2000). There was still a high level of variability of SOC within the medium- and fine-textured strata for cropland and grassland; therefore, these strata were split further. We set additional thresholds at 17% clay and 35% clay to separate the medium and fine-textured strata into two strata each: 'medium I' with a clay content ≥12% and <17% or a clay content <12% and a silt content ≥ 50%, 'medium II' with a clay content ≥17% and <25%, 'fine I' with a clay content ≥25% and <35%, and 'fine II' with a clay content ≥35%. These additional thresholds were only applied to the cropland and grassland strata.

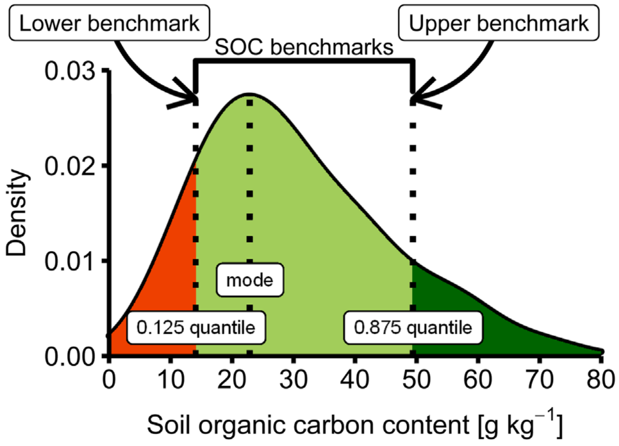


**FIGURE 1** Scheme for the definition of soil organic carbon (SOC) benchmarks along the distribution of the SOC content within a site-specific stratum. The benchmarks are defined as a value range, with the lower benchmark defined as the 0.125 quantile and the upper benchmark as the 0.875 quantile, thus omitting extreme values at either end. The red area indicates SOC values below the site-specific benchmark, light green shows SOC values within the benchmarks and dark green shows SOC values above the upper benchmark

To identify optimal thresholds for continuous stratification factors (C/N ratio and MAP), we stepwise divided the strata that had already been defined into two further strata with varying strata thresholds. The SOC benchmarks of the new strata were computed, and the summed benchmark value ranges and summed differences between the strata were then visualised. The thresholds were determined individually based on these visualisations and the above-mentioned criteria for stratification.

## 2.3 | Definition of benchmarks

For each defined site-specific stratum, we calculated benchmarks, defined between the 0.125 quantile of the SOC contents as the lower benchmark and the 0.875 quantile of the SOC contents as the upper benchmark. Thus, 25% of the extreme SOC contents were excluded (Figure 1). This definition of sites that can be considered site-specific for the stratum was taken from Capriel (2010), and is intended to exclude sites with non-site-specific SOC levels, particularly those caused by agricultural management. Besides the lower and upper benchmarks, the mode value defined as the maximum of the kernel density estimation was given as most site-specific SOC content within one stratum.

However, the exclusion of 25% of sites that have extreme SOC contents is arbitrary. After calculating the SOC benchmarks for each stratum, we therefore analysed whether historical land use, land-use changes or type of agricultural management at the sites explained and thus justified the exclusion of these sites with SOC contents below or above the designated SOC benchmarks. We analysed the effect of the following agricultural management variables that are known to have a large impact on SOC levels: (1) historic peatland, (2) historic heathland, (3) historic cropland use at grassland sites within the last 100 years, (4) historic grassland use at cropland sites within the last 50 years, (5) organic farming, (6) conservation tillage in more than 80% of the reported years, (7) high average groundwater level, (8) annual organic C input via harvest residues, cover crops, stubbles and roots and (9) annual organic C input via organic fertilisers (including manure and biogas digestates). The long-term average groundwater level was included as a possible explanatory variable, although it is mostly considered as an inherent site property rather than a dynamic site property, that is, influenced by land use and agricultural management. As the measurement of groundwater level requires special equipment and expert knowledge, groundwater level was not included as a stratification factor. However, the groundwater level of a site is positively correlated with its SOC content and is an important predictor of the variability of SOC stocks in the topsoil (Vos et al., 2019). Therefore, we analysed whether the long-term average groundwater level is an explanatory variable for sites outside the benchmarks and thus needs to be considered when applying the benchmark framework. All analysed variables were available in the dataset of the German Agricultural Soil Inventory (Poeplau et al., 2020).

To obtain an initial understanding of the effects of the agricultural management variables on extreme SOC contents, we calculated the mean within the three categories ‘below the SOC benchmark’, ‘within the SOC benchmarks’ and ‘above the SOC benchmark’ for continuous variables. For categorical variables, the relative proportion within the three categories was calculated. The effect of management factors (e.g., organic farming yes/no) on one of the three categories (below/within/above SOC benchmarks) was then assessed with a logistic regression. Three individual models were each fitted with two of the three categories as dependent variables (e.g., below vs. within the SOC benchmarks) and the management factors (e.g., organic farming yes/no) as independent variables. All data analyses were performed using R version 4.0.3 (R Core Team, 2020), at a significance level of $p < 0.05$.

## 3 | RESULTS AND DISCUSSIONS

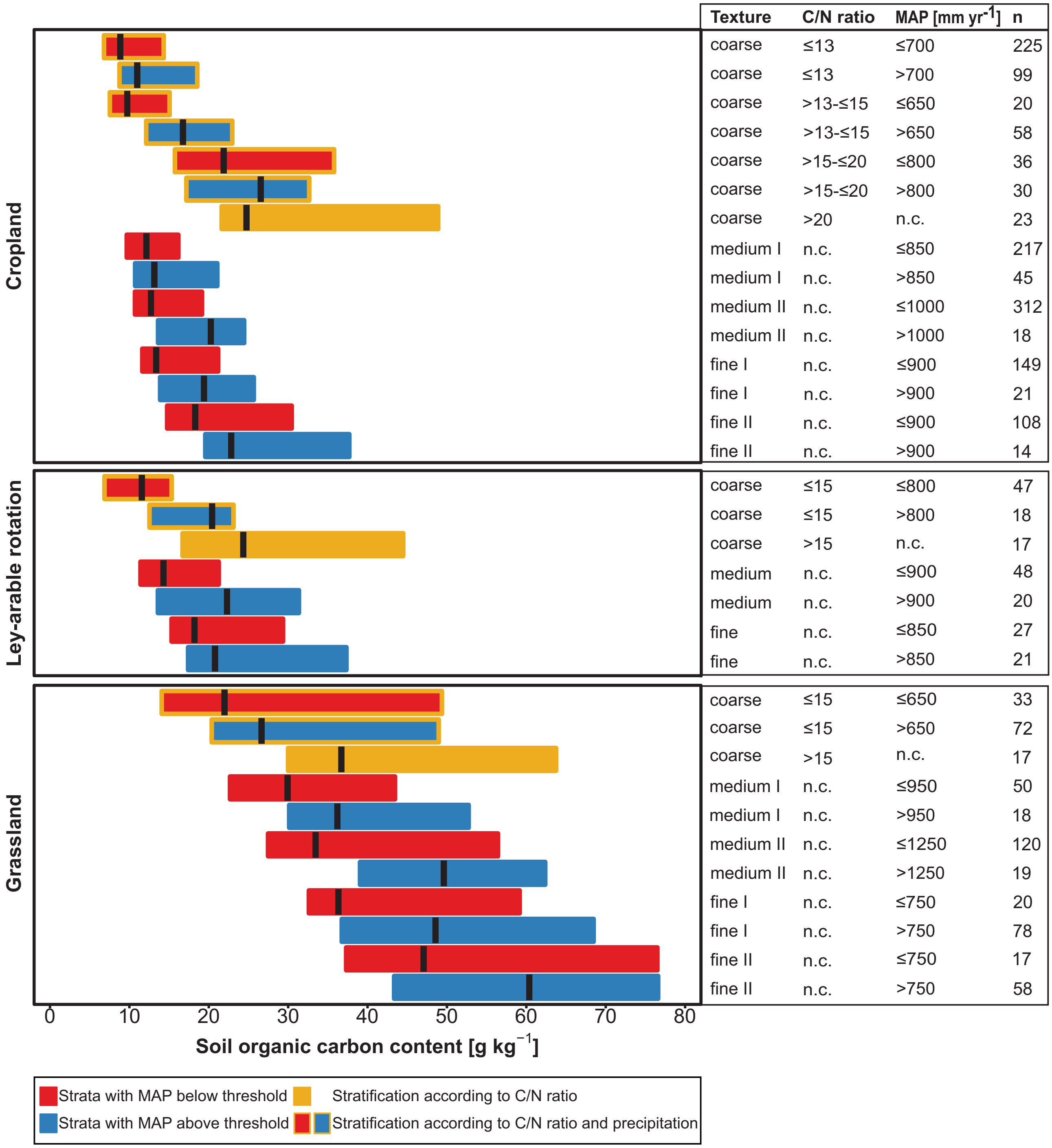
### 3.1 | Stratification and soil organic carbon benchmarks

In total, the stratification according to land use, texture, C/N ratio and MAP resulted in 33 strata for which site-specific benchmarks were derived (Figure 2). The benchmarks were transferred to an online tool (https://humuscheck.thuenen.de; in German) and made freely accessible. The tool allows easy classification of measured SOC contents into the respective site-specific SOC stratum and provides the corresponding site-specific SOC limits.

The stratification of the dataset according to three land-use types led to significantly different distributions of SOC contents ($p < 0.001$) (Figure 3). The mean difference in SOC content between the three land-use types ranged from 3.2 g kg$^{-1}$ (cropland vs. ley-arable rotation) to 11.9 g kg$^{-1}$ (cropland vs. grassland). The average SOC benchmark ranges (upper benchmark-lower benchmark) were more than twice as high for grasslands (29.46 g kg$^{-1}$) than for croplands (12.65 g kg$^{-1}$) (Figure 2). This may be due to the higher variability in the site properties of grasslands and the greater diversity of management intensity in grasslands compared with croplands (Vogt et al., 2019).

After the stratification by land use, the three to five strata were defined according to the soil texture of the site (Figure 4). With increasing clay content and decreasing sand content, the SOC benchmarks increased for all land-use types (Figure 2). For ley-arable rotation, the SOC distributions in potential texture strata ‘medium I’ and ‘medium II’ did not differ significantly from each other ($p = 0.33$). The same was true for the texture strata ‘fine I’ and ‘fine II’ ($p = 0.10$). This was probably due to the smaller number of sites with ley-arable rotation, making up just 9.7% of all sites. Sites with ley-arable rotation were therefore only classified into the three texture strata (Figure 4). The final chosen stratification based on the VDLUFA texture classes offers a practical solution, as in Germany these strata are included in many routine agricultural soil analyses and thus are already available to many farmers. Moreover, despite potential small-scale variability in texture within an agricultural field, the rather broad definition of the strata allows a clear assignment to one of the texture strata.

All coarse-textured, sandy sites were further stratified by C/N ratio. The influence of a wide C/N ratio on the benchmarks was particularly pronounced. The SOC content in these sites with a C/N ratio >15 and a clay content <12% (texture class ‘coarse’) was found to be as high as in very fine-textured soils with a clay content ≥35% (texture class ‘fine II’) (Figure 2). We defined two strata for grassland and ley-arable rotation with a C/N ratio of 15 as the threshold. For cropland, the variability of SOC content within the two strata was still high. Thus, we defined two additional strata with thresholds at C/N ratios of 13 and 20. The stratification by C/N ratio was intended to separate out ‘Black Sands’ into a separate stratum; thus, the stratification was also only applied to coarse-textured soils. ‘Black Sands’ are coarse-textured soils that have a wide C/N ratio and, despite their texture, have extremely high SOC contents. Overesch (2007), Sleutel et al. (2010), Springob et al. (2001) and Vos et al. (2018) found these sites in different regions in northwest Europe and attributed the high SOC contents to a historic occurrence of heathland or peatland and plaggen use with poorly degradable plant material. As texture is not a good predictor of SOC content at these sites, it is important not to include these sites in the benchmarks for sandy soils. Around 9% of sites in the dataset had the characteristics of ‘Black Sands’ with a sand content above 80% and C/N ratio wider 13; thus, these sites were not excluded completely, but defined as a separate stratum. Consequently, historic land use was also considered within the benchmark framework and thus defined as an inherent site property. The regional abundance of sites with a wide C/N ratio confirmed the particular case of ‘Black Sands’: a clear cluster of these sites is found in former heathland and peatland areas in northwest Germany (Aerts & Heil, 1993) and, compared with other coarse-textured soils, corresponds with extremely high SOC contents (Figure 5).



| Texture | C/N ratio | MAP [mm yr$^{-1}$] | n |
|---|---|---|---|
| coarse | ≤13 | ≤700 | 225 |
| coarse | ≤13 | >700 | 99 |
| coarse | >13-≤15 | ≤650 | 20 |
| coarse | >13-≤15 | >650 | 58 |
| coarse | >15-≤20 | ≤800 | 36 |
| coarse | >15-≤20 | >800 | 30 |
| coarse | >20 | n.c. | 23 |
| medium I | n.c. | ≤850 | 217 |
| medium I | n.c. | >850 | 45 |
| medium II | n.c. | ≤1000 | 312 |
| medium II | n.c. | >1000 | 18 |
| fine I | n.c. | ≤900 | 149 |
| fine I | n.c. | >900 | 21 |
| fine II | n.c. | ≤900 | 108 |
| fine II | n.c. | >900 | 14 |
| coarse | ≤15 | ≤800 | 47 |
| coarse | ≤15 | >800 | 18 |
| coarse | >15 | n.c. | 17 |
| medium | n.c. | ≤900 | 48 |
| medium | n.c. | >900 | 20 |
| fine | n.c. | ≤850 | 27 |
| fine | n.c. | >850 | 21 |
| coarse | ≤15 | ≤650 | 33 |
| coarse | ≤15 | >650 | 72 |
| coarse | >15 | n.c. | 17 |
| medium I | n.c. | ≤950 | 50 |
| medium I | n.c. | >950 | 18 |
| medium II | n.c. | ≤1250 | 120 |
| medium II | n.c. | >1250 | 19 |
| fine I | n.c. | ≤750 | 20 |
| fine I | n.c. | >750 | 78 |
| fine II | n.c. | ≤750 | 17 |
| fine II | n.c. | >750 | 58 |

**FIGURE 2** Soil organic carbon benchmarks for German mineral soils under agricultural use. The benchmarks are defined as value ranges between the 0.125 quantile as the lower benchmark and the 0.875 quantile as the upper benchmark for 33 strata, stratified according to land use, soil texture, C/N ratio and mean annual precipitation (MAP). Some stratification factors are not considered (n.c.) in all the strata. The mode value within one stratum is given by the black line and represents the most site-specific SOC content for the respective stratum. '*n*' indicates the number of sites within the benchmarks. Values for this figure can be found in Table S1. An online tool for the benchmarks is available at https://humuscheck.thuenen.de (in German)

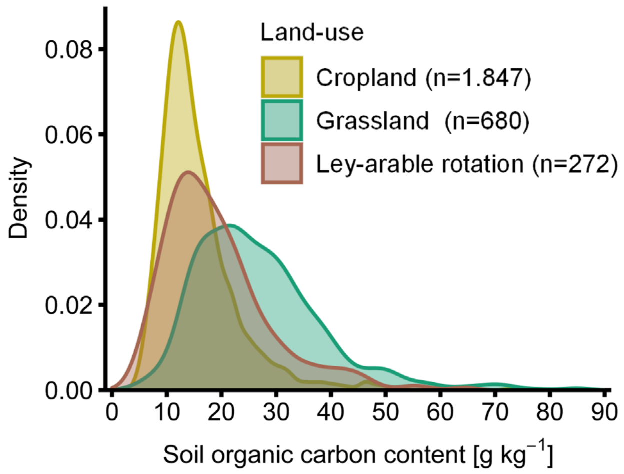


**FIGURE 3** Distribution of soil organic carbon contents within the three land-use types. For comparability, sampling depth was averaged over 0–30 cm depth for all land-use types

All the strata were split further into two strata by MAP, except for the three strata with wide C/N ratios. The criterion of a minimum of 20 sites (0.6% of agricultural land in Germany) within a stratum did not leave enough sites for further stratification of these strata with wide C/N ratios. The thresholds for separating two MAP strata were chosen individually for each stratum after analysing the summed benchmark value ranges and the summed differences between the benchmarks for varying strata thresholds according to the set criteria, and ranged from 650 to 1250 mm y$^{-1}$. For all strata with a higher MAP (above the threshold), we found higher SOC benchmarks, which is in line with Hobley et al. (2015), for example, and might be explained by decreased SOC turnover due to longer periods of water-saturated soil conditions and increased C input into the soils due to higher yields.

### 3.2 | Effect of the number of strata on soil organic carbon benchmarks

The average benchmark range and average coefficient of variation of SOC within the strata were calculated for different numbers of strata to show how the number of strata influences the SOC benchmarks (Figure 6). We found that stratification by land use led to a clear decrease in the mean (± SD) benchmark range from 32 g kg$^{-1}$ to 20 ± 4 g kg$^{-1}$ and reduced the coefficient of variation of SOC from 69% to 48%. Further stratification decreased the mean (± SD) benchmark range only slightly further to 15 ± 4 g kg$^{-1}$ with 33 strata (Figure 6). A finer division of the strata was always limited by the fact that either the number of sites within one stratum would not have been sufficient or there would have been many strata, which would be contrary to the aim of an easy-to-use framework. For all stratification factors, especially for continuous factors with a linear correlation with SOC content, a further division would have been possible. Therefore, a trade-off between practicability for the user and accuracy was always necessary. This also applied to the integration of additional stratification factors.

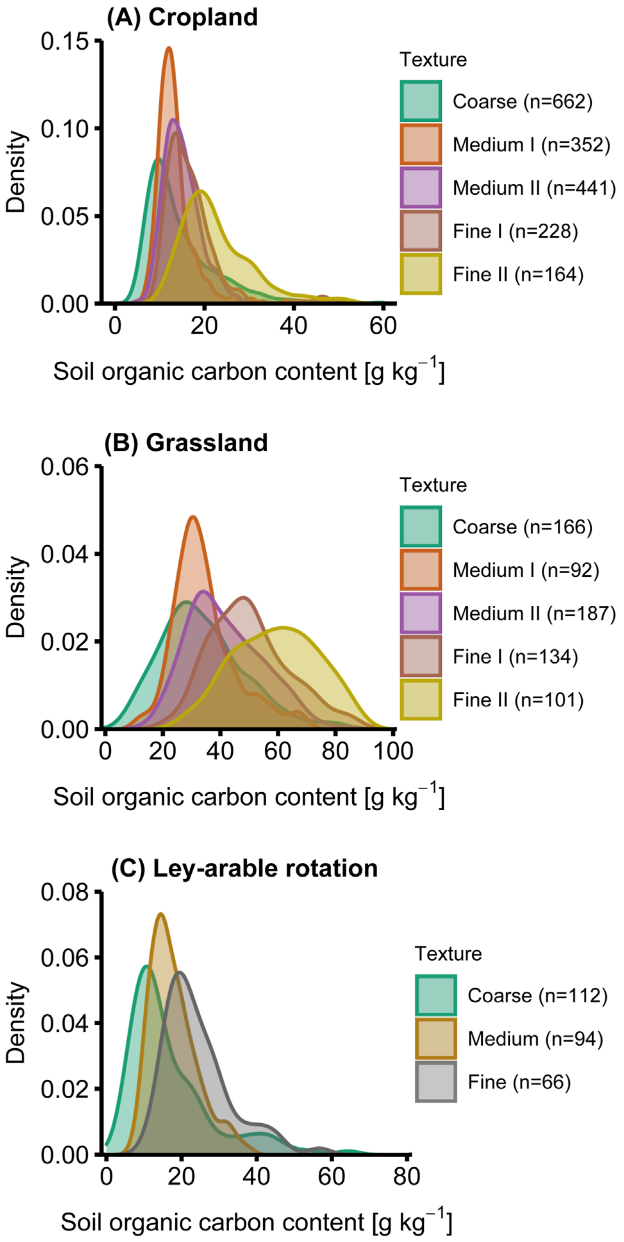


**FIGURE 4** Distribution of soil organic carbon contents within the texture strata for (A) cropland, (B) grassland and (C) ley-arable rotation

### 3.3 | Comparison with regional soil organic carbon benchmarks and effects of agricultural management

The site-specific SOC benchmarks were surprisingly comparable with those developed by Capriel (2010), who used a similar approach to derive SOC benchmarks on a regional scale in Germany (Bavarian cropland) (Table S2). Capriel (2010) used a sampling depth of 0–15 cm rather than the sampling depth of 0–30 cm defined here for cropland. However, this difference did not appear to affect SOC benchmarks as the majority of cropland soils are ploughed and thus homogenised to around 30 cm depth. A major difference between the stratification applied by Capriel (2010) and that in the present study is that Capriel (2010) used elevation as a stratification factor rather than the MAP

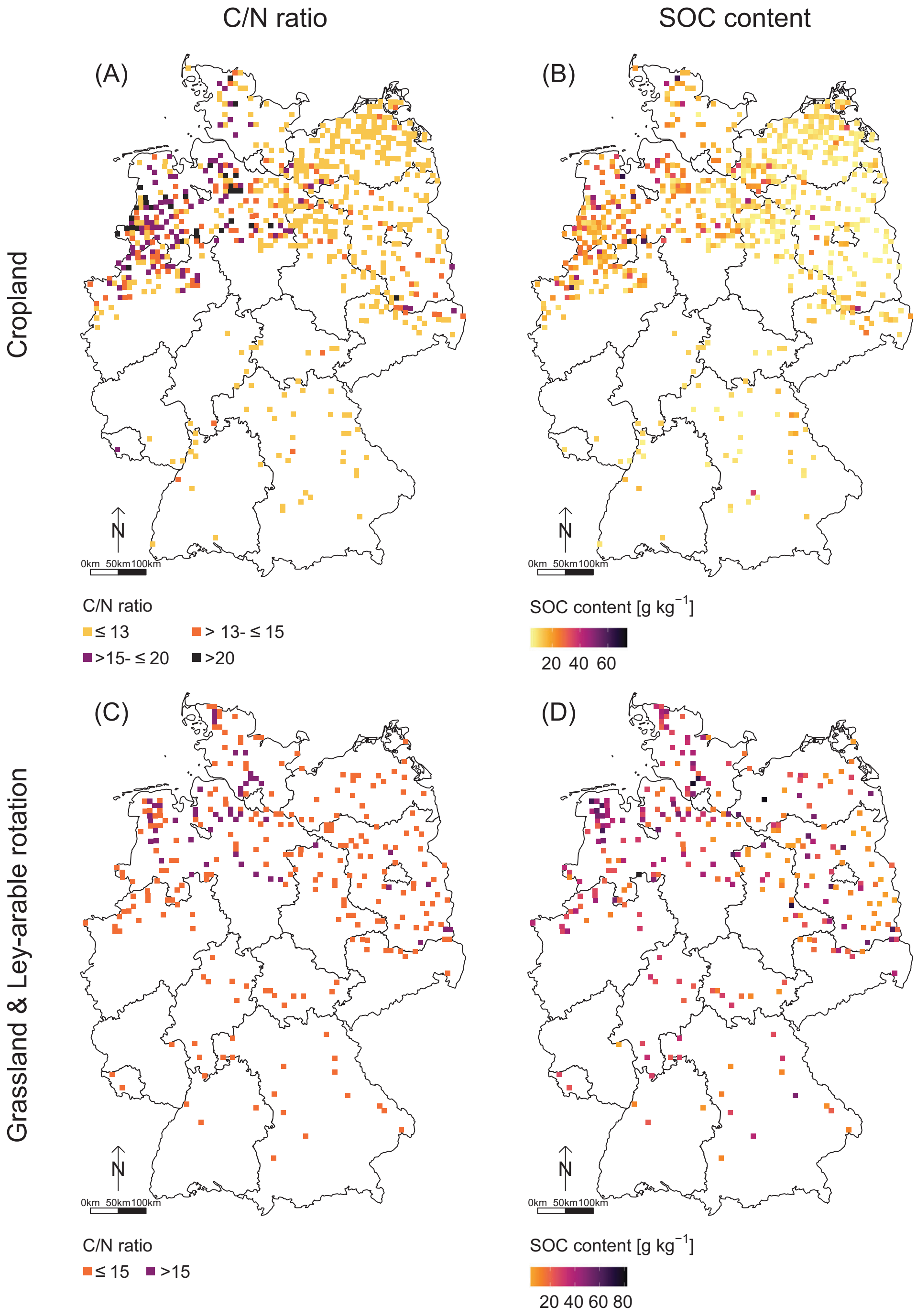


**FIGURE 5** Spatial distribution of the C/N ratio strata and corresponding soil organic carbon (SOC) content for sites in the German Agricultural Soil Inventory with a coarse texture (clay content <12% and silt content <50%), divided into (A) and (B) cropland, and (C) and (D) grassland and ley-arable rotation

used in this study, and that three elevation strata were used by Capriel (2010) instead of two MAP strata. Stratification by texture, however, was more differentiated in our study. The differences between the stratification used by Capriel (2010) and that used in the present study underline the need to stratify the dataset so that regional differences are well represented. 'Black Sands', for example, do not exist in the study region analysed by Capriel (2010); hence, a stratification by C/N ratio is not needed. Thus, benchmarks derived for one region are not always transferable to another region. However, a comparison of the benchmarks in this study at the scale of Germany with those for Bavaria demonstrated that regional-specific benchmarks are not always better and more specific (smaller benchmark range) than benchmarks developed for larger regions. The limiting factor is rather available site-specific data that allows for further stratification.

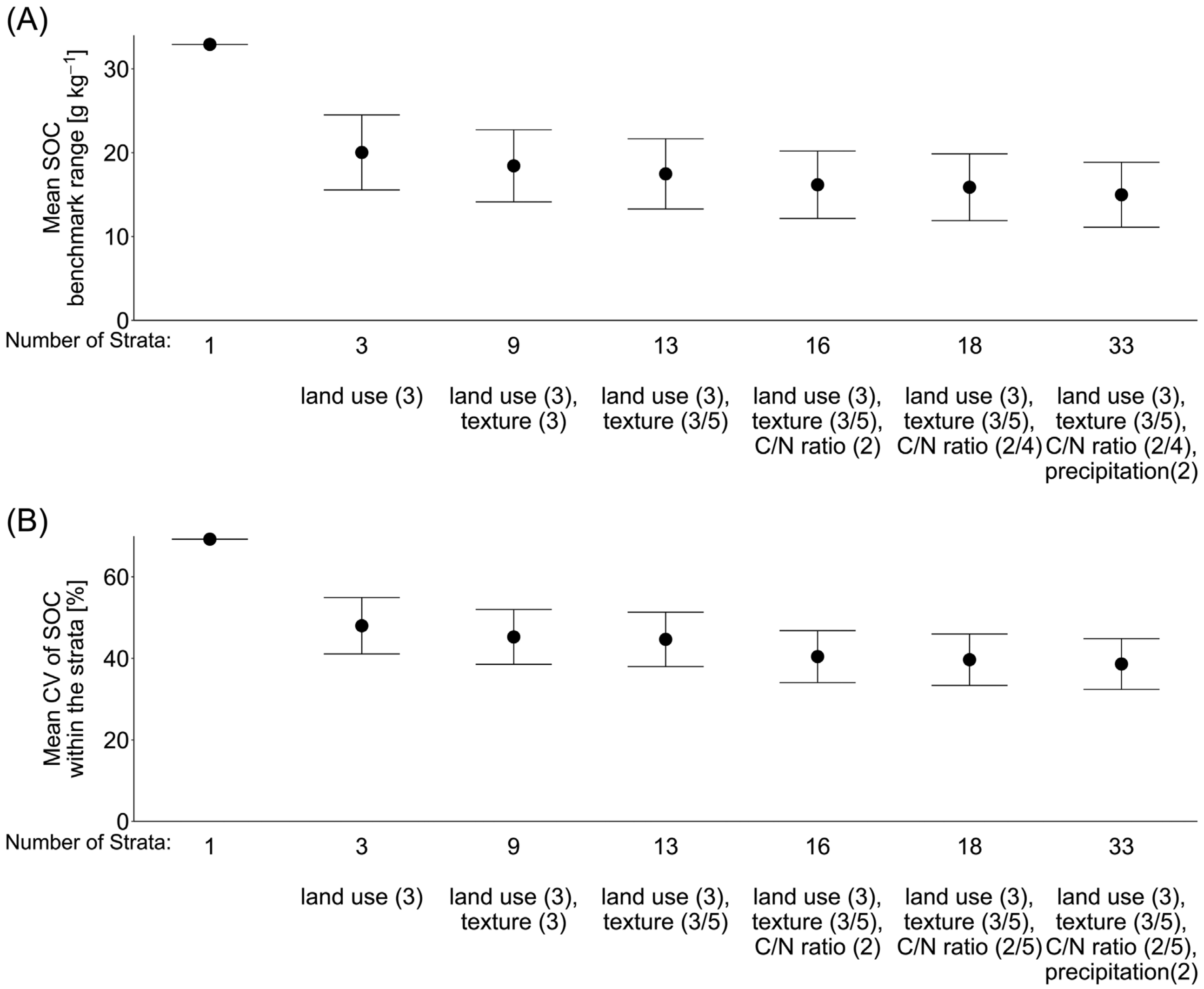


**FIGURE 6** (A) Mean soil organic carbon (SOC) benchmark range (upper benchmark–lower benchmark) and (B) mean coefficient of variation (CV) of SOC within strata with an increasing number of strata. The means were calculated as weighted arithmetic means based on the number of sites. Error bars indicate standard deviation of the mean

Compared with potential changes in the SOC level of a site after adopting C sequestration practices, the derived benchmark ranges are large. The mean of the benchmark range (upper benchmark–lower benchmark) for cropland is 12.65 g kg$^{-1}$ SOC. In a meta-analysis, Gattinger et al. (2012) found 1.8 g kg$^{-1}$ higher SOC contents with organic farming than with non-organic farming systems. The introduction of cover crops can lead to an average increase of 1.6 g kg$^{-1}$ SOC within 20 years (Poeplau & Don, 2015). This illustrates that even with the long-term adoption of C farming practices, sites will often not reach SOC contents above the upper site-specific benchmark. Site properties largely determine the variability of SOC contents, whereas the influence of agricultural management is relatively small. This is supported by Vos et al. (2019), who found that agricultural management variables, except for land use, have a minor influence on topsoil SOC. However, it should be emphasised that agricultural management is responsible for SOC changes and a small SOC increase can have a large impact, for example, on SOC storage and the climate change mitigation function of soils (Minasny et al., 2017). To detect management-induced changes in the SOC stock of a site, it is therefore important to monitor the temporal SOC change.

## 3.4 | Requirements for the database

The aim of this study was to derive site-specific benchmarks based on the current status of SOC contents in Germany. For this data-driven approach, the database is particularly important. The dataset of the German Agricultural Soil Inventory provided a sufficiently representative and consistent database, including a range of explanatory variables for SOC content. To demonstrate how the number of sampled sites influences SOC benchmarks, a decreasing number of sites from the dataset were sampled for each stratum, adjusted SOC benchmarks were calculated and then compared with the original benchmarks as presented above (Figure 2). For each stratum, we used

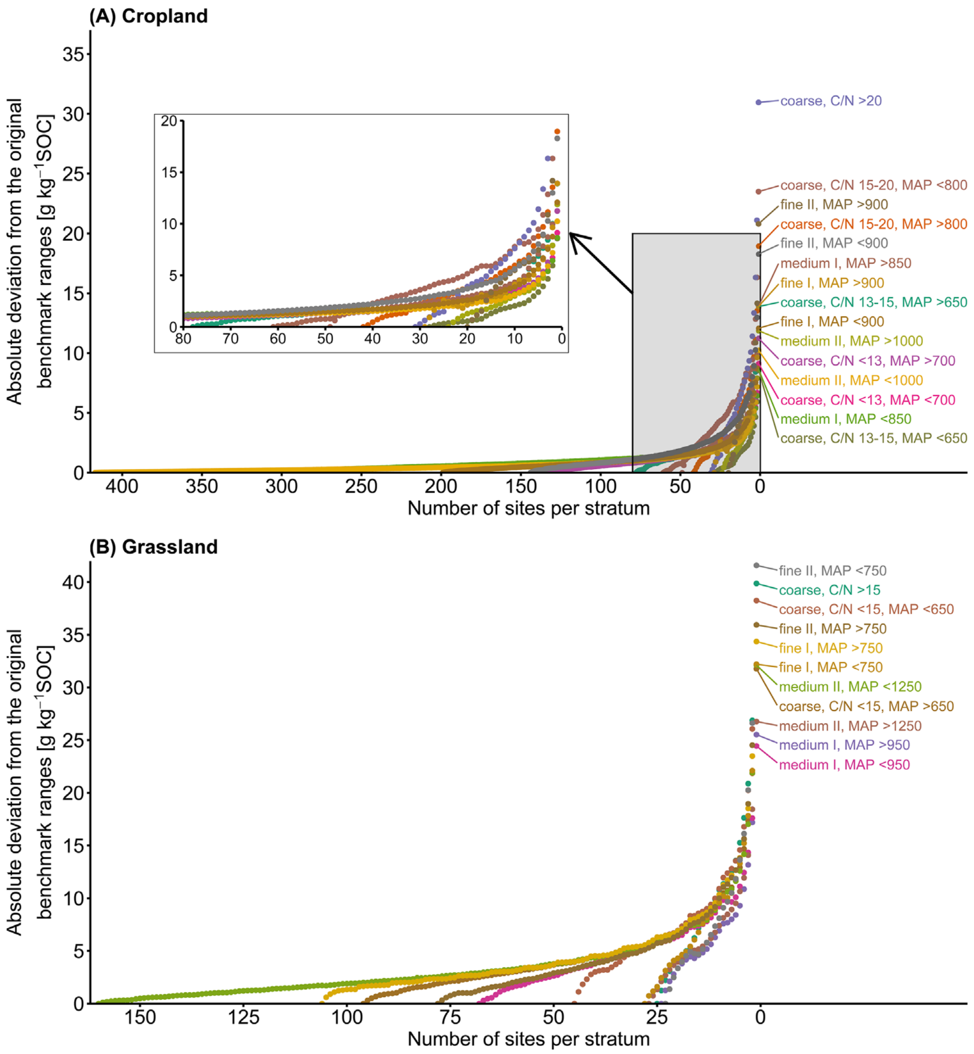


**FIGURE 7** Absolute deviation from original SOC benchmarks with a decreasing number of sites per stratum for (A) all cropland strata and (B) all grassland strata. Strata were defined according to texture (fine to coarse), C/N ratio and mean annual precipitation (MAP) as displayed in Figure 2

10,000 bootstrap replicates and calculated the mean and absolute deviations.

Both cropland and grassland strata showed an exponential relationship between the absolute deviation from the original benchmarks and the number of sampled sites, indicating that if the number of sites within a stratum is fewer than 15–25, the resulting benchmarks become increasingly flawed and lose their robustness (Figure 7). This illustrates that a minimum number of sites within one stratum is needed to ensure robust benchmarks. The importance of having enough sampling sites for each stratum is particularly evident for strata with high SOC variability, which can be seen when comparing cropland strata with grassland strata. Compared with cropland sites, grassland strata have fewer sites per stratum on average with a higher SOC variability within the strata, and therefore the influence of the number of sampled sites is more pronounced. With the planned resampling of the sites in the German Agricultural Soil Inventory every 10 years, a re-calculation of the benchmarks might be reasonable in order to make them even more robust. Furthermore, updated benchmarks after resampling offer the possibility of always providing an up-to-date baseline that represents the current status of SOC levels since SOC levels might change regardless of agricultural management due to climate change (Riggers et al., 2021).

## 3.5 | Factors contributing to soil organic carbon contents outside the benchmarks

In total, we were able to identify factors that contributed to SOC levels below or above the benchmarks for 511 (71%) of the excluded sites (Figure S1). Sites under organic farming and grassland sites with historic cropland use were found significantly more often to have SOC levels below the lower SOC benchmark (Table 1), while a high average groundwater level was associated with SOC levels above the site-specific benchmarks for 6% of the excluded sites, mostly in the

**TABLE 1** (A) Proportion of sites (for categorical factors) and (B) arithmetic mean (for continuous factors) within the three categories below, within and above soil organic carbon (SOC) benchmarks for possible influencing factors. '*n*' indicates the total number of sites for the respective factor over all categories. The association of management factors and allocation to one of the three categories was assessed using logistic regression models, the effects are indicated by superscript letters. Different superscript letters within a row indicate a significant effect ($p < 0.05$)

**(A) Proportion of sites (%) with …**

| | *n* | Below SOC benchmarks | Within SOC benchmarks | Above SOC benchmarks |
|---|---|---|---|---|
| Expected* | | 12.5 | 75.0 | 12.5 |
| Historic peatland | 78 | 2.6$^{a}$ | 70.5$^{b}$ | 26.9$^{c}$ |
| Historic heathland | 167 | 10.8$^{a}$ | 74.3$^{a}$ | 15.0$^{a}$ |
| Grassland sites with historic cropland use | 426 | 16.0$^{a}$ | 73.7$^{b}$ | 10.3$^{b}$ |
| Cropland sites with historic grassland use | 359 | 6.4$^{a}$ | 66.3$^{b}$ | 27.3$^{c}$ |
| Organic farming | 196 | 17.4$^{a}$ | 68.9$^{b}$ | 13.8$^{a,b}$ |
| Conservation tillage | 450 | 13.1$^{a}$ | 74.2$^{a}$ | 12.7$^{a}$ |
| High average groundwater level | 204 | 6.9$^{a}$ | 56.9$^{a}$ | 36.9$^{b}$ |

**(B) Mean (± SD) annual organic carbon input (Mg ha$^{-1}$ y$^{-1}$) via …**

| | *n* | Below SOC benchmarks | Within SOC benchmarks | Above SOC benchmarks |
|---|---|---|---|---|
| Expected* | | | Equal C input | |
| Harvest residues, cover crops, stubbles and roots | 2625 | 3.15 ± 1.07$^{a,b}$ | 3.16 ± 1.05$^{a}$ | 3.01 ± 1.02$^{b}$ |
| Organic fertilisers | 2625 | 0.42 ± 0.61$^{a}$ | 0.57 ± 0.74$^{b}$ | 0.61 ± 0.63$^{b}$ |

*If Expected distribution if the factor has no contributed to why sites have SOC levels outside the benchmarks.

grassland and ley-arable strata (Figure S2). Sites with historic peatland and cropland sites with historic grassland use were found to be above the SOC benchmarks significantly more often, but were also associated with SOC values below the SOC benchmarks. A low mean annual C input via harvest residues, cover crops, stubbles and roots contributed to SOC levels above the benchmarks. A low mean annual C input via organic fertilisers was associated with SOC levels below the benchmarks. Thus, for sites with a C input below the median C input, C input was counted as a contributing factor (Figure S1). Tillage and historic heathland did not contribute significantly to explaining why sites had SOC levels outside the benchmarks. This was also the case when different land uses were examined separately (not shown).

For organic farming, this result was in contrast to the expected higher SOC contents associated with organic farming (Gattinger et al., 2012). However, the evidence was only weak ($p = 0.047$). Reasons for the association of organic farming with SOC contents below the benchmarks could be that organic farming is often practised on sites with less favourable site conditions (Schmidtner et al., 2012) or is associated with lower yields (Seufert et al., 2012) and thus potentially lower C input in the soil. This could, however, be compensated for by a higher root C allocation with organic farming (Hirte et al., 2021). Another reason could be that the sites had not reached a new equilibrium of SOC levels at the time of sampling after the conversion from conventional to organic farming. The proportion of farms with organic farming in Germany has increased in recent years (Federal Ministry of Food and Agriculture, 2021). It is therefore likely that many of the sites which are under organic farming today were still conventionally farmed a few years ago and a difference in terms of SOC content is not yet apparent.

Another unexpected result was that historic grassland use of cropland sites was associated not only with SOC contents above the benchmarks but below them as well, that is, there were significantly disproportionately fewer sites below than expected (Table 1). This was also the case for peatland history, and suggests that these factors also have a positive influence on the SOC values within the benchmarks. Organic C input did have a significant effect on SOC levels falling outside the benchmarks. Low C input via organic fertilisers contributed to SOC levels being below the benchmarks. This confirms the positive effect of organic fertilisation on SOC content (Maillard & Angers, 2014). However, low C input via harvest residues, cover crops, stubbles and roots were unexpectedly associated with SOC levels above the benchmarks, which is in contrast to the positive effect of high root inputs in particular on SOC content (Kätterer et al., 2011). Similar to the effect of organic farming, one reason for this could be that there is a gap between current agricultural management (C input was recorded for the last 10 years before sampling) and current SOC level. The effect of agricultural management on SOC levels is only evident in the long term and is relatively small compared with inherent SOC variability (see also Section 3.3). Thus, past agricultural management and land-use changes could overlap with the effect of current C input on SOC levels.

The analysis showed the difficulty of assessing whether agricultural management leads to SOC levels outside the benchmarks. Although the dataset contained considerable information about the agricultural management of the sites with good data quality, some unexpected effects were shown, and 29% of sites with SOC levels below or above the benchmarks remained completely unexplained. Only a high average groundwater level, historic cropland use on grassland sites and low C inputs via organic fertilisers clearly contributed to sites falling outside the value ranges. It was therefore not possible to directly link SOC levels below the benchmarks to unfavourable agricultural management in the past, or to attribute SOC levels above the benchmarks to best management practices. Nevertheless, it would be worthwhile taking a closer look at possible causes of sites falling outside site-specific SOC benchmarks, as this can indicate particular regional differences (e.g., peatland history or a high average groundwater level) or past agricultural management (e.g., land-use changes).

## 4 | CONCLUSIONS

This study derived site-specific SOC benchmarks for mineral soils under agricultural use at the scale of Germany for the first time. The methods presented demonstrate how an easy-to-use framework could be derived to allow farmers to provide a relative assessment of their measured SOC content. The derived benchmarks were fit to the dataset of the first German Agricultural Soil Inventory, which provides a consistent and representative dataset. The benchmarks describe the current status of SOC contents in Germany, which result from a mix of inherent pedo-climatic properties and past agricultural management, and exclude 25% of extreme SOC levels. They illustrate the high variability of agricultural soils in Germany and their SOC contents. SOC contents between 6.8 and 76.6 g kg$^{-1}$ were found to be site-specific SOC benchmarks in mineral soils. This variability needs to be recognised when making agricultural land management decisions, and when initiating, evaluating and rewarding C farming practices. Despite the very comprehensive and consistent available dataset on agricultural management, consistent factors contributing to the sites being outside the benchmarks could only be found for less than half of the excluded sites. To account for SOC changes related to agricultural management decisions, site-based monitoring of temporal SOC changes is needed using appropriate sampling or modelling tools. The benchmarks can serve as a starting point giving the SOC content expected for the site, but do not provide a means to judge on the C management status of a site. They can be used by farmers and agricultural extension services to easily compare their own measured SOC data with the benchmarks, and provide initial insights into the SOC status of a site. In this way, the benchmarks can help to raise awareness of differences between sites in terms of SOC storage.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in OpenAgrar at http://www.OpenAgrar.de, https://doi.org/10.3220/DATA20200203151139.

## ORCID

*Sophie Drexler* https://orcid.org/0000-0002-7232-1650

*Axel Don* https://orcid.org/0000-0001-7046-3332

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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