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RESEARCH ARTICLE

A simple soil organic carbon level metric beyond the organic carbon-to-clay ratio

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Abstract

Soil is a precious and non-renewable resource that is under increasing pressure and the development of indicators to monitor its state is pivotal. Soil organic carbon (SOC) is important for key physical, chemical and biological soil properties and thus a central indicator of soil quality and soil health. The content of SOC is driven by many abiotic factors, such as texture and climate, and is therefore strongly site-specific, which complicates, for example, the search for appropriate threshold values to differentiate healthy from less healthy soils. The SOC:clay ratio has been introduced as a normalized SOC level metric to indicate soils' structural condition, with classes ranging from *degraded* (<1:13) to *very good* (>1:8). This study applied the ratio to 2958 topsoils (0–30 cm) in the German Agricultural Soil Inventory and showed that it is not a suitable SOC level metric since strongly biased, misleading and partly insensitive to SOC changes. The proportion of soils with SOC levels classified as *degraded* increased exponentially with clay content, indicating the indicator's overly strong clay dependence. Thus, 94% of all Chernozems, which are known to have elevated SOC contents and a favourable soil structure, were found to have either *degraded* (61%) or *moderate* (33%) normalized SOC levels. The ratio between actual and expected SOC ($SOC:SOC_{exp}$) is proposed as an easy-to-use alternative where expected SOC is derived from a regression between SOC and clay content. This ratio allows a simple but unbiased estimate of the clay-normalized SOC level. The quartiles of this ratio were used to derive threshold values to divide the dataset into the classes *degraded*, *moderate*, *good* and *very good*. These classes were clearly linked to bulk volume (inverse of bulk density) as an important structural parameter, which was not the case for classes based on the SOC:clay ratio. Therefore, $SOC:SOC_{exp}$ and its temporal dynamic are proposed for limited areas such as regions, states or pedoclimatic zones, for example, in a soil health monitoring context; further testing is, however, recommended.

KEYWORDS

bulk volume, clay content, indicator, SOC:Clay, soil functions, soil organic matter, soil quality

1 | INTRODUCTION

Soil organic carbon (SOC) has diverse and manifold positive effects on soil functional properties, such as water-holding capacity, aggregate stability, compactibility and erodibility, nutrient storage, cation exchange capacity and acid buffering capacity (Murphy, 2015). All those properties are directly coupled to the services that soils provide, such as food security, water security or biodiversity protection (Kopittke et al., 2022), making SOC an important indicator of soil quality and health (Bünemann et al., 2018). The definition and differentiation or non-differentiation of both terms vary across authors, but here we focus on soil health as the 'capacity of a soil to perform its key functions and provide ecosystem services' (Bonfante et al., 2020). In light of a steadily increasing global population, severe soil degradation and climate change, healthy soils and the definition of measurable and potentially litigable soil health indicators are becoming increasingly important (Allen et al., 2011; Lehmann et al., 2020; van Es & Karlen, 2019). The European Union is currently developing a Soil Health Law as a legal framework to achieve the objectives of the European Soil Strategy (Panagos et al., 2022). The vision is that all soils in the European Union will be healthy and that the protective and sustainable use of soils will be the norm by 2050. Possible soil health indicators and respective threshold or reference values are currently being discussed at multiple scientific and political levels, with SOC content always among the first to be highlighted (Bünemann et al., 2018). However, deriving a good, sufficient or even optimal level of SOC is a complex task and remains soil-specific and hard to generalize because (i) SOC is simultaneously relevant for various biological, chemical and physical soil properties, for all of which SOC content may have individual ranges and thresholds, and (ii) SOC levels are site-specific and depend on many abiotic factors such as soil texture and climate (Drexler et al., 2022). A definition of universal SOC threshold values that could be developed using other indicators, such as pH or contents of heavy metals, is thus not feasible. SOC levels are, to a large extent soil-intrinsic and can thus not be changed completely by management. Any indicator that aims at evaluating the success of soil management thus needs to consider the SOC variability derived from non-changeable soil properties.

Clay content is an abiotic factor often found to be among the most powerful explanatory variables of SOC content at a regional scale, especially in agricultural soils of near-neutral pH (Martin et al., 2011; Poeplau et al., 2020; Prout et al., 2021; Rasmussen et al., 2018). This can be related to clay's SOC-stabilizing properties, for example, its high specific surface area and ability to form stable micro-aggregates (Oades, 1988; Wagner et al., 2007). At first glance, it might thus make sense to normalize SOC by clay content in a SOC:clay ratio to establish a clay-independent indicator of the actual SOC level that allows soils to be compared (Prout et al., 2022).

A framework of different SOC:clay threshold values for judging soil structural conditions has been introduced by Johannes, Matter, et al. (2017). According to the authors, soils with a ratio of 1:8 or greater are considered to have *very good*, between 1:8 and 1:10 *good*, between 1:10 and 1:13 *moderate* structural conditions, while SOC:clay ratios smaller than 1:13 would indicate soils that are likely to have a *degraded* soil structure (Johannes, Matter, et al., 2017; Prout et al., 2021). These classes were derived from an assessment of simple porosity parameters, namely bulk volume, as well as water and air content at a specific matric potential (−10 hPa), using a limited dataset (161 data points from one broad soil group), with a similarly limited range in SOC (8–39 $\mathrm{g\,kg^{-1}}$) and clay content (100–340 $\mathrm{g\,kg^{-1}}$). It should also be noted that across the full range of soils, SOC content alone showed a higher correlation with all assessed structural parameters than the SOC:clay ratio, suggesting a disconnect between the SOC:clay ratio and the related structural soil property (Johannes, Matter, et al., 2017). Prout et al. (2021) adopted the framework and applied it to a large number of soils (3809) from the UK, Poland and Switzerland, and suggested that it is a meaningful index of the general state of agricultural soils that should be used in other, similar climate zones as well. However, statistically, the use of ratios to control or eliminate the influence of the denominator can be problematic and needs to be handled with care (Allison et al., 1995). They can be prone to extreme biases, which is also likely in the case of the SOC:clay ratio. The natural range in clay content is extensive, with anything from <10 to >800 $\mathrm{g\,kg^{-1}}$ being observed, even in managed agricultural soils (Martin et al., 2011; Poeplau et al., 2020). In contrast, the range in SOC contents of mineral soils is approximately one order of magnitude smaller, leading to a foreseeable clay bias in the ratio. The present study aimed to challenge the use of the SOC:clay ratio as a normalized SOC level metric by applying it to 2958 topsoils (0–30 cm) from the German Agricultural Soil Inventory dataset with a broad range of soil types, textures and SOC contents. A further objective of this study was to develop an unbiased alternative indicator based on the linear relationship between SOC and clay content that could serve as a flexible, straightforward solution using clay to normalize SOC contents at a regional scale.

2 | MATERIALS AND METHODS

The dataset used in this study was compiled in the first German Agricultural Soil Inventory conducted between 2011 and 2018. Sampling and analyses have been described in detail by Poeplau et al. (2020) and the dataset is published online (https://doi.org/10.3220/DATA20200203151139). A total of 3104 soil profiles in an 8 × 8 km grid were sampled to a depth of 100 cm. In this study, the analysis was restricted to mineral topsoils, i.e. the upper 30 cm, with average SOC contents of <87 g kg^{-1} ($n = 2958$, consisting of 2254 cropland and 704 grassland soils). The relevant depth intervals for this study were 0–10 and 10–30 cm. Topsoil values (0–30 cm) for SOC and clay contents were derived by mass-weighted averaging of the 0–10 and 10–30 cm depths, using the respective fine soil (<2 mm) amount of each depth increment. Derived topsoil SOC and clay content ranges were 2.6–122.9 g kg^{-1} and 9.6–822.5 g kg^{-1}, respectively. SOC:clay ratios were calculated for all sampling points and grouped into the above-mentioned categories of Johannes, Matter, et al. (2017), Johannes, Weisskopf, et al. (2017), i.e. *very good* (>1:8), *good* (1:8–1:10), *moderate* (1:10–1:13) and *degraded* (<1:13). Although initially developed in the context of soil structure, the rationale behind this index is to provide a basis for comparing actual SOC levels of differently textured soils. The developed score ranging from *degraded* to *very good* thus basically refers to a normalized SOC level that has been used and could be used further completely decoupled from soil structure (Prout et al., 2022) but rather as a reference system for judging the actual SOC level. In the present study, these classes were also used to evaluate SOC levels per se.

In the first part of the study, the clay dependency of the SOC:clay ratio was tested by (i) performing a direct assessment of the SOC:clay ratio as a function of clay content and (ii) calculating the proportions of *degraded*, *moderate*, *good* and *very good* SOC levels along the whole range of clay contents in seven increment classes of 100 g kg^{-1} each (<100, 100–199, 200–299, 300–399, 400–499, 500–599, >600). In addition, differences in the normalized SOC levels per land use (cropland and grassland), as well as soil group based on the World Reference Base (WRB) classification, were also evaluated. Permanent grasslands were defined as sites that were used as grasslands for at least five consecutive years. A certain proportion of croplands and grasslands in the dataset had a land use change from the respective other category in the last decades and it can be expected that SOC contents will continue to rise or fall in these cases (Springob et al., 2001). However, in this clustering approach, land use history was ignored.

In the second part of the study, a less clay-biased ratio was developed and tested as an alternative. To do this, first, the regression equation for a linear regression between SOC and clay content was derived. This was done to establish an average SOC value that can be expected at a certain clay content in German agricultural topsoils (SOC_{exp}). The actual SOC content of each site was then divided by SOC_{exp} to derive a ratio that would inform how much SOC is currently stored compared with what might be expected from the site's clay content. The quartiles of this SOC:SOC_{exp} ratio dataset were then used in a similar way to Johannes, Matter, et al. (2017) to determine the four previously introduced SOC-level classes and their threshold values. In this case, the threshold values were not derived in response to any functional properties, but rather exemplarily in the most pragmatic way. Soils with SOC contents below the regression line of SOC and clay content were considered to have *degraded* (1st quartile) or *moderate* (2nd quartile) SOC levels, while SOC levels of soils with SOC contents above this line were considered *good* (3rd quartile) or *very good* (4th quartile). Second, these classifications, based on the newly introduced operationally defined normalized SOC levels, were compared with the classifications based on the suitability of the SOC:clay ratio as an indicator of soil structural conditions. This was done using the inverse of bulk density (bulk volume, 1/BD, cm^3 g^{-1}) that describes soil porosity as an important structural parameter (Johannes, Matter, et al., 2017; Johannes, Weisskopf, et al., 2017). Differences in bulk volume between SOC level classes in each of the two schemes were tested using the non-parametric Kruskal-Wallis test and the Wilcoxon test as a post hoc test. Significance was assessed at $p < .05$. Calculations and plotting were performed using R version 4.2.1 (R Development Core Team, 2010) and the packages tidyverse and ggplot2 (Wickham, 2016; Wickham et al., 2019).

3 | RESULTS AND DISCUSSION

3.1 | Evaluation of the SOC:clay ratio

Using the SOC:clay ratio scheme, 37% of all cropland and 14% of all grassland topsoils in Germany were found to have *degraded* SOC levels (Table 1). This might appear reasonable since cropland soils are acknowledged to be depleted in SOC as compared with soils under grassland (Guillaume et al., 2021). The proportions of soils with degraded SOC levels were similar to those found for soils in the UK, Switzerland and Poland, where 38% and 7% of all cropland and grassland soils had *degraded* SOC levels (Prout et al., 2021). However, a closer look at the different soil reference groups revealed that the use of SOC:clay ratio as an indicator was problematic and certainly misleading: clay-poor Podzols, irrespective of land use, were always found to have *very good* SOC levels, with median SOC:clay ratios around 1:1. The ratio is thus not sensitive enough to indicate degradation of sandy soils since all these sandy soils were far beyond the defined threshold values of 1:8. The opposite applied to more fine-textured soils: 97% of

TABLE 1 Proportions (%) of cropland and grassland topsoils (n) classified in the four different levels based on the SOC:clay ratio score proposed by (Johannes, Matter, et al., 2017) by World Reference Base (WRB) soil group and land use, and median SOC:clay ratios.

Land use	Soil class	*n*	Degraded	Moderate	Good	Very good	Median SOC:Clay
Cropland	Anthrosols	178	21	7	6	66	0.25 (1:4)
	Cambisols	609	28	19	12	41	0.10 (1:10)
	Chernozems	89	61	33	4	2	0.07 (1:14)
	Fluvisols	12	50	33	8	8	0.07 (1:14)
	Gleysols	175	21	12	4	63	0.19 (1:5)
	Luvisols	321	39	26	17	19	0.08 (1:12)
	Phaeozems	211	48	23	13	16	0.08 (1:12)
	Podzols	84	0	0	0	100	0.74 (1:1.3)
	Regosols	224	68	15	7	10	0.06 (1:17)
	Stagnosols	293	35	18	14	33	0.09 (1:11)
	Vertisols	58	97	0	3	0	0.05 (1:21)
	All	2254	37	18	10	35	0.09 (1:11)
Grassland	Anthrosols	60	8	8	2	82	0.28 (1:4)
	Cambisols	222	9	21	22	48	0.12 (1:8)
	Chernozems	1	100	0	0	0	0.06 (1:14)
	Fluvisols	3	33	33	33	0	0.10 (1:10)
	Gleysols	106	8	12	9	70	0.19 (1:5)
	Luvisols	28	11	39	18	32	0.10 (1:10)
	Phaeozems	91	12	40	20	29	0.10 (1:10)
	Podzols	20	0	0	0	100	1.01 (1:1)
	Regosols	52	35	15	17	33	0.10 (1:10)
	Stagnosols	103	17	18	26	38	0.11 (1:9)
	Vertisols	18	61	33	6	0	0.07 (1:15)
	All	704	14	21	17	48	0.12 (1:8)

all clay-rich Vertisols had *degraded* SOC levels (median SOC:clay ratio of 1:21) and it would require immense efforts (+62% SOC) to achieve even a shift from *degraded* to *moderate* (threshold of 1:13). Moreover, Chernozems are also fine-textures soils and are considered the most fertile soils with generally high SOC contents and a favourable soil structure (Šimansky & Jonczak, 2016). Nonetheless, according to the SOC:clay ratio, only 2% of all chernozems under agricultural use in Germany had *very good* SOC levels, while 61% only *degraded*. Even the one single Chernozem under grassland was *degraded*. These cases highlighted the over-dependence of SOC:clay ratios on clay content, as visualized in Figure 1a,b.

The proportion of soils with *degraded* SOC levels, which was close to zero in coarse-textured soils, increased exponentially with clay content (Figure 1b). It is not realistic for clay-rich soils to be particularly depleted in SOC, e.g. by agricultural management, since there is a positive correlation between the fine particle content (clay and fine silt) and the relatively stable mineral associated SOC (Hassink, 1997). In coarse-textured soils, particulate organic matter is the dominant form of organic matter, which is considered more labile and more responsive to disturbances such as land use change or agricultural management (Lavallee et al., 2020; Poeplau & Don, 2013; Vos et al., 2018). This fits well with the fact that Prout et al. (2022) observed more pronounced SOC losses for agricultural soils in England and Wales with higher SOC:clay ratios, and might suggest that the SOC:clay ratio could be used as a rough proxy for the amount of unprotected SOC prone to losses (Dexter et al., 2008).

However, the indicator's extreme clay dependency hampered both the comparison of soils within a similar textural class as well as a comparison across all textural classes. In both, coarse and fine-textured soils, the indicator is insensitive to changes in SOC content. Losses or gains in SOC needed to change class are beyond expectable SOC changes because of management, land use or climate change within years to a few decades. For example, in the Ultuna Frame Trial, a Swedish long-term fertilization experiment that started in 1956 on soil with a high clay content, different types of organic amendments were

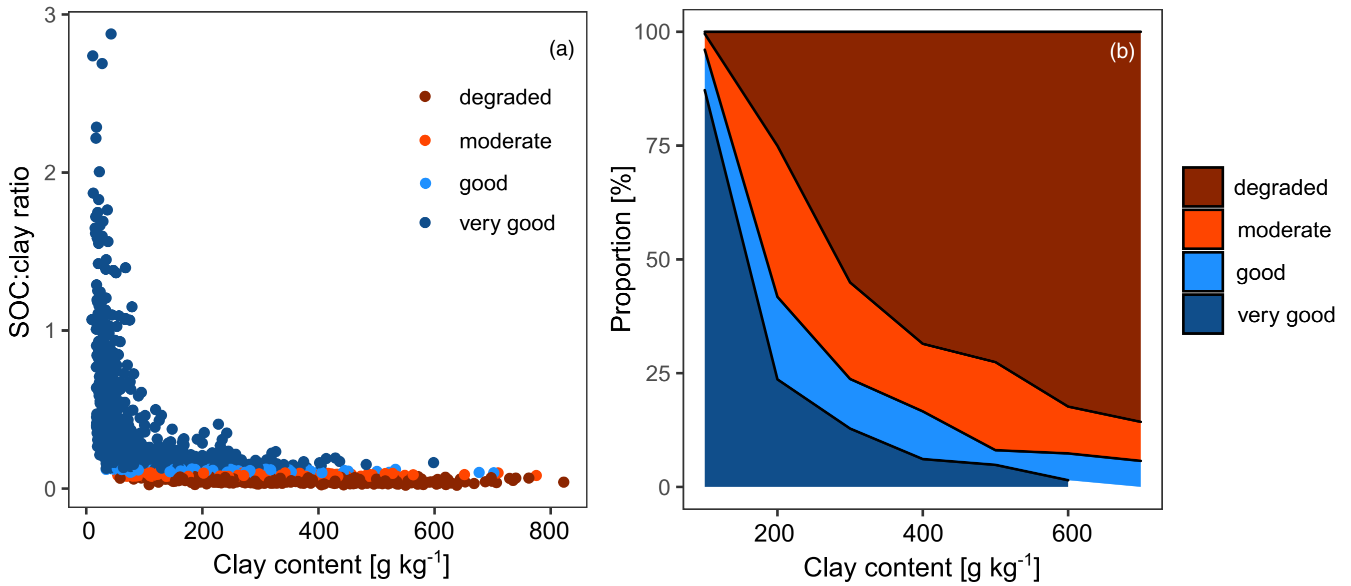

FIGURE 1 (a) Soil organic carbon (SOC)-to-clay ratio as a function of clay content, using the four SOC level classes suggested by Johannes, Matter, et al. (2017), applied to German agricultural topsoils (0–30 cm, 2958 sites under cropland and grassland use) and (b) the proportion of each class as a function of clay content. In this case, the data were aggregated in steps of 100 g kg^{-1} clay content (therefore starting with 100 g kg^{-1} as the first data point).

applied to the soil in doses of 4 Mg C every 2 years. The organic amendments included straw, green manure, farmyard manure, sewage sludge, sawdust and peat (Kätterer et al., 2011). At the start of the trial, the soil had an average SOC content of 15 g kg^{-1} (SOC:clay ratio of 1:24). After 54 years of continuous organic fertilization, only peat, sawdust and sewage sludge amendments—all rarely used organic fertilizers on agricultural soil—resulted in a change of SOC level from *degraded* to *moderate*, while SOC in all other treatments remained at the *degraded* level. This is in contrast to the results of the Woburn experiment highlighted by Prout et al. (2021), in which farmyard manure addition was able to change the SOC level from *degraded* to *good* within 7 years. The main difference between the two experiments was the clay content, which was 78–131 g kg^{-1} in Woburn and 365 g kg^{-1} in Ultuna.

It could be argued that only the extreme soils within the whole texture range would be affected by this clay bias and that those could simply be neglected when applying the SOC:clay ratio indicator. Nevertheless, Johannes, Matter, et al. (2017), Johannes, Weisskopf, et al. (2017) developed the scheme for soils with clay contents of between 100 and 340 g kg^{-1}. However, even within such a restricted range of clay contents, the SOC:clay ratio is strongly biased: the same amount of additional SOC would lead to a 3.4 times higher absolute increase in the SOC:clay ratio for a 100 g kg^{-1} clay soil than for a 340 g kg^{-1} clay soil. Furthermore, a general SOC-level metric should only qualify as such when it is broadly applicable. In regions with glacial or glacio-fluvial sediments, coarse-textured soils with low clay contents are common (Gebauer et al., 2022). Finally, and perhaps most importantly, sandy soils are mostly low in SOC and also have a poor soil structure. In addition to having a low water-holding capacity, they also have a comparatively low pH, low cation exchange capacity and low nutrient storage. With regard to soil functions, ecosystem resilience and yield stability, sandy soils may thus be most in need of SOC, which is able to bring about positive change in most of the properties mentioned (Moinet et al., 2023; Murphy, 2015). However, the SOC:clay ratio, as it is used now, would indicate the exact opposite: sandy soils are generally classified as in *very good* structural condition and SOC level and improving them is neither needed nor possible. According to the SOC:clay indicator, clay-poor soils with, for example, 50 g kg^{-1} clay are in the *very good* SOC level with as little as 6.2 g kg^{-1} SOC. Thus, the strong clay dependency of this indicator makes it inappropriate for its use in a soil health context.

3.2 | The newly introduced SOC:SOC$_{exp}$ Ratio

Despite clay content being too strong a denominator for the normalization of SOC, its use might still be meaningful. It is a widely available standard soil property and is often observed to be a strong predictor of SOC in regional-scale case studies, at least in temperate regions (Martin et al., 2011). One option that is proposed and tested here is to use the correlation between SOC and clay content to establish an average expected SOC content (SOC_{exp}) depending on the clay content as a denominator. This normalization of SOC is less strong than clay content as a denominator. When the $SOC:SOC_{exp}$ ratio is >1, the SOC content is above expected SOC and thus above average SOC, and when the ratio is below 1 the soil is rather SOC-depleted and below average. The correlation between clay and SOC contents for all German Agricultural topsoils provided the new denominator with $SOC_{exp} = clay \times 0.0288 + 13.674$, where R^2 was 0.11. Although the correlation was highly significant ($p < .001$), R^2 was relatively low because of a certain group of soils, which are recognized as 'black sands' (Vos et al., 2018) and deviate strongly from the SOC ~ clay relationship (Figure 2a). These coarse-textured soils are characterized by high SOC contents, mainly in the form of recalcitrant plant litter originating from historic land cover as heathland or peatland (Springob et al., 2001; Vos et al., 2018). However, as an important part of the whole ensemble of German agricultural soils, they were not excluded from the derivation of SOC_{exp} here. The derived threshold values of the $SOC:SOC_{exp}$ ratio for the classification of German agricultural soils were 0.65 (threshold between *degraded* and *moderate*), 0.83 (*moderate*/*good*) and 1.16 (*good*/*very good*). Using these thresholds, this study found that 32% of all cropland soils and only 3% of all grassland soils had *degraded* normalized SOC levels (Table 2). This was of a comparable magnitude to those observed for the SOC:clay ratio for our dataset. However, of the 940 topsoils that had degraded SOC levels using the SOC:clay ratio, only 407 (43%) also had degraded SOC levels using the $SOC:SOC_{exp}$ ratio. This indicates that the two approaches classified the soils differently. Importantly, as depicted in Figure 2b, there was no clay dependency of the classification based on the $SOC:SOC_{exp}$ ratio. Also for the Ultuna long-term experiment, on a fine-textured soil, $SOC:SOC_{exp}$ was far more sensitive to management changes than the SOC:clay ratio: Depending on the organic amendment treatment, the initially degraded SOC level of this trial was changed into all possible classes within the first 20 years. Of course, these thresholds are operationally defined and specific to the set of samples used. Nevertheless, this example showed that the metric derived from German agricultural topsoils could produce meaningful results also for an experiment in Central Sweden.

Soil organic carbon is acknowledged to affect many soil functional properties (Bagnall et al., 2022; Murphy, 2015). However, to qualify as an indicator in a soil health context, also a SOC level metric should be related to soil functions. The SOC:clay ratio was initially developed together with soil structure indicators (Johannes, Matter, et al., 2017). Also here we exemplary use bulk volume as an indicator of porosity to evaluate which SOC level metric can be better linked to soil structural condition. As shown in Figure 3, $SOC:SOC_{exp}$ was a better indicator of soil structure than the SOC:clay ratio: In the case of SOC:clay, the different classes differed only slightly in their average porosity and in part not significantly: The class *good* had the highest porosity, while *very good* and *moderate* were not statistically different. In contrast, the classes based on the $SOC:SOC_{exp}$ ratio were in the expected order and

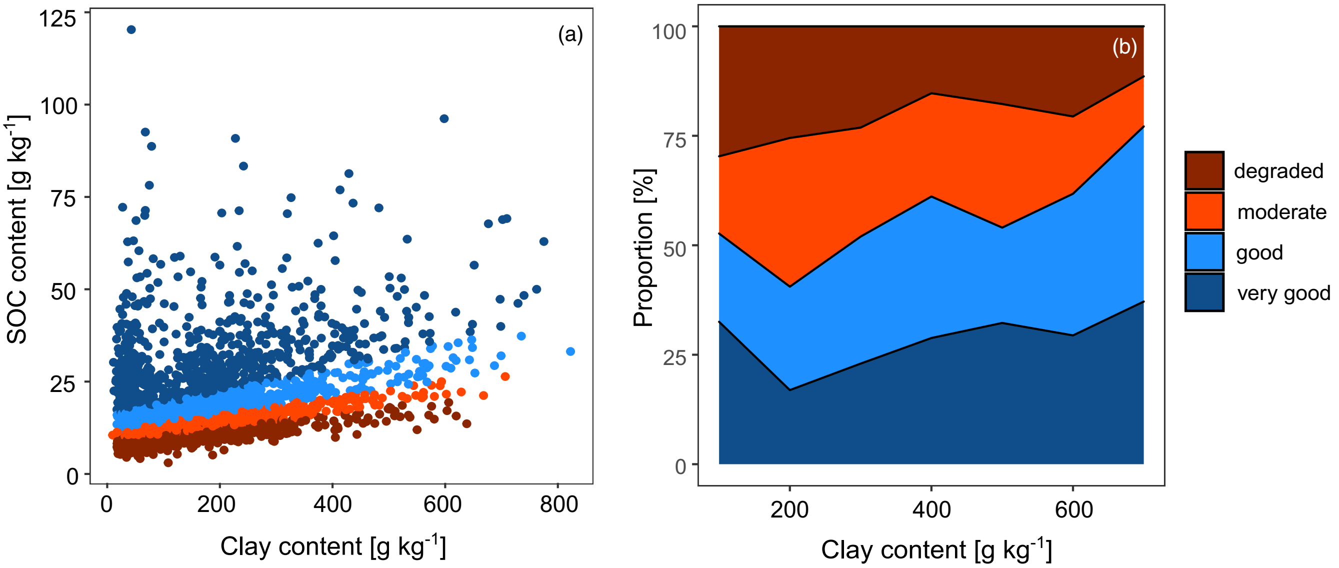

FIGURE 2 (a) Soil organic carbon (SOC) content as a function of clay content in 2958 German agricultural topsoils (0–30 cm depth) with the four classes based on the $SOC:SOC_{exp}$ ratio, and (b) the proportion of soils in each class as a function of clay content. In this case, the data were aggregated in steps of 100 g kg^{-1} clay content.

TABLE 2 Proportions (%) of the different normalized soil organic carbon (SOC) level classes for topsoil (0–30 cm depth) based on the quartiles of the SOC:SOC$_{exp}$ ratio by World Reference Base (WRB) soil group and land use, with the number of observations (n) and median SOC:SOC$_{exp}$ ratio.

Land use	Soil class	*n*	Degraded	Moderate	Good	Very good	Median SOC:SOC$_{exp}$
Cropland	Anthrosols	178	18	19	22	40	1.00
	Cambisols	609	34	34	23	8	0.72
	Chernozems	89	20	35	43	2	0.78
	Fluvisols	12	8	42	33	17	0.78
	Gleysols	175	11	20	28	41	1.04
	Luvisols	321	58	32	8	1	0.62
	Phaeozems	211	30	37	24	9	0.73
	Podzols	84	5	2	21	71	1.60
	Regosols	224	34	28	30	7	0.75
	Stagnosols	293	26	35	24	14	0.77
	Vertisols	58	38	33	24	5	0.70
	All	2254	32	30	23	15	0.75
Grassland	Anthrosols	60	5	12	25	58	1.32
	Cambisols	222	4	10	32	55	1.21
	Chernozems	1	0	0	100	0	0.96
	Fluvisols	3	0	0	67	33	0.94
	Gleysols	106	3	3	26	68	1.45
	Luvisols	28	7	39	32	21	0.84
	Phaeozems	91	1	7	33	59	1.23
	Podzols	20	0	0	0	100	2.21
	Regosols	52	4	8	23	65	1.37
	Stagnosols	103	3	7	38	52	1.19
	Vertisols	18	11	0	44	44	1.14
	All	704	3	9	30	58	1.25

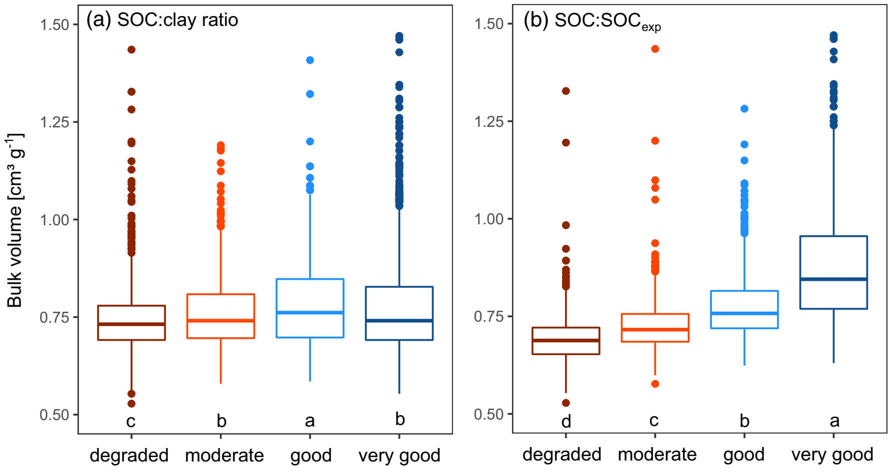

FIGURE 3 Soil porosity of 2958 soil samples as distributed into classes derived according to (a) the soil organic carbon-to-clay (SOC:clay) ratio (Johannes, Matter, et al., 2017) and (b) the quantiles of the measured-to-expected SOC ratio (SOC:SOC$_{exp}$). Letters depict significant differences between classes ($p < .05$).

all statistically different from each other. Despite a certain overlap across SOC-level classes, the boxes were also much smaller than for the classes based on SOC:clay, indicating a better separation. This can be seen as an independent validation of SOC:SOC$_{exp}$ being preferable over SOC:clay even as a structural indicator.

3.3 | Challenges of deriving SOC classification schemes and potential ways forward

The results of this study clearly suggest that a revised and attenuated version of the SOC:clay ratio, that is, using the average regression equation of SOC vs. clay content as a denominator instead of clay content, is preferable. However, the first challenge is that both the SOC ~ clay relationship, as well as SOC per se, are strongly dependent on the pedoclimatic zone as well as on the spatial scale. Rasmussen et al. (2018) showed that the suitability of clay as a predictor of SOC depends much on the type of minerals present, as well as on soil pH. Also, on larger scales (continental to global), climatic factors become increasingly important and mask the clay effect to a certain extent (Delgado-Baquerizo et al., 2017; García-Palacios et al., 2021). Within the European Union, it will thus not be possible to have one desirable SOC level and simple SOC classification scheme (e.g. by clay content or texture class) that fits equally well for all soils, e.g. Scandinavian and Mediterranean soils. However, as a first step, the pragmatic approach taken here could be adopted by others and applied using regional SOC ~ clay relationships and related quartiles. Apart from the fact that the SOC:SOC$_{exp}$ ratio is not clay-biased, it also has the advantage that the absolute numbers can be compared across different pedoclimatic regions, soil depths and land use types because it resembles a normalization by what is observed on average in a given region at a given clay content. This means that SOC ~ clay relationships in 0–30 cm soil depth will differ in intercepts and slopes from the same relationship in 0–10 cm, which is also true for different pedoclimatic zones, for example. This is not the case for the SOC:clay ratio, which does not take context into account at all. Subsoil (30–100 cm) data are not shown in this study, but similar results for the SOC:SOC$_{exp}$ ratio were obtained. Depending on the question, this might also be a disadvantage of the SOC:SOC$_{exp}$ metric: it might not necessarily be helpful to evaluate the absolute average SOC content of a country or region compared with others; it does not relate measured SOC to a certain fixed reference content and is thus solely based on the population used to build the model. In this respect, the approach is similar to that taken by Drexler et al. (2022), who defined benchmark SOC contents for German agricultural soils using several important explanatory variables such as texture, C:N ratio and precipitation. This scheme was developed for farmers and thus requires little soil data, but allows farmers' measured SOC contents to be compared with those of similar sites. In their case, the benchmarking was also done with current SOC contents found in German agricultural soils that might not be optimal or desirable. Likewise, Chen et al. (2019) used a data-driven clustering approach to derive carbon-landscape clusters in France and calculated the highest possible SOC content within each individual cluster using the percentile of 0.9, for example. This was mainly done to estimate the SOC storage potential of arable land in France, but could potentially be used to define a cluster-specific range of SOC contents as related to a certain achievable SOC content. Again, the problem is that the highest values within a specific cluster do not necessarily have to resemble the highest achievable SOC content if, for example, the whole cluster is SOC depleted. In each case, the chosen thresholds (quartiles in the present study), or the 0.9 quartile are somewhat arbitrary, but (i) we were able to show that the quartile thresholds used in this study were able to separate soils with significantly different porosities and (ii) a standardized methodology across different countries or regions might be more important than the question at which exact threshold a soil changes from one to the other SOC level.

The data in the present study show, for example, by the relatively low regression coefficient, that it is a simplification to derive an expected SOC content for a site solely by the parameter clay content. Numerous other soil properties determine the SOC content, with groundwater level among the most prominent (Poeplau et al., 2020). The high fraction of groundwater-influenced Gleysols classified as *good* and *very good* indicates that beyond clay content, the water regime also positively influences SOC contents (Table 2). Furthermore, Doetterl et al. (2015) highlighted the strong impact of geochemistry, so basically bedrock properties, on SOC contents. This might be more accounted for, when, for example, certain landscape units, pedo-climatic zones or similar are used as a grouping variable (Chen et al., 2019). At the same time, such spatial clusters can also be highly heterogeneous so that such a clustering might not necessarily lead to a clear separation either (Chen et al., 2019). It is therefore questionable and certainly context-specific, how the denominator in such a SOC:SOC$_{exp}$ should optimally look like. Even more sophisticated and potentially applicable on large spatial scales is the reciprocal modelling approach using machine learning, as introduced by Schneider et al. (2021). Here, beyond clay also many other drivers could be used to model a pedo-climatic reference SOC. Such reference SOC content would also need to be defined, e.g. that of grassland soils, and a statistical model used to estimate how much the SOC content of a given cropland soil deviates from its hypothetical grassland SOC content. The resulting residue could then potentially be scaled into an indicator of degradation. Such an approach is data hungry and also has its weaknesses, mainly in the critical assumptions that need to be made (Schneider et al., 2021). However, this approach should be investigated further for data-rich regions as a potential way forward towards a comprehensive evaluation scheme for SOC. Finally, we argue that clay content is a soil property that (i) has been shown to strongly affect SOC storage, (ii) is mostly available and (iii) does not severely change over time and thus qualifies to be used in such a normalization approach. More dynamic soil properties that also influence SOC, such as groundwater level or pH, might be better suited as explanatory variables for changes in the numerator. For example: If drainage is introduced in a certain area, leading to an increased mineralization of SOC (Castellano et al., 2019), this will be reflected in the SOC:SOCexp over time.

To overcome the problem of SOC:SOC$_{exp}$ only providing meaningful insights in relation to the current situation of the whole population, it is proposed that the SOC:SOC$_{exp}$-derived classes be understood as a simple baseline benchmarking system (e.g. country-specific) that could be used to monitor and evaluate SOC over time. The regression is established with the given baseline dataset at a certain time, in which the whole dataset is classified into equal shares (quartiles) of *degraded*, *moderate*, *good* and *very good*. The quartile thresholds will then be fixed for the country (or similar spatial unit) and changes over time will always be related to exactly those thresholds of initial SOC conditions. Then, in repeated soil inventories, for example, the development in the proportions of the different classes over time can be evaluated. Specific goals such as 'no soils with *degraded* SOC levels by year x', or '25% more soils with *very good* SOC levels by year y' could be set as political targets. The major advantage of a scoring approach of this kind over simply following the trends in SOC per se would be the direct comparability across countries (e.g. within the EU), which have their individual baseline levels, established sampling depths and also different analytical methods. It could potentially also be embedded in more complex soil health-scoring functions including other indicators, comparable to the CASH framework (Fine et al., 2017).

However, a more general problem is that an *optimal*, *sufficient* or *degraded* SOC content is difficult to define and the definition may greatly depend on the desired functions of SOC. For biological and chemical functions, such as fuelling soil biota and increasing nutrient storage, there could be something like an optimum value that should not be exceeded in order to avoid negative environmental impacts such as nitrate leaching or increased N_2O emissions (Yanai et al., 2003). In contrast, for soil physical properties such as water-holding capacity and structural stability, there seems to be a positive linear relationship with SOC content (Chaney & Swift, 1984; Johannes, Matter, et al., 2017). The desired function might then also be soil-specific, as discussed earlier. In a coarse-textured soil, SOC could be much more important to compensate for the lack of soil structure than in a loamy soil (Moinet et al., 2023). This also raises the question of whether the SOC level of any soil can be called *degraded* when a certain defined proportion of a reference SOC content is not reached. This all converges into the need for (i) a precise definition of what a healthy soil is, (ii) a better understanding of which soils and soil functions are supported by organic matter to what extent, and finally (iii) how the derived classes of the new SOC level metric fit to other soil parameters and functions. At the same time, the soil health context is only one example for a potential use of the proposed SOC level metric. The SOC: SOCexp value has the potential to also be used as a continuous variable to evaluate the effect of agricultural management practices across soils with different textures The three major limitations of the approach taken here can be summed up as follows: 1. It is a simplification to use only clay for normalizing SOC levels across soils. This leaves other factors unaccounted and restricts its use to regions and soils, in which clay minerals play a significant role for SOC stabilization and as such. The indicator can potentially grow in complexity and also other drivers could be used to derive SOC$_{exp}$, but data availability is a key limiting factor. 2. The derived classes are highly context-specific because they are derived from the distribution of data in a specific dataset. Here, the context was German agricultural soils. Including forest soils, or data from, for example, neighbouring countries, would have shifted the regression between SOC and clay content and in turn also the thresholds between classes. Those classes should thus be related to the specific context only and the focus should be on temporal changes of the classes or individual SOC:SOC$_{exp}$ values. The LUCAS dataset could be used to develop such a reference SOC-level system based on SOC:SOC$_{exp}$ for different EU member states. 3. The classes, which now have explicit names like 'degraded' or 'very good', are only weakly linked to soil functions. This would however be necessary, to better tie the indicator to the actual concept of soil health. It was recently highlighted, that the SOC content that is actually needed to maintain certain soil functions is most likely also dependent on various other soil properties (Moinet et al., 2023). Although not straightforward, this should be accounted for in future experimental approaches.

4 | CONCLUSIONS

The findings of this study suggest that the SOC:clay ratio is not an appropriate indicator for evaluating the SOC level of soils, e.g. in a soil health framework. The ratio is misleading because of the overly strong influence of clay content. As an alternative, a less clay-biased normalization metric was introduced that could offer a simple way forward for judging the SOC level of a specific soil in a specific region. The study was able to show that this metric is better related to soil porosity than the SOC:clay ratio. However, the metric also has its drawbacks, e.g. it relates only to the current situation of the assessed population, rather than to some fixed optimum level that would be universally applicable. However, when following the temporal trend of such established baseline threshold values, the approach could be used as a simple scoring system featuring SOC classes that are comparable across countries, regions or similar spatial units. For a more generic evaluation of SOC contents and their functions, a more refined framework might be needed. This manuscript aims to encourage soil scientists to increase testing, especially with the prospect of ever-increasing soil datasets and improved data availability.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Openagrar at https://www.openagrar.de/receive/openagrar_mods_00054877.

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