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COMMENTARY

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# The organic carbon-to-clay ratio as an indicator of soil structure vulnerability, a metric focused on the condition of soil structure

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**Abstract**

The soil organic carbon to clay ratio (SOC:clay) is a metric used in soil quality management. In Switzerland and the United Kingdom, for example, threshold values for SOC:clay ratios have been determined to indicate very good (>1:8) to degraded (<1:13) soil structures. A recent article in Soil Use and Management by Poeplau and Don, however, suggested that this metric is 'strongly biased and misleading', based on their observation that German sandy soils and heavy clay soils tend to show very high and very low SOC:clay ratios, respectively. An alternative metric was proposed based on the ratio of actual SOC to expected SOC level for a considered area. We offer a commentary on the proposal, arguing that because soil structure quality is overlooked by the approach, it fails to provide appropriate SOC levels for soil health and could lead to soils with highly depleted SOC being classified 'good'. The SOC:clay ratio, on the other hand, does address soil structure condition, providing a structure vulnerability index, a key function independent of local soil management conditions. When soils are found to have high structure vulnerability, as indicated by the SOC:clay ratio, the cropping practices at the site should be investigated and ways to increase the SOC content considered. Structure condition threshold values may only need to be reassessed if it is shown that the average structure quality observed is not in conformity with the present thresholds, which would be expected for some soils, such as Andosols.

**KEYWORDS**

clay content, soil organic carbon, structure quality, structure vulnerability

## 1 | INTRODUCTION

An article published recently in this journal by Poeplau and Don (2023) investigated whether the soil organic carbon to clay ratio (SOC:clay) adequately characterizes the structural condition of soils, as implied by the proposition of using a 1:13 value of the SOC:clay ratio as a metric for healthy soils in the European Soil Monitoring Law (European Commission, 2023). Poeplau and Don (2023) used German Agricultural Soil Inventory data from 2958 topsoil samples (0–30 cm) to evaluate the suitability of the SOC:clay ratio, and concluded that it is not a suitable SOC level metric since it is strongly biased, misleading and partly insensitive to SOC changes.

Their statement was based on the observation that at low and high clay content, soils tend to show large and small SOC:clay, respectively, regardless of SOC content. As a suggested unbiased alternative to the SOC:clay ratio, Poeplau and Don (2023) proposed a new metric that is based on the ratio between actual and expected SOC ($SOC_{exp}$) levels, the latter being derived from a regression between local data for SOC and clay content. In this context, the purpose of this article was to address criticisms of the SOC:clay ratio, and to provide a balanced perspective on metrics associated with the structural condition of soils.

## 2 | BACKGROUND

Some background information is useful to understand the arguments presented by Poeplau and Don (2023). Feller and Beare (1997) initially demonstrated that the SOC:clay ratio influenced aggregate stability. Building on this, Dexter et al. (2008) later used the ratio to emphasize the interplay between clay and carbon in controlling soil structure stability, proposing a 'complexed organic carbon' theory. They concluded that an optimum SOC content was equal to 10% of the soil clay content. However, Johannes, Weisskopf, et al. (2017), reported that the relationship between structure quality and SOC content was not linear. Working with 161 soil samples (5–10 cm depth) obtained in Swiss cropland and whose structural quality they evaluated visually based on the Visual Evaluation of Soil Structure (VESS) method (Ball et al., 2017), they reported that the relationship followed a 'broken stick' pattern. A rapid drop in SOC content was observed in the good to acceptable structure quality range (VESS scores from 1 to 3), followed by a slower drop from acceptable to degraded structure quality (VESS scores from 3 to 5). Johannes, Matter, et al. (2017) suggested that there is no optimal SOC value corresponding to a fraction of the clay content, contrary to Dexter et al. (2008), and observed that the SOC:clay ratio decreased monotonically with structural quality.

On that basis, they determined empirically that thresholds of the SOC:clay ratio of 1/8, 1/10 and 1/13 indicated the boundaries, respectively, between 'very good', 'good', 'moderate' and 'degraded' levels of average structure quality across seasons and rotations. Prout et al. (2020) subsequently tested the SOC:clay index using data from the initial sampling (1978–83) of the National Soil Inventory of England and Wales, covering 3809 sites under arable land, grassland and woodland, and found that the threshold values identified by Johannes, Matter, et al. (2017) were applicable to this much larger data set. This led Prout et al. (2020) to suggest that, although by no means absolute, these thresholds might also be applicable in soils in similar climatic zones across Europe. More recent work by Prout et al. (2022) and Johannes et al. (2023) confirmed the practical usefulness of the thresholds of the SOC:clay index, respectively, in England/Wales and in the Jura region of Switzerland, in soils with up to 87% and 52% clay contents, respectively.

### 2.1 | Testing the applicability of SOC/clay thresholds is worthwhile

A first point concerning the recent article of Poeplau and Don (2023) is that any attempt to scrutinize the applicability of the SOC:clay index and its various thresholds in a different geographical context is entirely welcome. It is customary to insist on the fact that conclusions are tied to specific locations (Andrews et al., 2002; Bünemann et al., 2018), and therefore, studies using local references are required. Similarly, when considering the SOC:clay ratio to characterize the structural condition of soils, the range of applicability needs to be researched and the areas identified where refinements are needed.

In sandy soils, as an example, the SOC:clay ratio consistently tends to be very high and the structure is stable, thereby placing the soil in the optimal class in Johannes, Weisskopf, et al.'s (2017) ranking. In the data set used by Johannes, Matter, et al. (2017), the minimum clay content was 10%. In general, there is a need for a more sensitive description of sandy soils, which remains to be developed. This can be extended to all soils with low clay content, for instance, peat soils and chalky soils for which the concept of complexation of SOC on clay proposed by Dexter et al. (2008), as well as the concept of structure quality, may not apply. Indeed, these soils do not typically exhibit classical structural behaviour observed in soils with higher clay content. By studying the structural behaviour of undisturbed soil samples on a large range of clay content, Boivin (1990) found that sandy soils with less than 12% clay did not demonstrate structural shrinkage and behaved like particle beds. It is, therefore, likely that the structure condition of such soils cannot be linked to the SOC:clay ratio, though one could conclude that the vulnerability of their structure is low, which would be correct but of little interest.

Likewise, clayey soils pose a particular challenge. As pointed out by Johannes et al. (2023), some clay soils have SOC values above the 'good' or even 'very good' thresholds of the SOC:clay ratio, though the SOC content has to increase proportionately much more than in other soil types (Johannes, Matter, et al., 2017). Johannes et al. (2023) showed that under similar cropping practices, the structure quality and the SOC:clay ratio were independent of clay content over a wide range (16%–52%) of clay content, supporting the idea that the higher the clay content the easier it is to increase SOC. Again, some adjustment to the approach might be in order.

Both Johannes, Matter, et al. (2017); Johannes et al. (2023) and Prout et al. (2020, 2022) left the door open for such developments, as neither claimed that their conclusions were universal or absolute. On the contrary, both groups of authors pointed out that further research was needed to determine to what extent the SOC:clay index and its various thresholds could be applied in other areas than those in which the original investigations took place. For instance, Andosols are well known to show very large SOC content, and to be poorly dispersible (see Feller et al., 2001), thus leading to much higher SOC:clay ratios than those reported by Johannes, Matter, et al. (2017), Prout et al. (2020) and Poeplau and Don (2023).

Poeplau and Don (2023) also mentioned Vertisols and Chernozems. Vertisols, characterized as heavy clay soils showing uniform profiles with low SOC content to large depths because of their vertic properties, would likely show very low SOC:clay ratios in the topsoil. Generally, it can be expected that soils with large SOC protection, such as Andosols, and soils with high active carbonate fraction (Rabot et al., 2024) or Chernozems, will not present the same SOC:clay thresholds for their structure condition as the soils assessed in Johannes, Matter, et al. (2017) and Prout et al. (2020).

## 2.2 | Testing under identical conditions

For a broader assessment of the SOC:clay index to be meaningful, one could reasonably argue that it should be carried out under the same conditions as those used in the original articles that first described the approach. Whereas Johannes, Weisskopf, et al.'s (2017) and Johannes et al.'s (2023) soil samples were obtained from 5 to 10 cm, with structure quality assessed on the same samples, and Prout et al. (2020, 2022) used the top 15 cm of the soil profile, Poeplau and Don's (2023) data set consists of SOC and clay values from 0 to 30 cm layer of soils. Part of the rationale behind the Johannes, Weisskopf, et al. (2017); Johannes et al. (2023) and Prout et al. (2020, 2022) choice of soil samples is that this depth involves the portion of agricultural fields that tends to be homogenized by tillage, whose structure is affected by traffic and tillage activity, and is typically enriched in organic matter. The significantly deeper samples used in the data set by Poeplau and Don (2023) would mean that they included soil material that would tend to contain less organic matter and, possibly, more clay if clay illuviation took place in situ to any significant extent. Therefore, the data set used by these authors may not have been adequate to assess the robustness of the SOC:clay index approach, as originally devised by Johannes, Weisskopf, et al. (2017).

Poeplau and Don (2023) did not use soil structure quality but bulk density (BD) values in the second part of their studies, with no information on the depth at which undisturbed samples were collected. For SOC and clay contents, information from the 0 to 10 and 10 to 30 cm depth layers was aggregated, but how the BD values corresponding to the 0–30 cm layer were derived was not described.

## 2.3 | Centrality of soil structural condition

In another more fundamental respect, Poeplau and Don (2023) misrepresent, the essence of the SOC:clay index approach, when they wrote that 'although initially developed in the context of soil structure, the rationale behind the index is to provide a basis for comparing actual SOC levels of differently textured soils'. If the goal was indeed to compare actual SOC levels of differently textured soils, then a different route would certainly have been taken by Johannes, Matter, et al. (2017) than to rely on the SOC:clay ratio. Indeed, these authors clearly showed that physical parameters including the soil BD are far better correlated with the SOC content directly than with the SOC:clay ratio. A similar observation has been made by Poeplau and Don (2023) and was indeed reported long ago by many authors, as reviewed in Johannes, Matter, et al. (2017).

However, the objective pursued explicitly by Johannes et al. (2017, 2023), contrary to what Poeplau and Don (2023) wrote was to find how the level of SOC affects the soil *structural* condition. Consequently, they do not deal with a SOC content that could be achieved in relation to observed averages, as in Poeplau and Don (2023), but with a soil condition that should be achieved, referring to the functions associated with the structure and independently of the observed SOC distribution.

While many of the soil physical properties linearly correlate to SOC content, none alone successfully define the soil structure quality, as reviewed in Johannes et al. (2019). As explained in detail in Baveye et al. (2020, 2022) and Vogel et al. (2022), this question has huge practical consequences, since climatic change threatens the ability of soils to fulfil a number of essential services, for which soils having a resilient structure—now often referred to as their 'architecture'—and hence, an adequate SOC content, is a key requirement. In that context, Johannes, Matter, et al. (2017); Johannes et al. (2023) focused on purpose not only on soil physical parameters in general but also specifically on the architecture of soils, about which the BD, considered by Poeplau and Don (2023), is a poor descriptor.

Poeplau and Don (2023) appear to have overlooked this property of the SOC:clay ratio, which is not provided by the SOC content metric they proposed. The structure quality follows a broken stick pattern with respect to SOC (Johannes, Matter, et al., 2017), as well as the structural porosity volume, which is a key parameter of soil structure quality. Indeed, in the general context of the influence of SOC on the structural quality of soils, the results of Johannes, Weisskopf, et al. (2017) and Prout et al. (2020) suggest a method to assess the structure *vulnerability* of cropped soils.

Their data were collected across a wide range of cropping practices, soil use and seasons. The observed average structure quality was, therefore, the result of their resistance and resilience under multiple stresses, which are key components of soil quality (Seybold et al., 1999). According to Kay (1998), structure vulnerability 'reflects the combined characteristics of resiliency and stability', and stability is the resistance of the structure to stresses. Various authors, including Seybold et al. (1999), have pointed out that vulnerability and structural condition evaluations are two critical components of soil structure assessment. In that respect, one could consider that the different average structural states of soils, delineated by the SOC:clay ratio thresholds identified by Johannes, Weisskopf, et al. (2017), reflect the combination of the resistance and resilience properties of soils (Kay, 1998; Seybold et al., 1999).

From this perspective, Fell et al. (2018), Dupla et al. (2021) and Johannes et al. (2023) proposed that the SOC:clay ratio should be seen as a 'structure vulnerability indicator' (SVI). Hu et al. (2023) recently pointed out that soil structural vulnerability assessments should focus on key soil structural indicators, such as pore network morphology or hydraulic properties. Bulk density is not informative in that context, in spite of what Poeplau and Don (2023) suggest. Moreover, Hu et al. (2023) pointed out a lack of studies demonstrating linkage between soil structural vulnerability and loss of soil functions or ecosystem services, which is consistent with the non-linear relationship between SOC or physical properties and structure quality. The SOC:clay ratio, if used as an SVI, may help to quantify such a link.

As Poeplau and Don (2023) acknowledge, the European Union is currently developing a Soil Health Law as a legal framework to achieve the objectives of the European Soil Strategy. In that respect, it is of key importance to introduce soil health metrics based on soil quality rather than on objectives that merely try to keep up the current situation.

## 2.4 | Observed SOC content is misleading

The indicator proposed by Poeplau and Don (2023) does not refer to soil functions but qualifies the SOC level from 'very good' to 'damaged' according to the current situation that could very well already be SOC depleted. In this respect, we believe that this indicator can be useful in enabling farmers to exchange information on the SOC content of their soils in relation to regional averages. But this should be done with the knowledge that in a context of SOC loss such as observed during the twentieth century, a field can show a locally 'good' SOC content with respect to this index (i.e. with respect to the regional average) and have a SOC content considered too low in terms of the soil's functions.

There is, therefore, disadvantage with this strategy in allowing or hiding a poor and decreasing structure condition. For instance, Dupla et al. (2021) showed that the SOC:clay ratio in the Geneva canton is far below the 'degraded' structure vulnerability threshold for most fields. As an illustration, Figure 1 presents the analyses of the fields from arable land of Geneva canton used in Dupla et al. (2021), with the structure vulnerability thresholds and the quality classes based on the metric introduced by Poeplau and Don (2023). It can be seen that these soils show a very low SOC content on the full clay content range, with an average SOC:clay of 0.06. However, there are examples of fields reaching the 1:8 SOC:clay over the full clay content range. The overall relationship between SOC and clay in this region is SOC = 0.0282.clay + 0.8018 and shows a $R^2$ of .2252, thus presenting a better determined relationship but a very similar slope than illustrated in Poeplau and Don (2023) (0.0282 and 0.0288, respectively).

## 2.5 | From SOC:clay ratio to soil vulnerability assessment

In the arable land of Geneva canton, 100%, 97%, 85% and 46%, of soil falling in the 'Degraded', 'Moderate', 'Good' and 'Very Good' SOC level classes proposed by Poeplau and Don (2023), respectively, are below the 1:13 SOC:clay ratio threshold, and are therefore considered to have vulnerable structure. For the 1:10 threshold, these categories are 100%, 100%, 99% and 83%, respectively. As shown in Dupla et al. (2021), in the neighbouring canton of Vaud, with similar soils but a different agriculture management

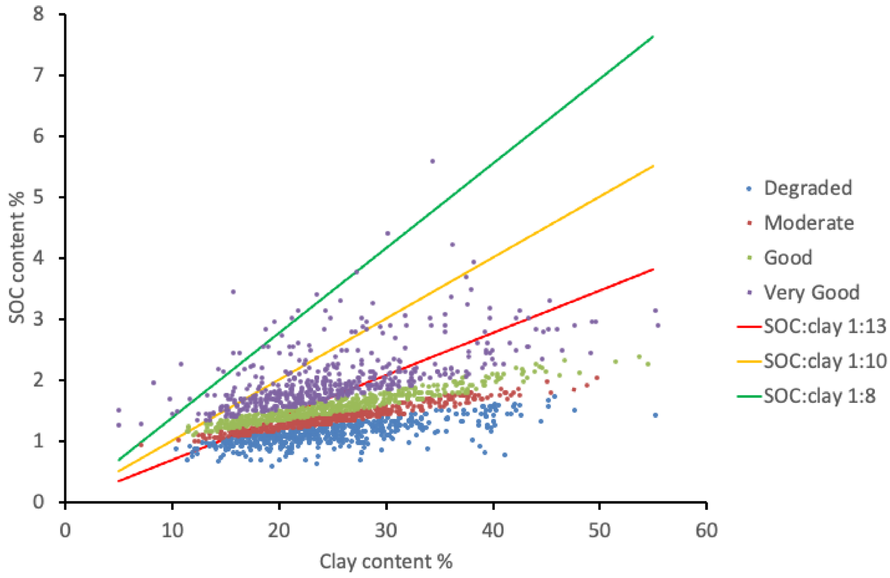


**FIGURE 1** Observed soil organic carbon (SOC) and clay content in % w/w in the fields from Geneva canton arable land. Dots represent the quality based on the SOC metric from Poeplau & Don, 2023. Bold lines represent the structure vulnerability thresholds as introduced in Johannes, Matter, et al., 2017.

history, the SOC:clay ratios are much higher, being typically above 1:13. Using Poeplau and Don's (2023) metric in Geneva state would significantly mislead farmers about their SOC level and structure vulnerability, as many of the 'good' and 'moderate' categories would actually correspond to very high vulnerability, requiring correction by increasing the SOC content.

Introduction of the SVI has made farmers aware of the dramatic condition of their soils. Many stated, however, that even reaching the moderate threshold was not feasible, or that such thresholds were out of reach in clayey soils, which was challenged by the field results presented in Dupla et al. (2022) and Johannes et al. (2023) in their regional surveys, with farmers managing to reach 'very good' SVI in all cases including clayey soils. In fact, Dupla et al. (2022) have shown that SOC levels are affected by agricultural practices and are now increasing rapidly throughout the region, making the 1:10 SOC:clay goal realistic for farmers and agriculture management. The practices identified by Dupla et al. (2022) that could significantly impact SOC change at the regional scale were, unsurprisingly, (i) soil tillage intensity, (ii) cover crops in terms of both duration and diversity and (iii) organic matter application. This is in line with conservation agriculture principles and can be used to assess cropping systems with respect to SOC management.

## 2.6 | Practical implications

Therefore, the observation that soils from some regions show low SOC:clay ratios in no way means that the threshold values are 'strongly biased or misleading'. From an agronomic point of view, this should lead us to question current farming practices, identify pioneering farmers who achieve a good SVI and understand how their practices can be applied more broadly on a larger scale.

Interestingly, Poeplau and Don (2023) presented figures that, though as a minority, show some large SOC:clay even in the large clay content range. The same observation could also be made in the Swiss cropland reported above, and investigating the corresponding farms may facilitate the identification of cropping practices that improve soils (Dupla et al., 2022).

It is clear that certain soil and climate conditions are not suitable for significant increases in SOC content, for example, non-irrigated arid regions. However, we observe a strong tendency to underestimate the achievable SOC level when soils are depleted. If SOC content targets should be adapted, it would require us to carefully address this issue, by investigating the cropping systems with respect to the SOC management principles, and identifying the best practices. This agri-environmental management standpoint should not be confused with the intrinsic response of soil health to the SOC:clay ratio. From a pedological and soil health point of view, observing low SOC values at the regional scale should lead us to assess the structure condition of the corresponding soil groups and reassess the structure vulnerability thresholds if it is shown that the observed structure quality does not match the thresholds published in Johannes, Matter, et al. (2017). From this point of view, the observations on the SOC:clay ratio reported by Poeplau and Don (2023) calls for both agronomical and pedological investigations that have not been carried out so far, before being able to conclude on the usefulness of the SOC:clay ratio.

This leads us to comment on the European Commission's proposal to use the SOC/clay ratio of 1:13 as a threshold for healthy soils. In should be noted that in this proposal, the depth of soil sampled is not defined.

If the soil has been ploughed and sampled within the ploughed layer, the sample depth probably makes no difference as the SOC profile would be fairly homogeneous. However, under reduced tillage and soil regeneration practices, SOC can accumulate nearer the surface. In such cases, the sampling depth is significant, with a larger 0–30 cm layer arguably masking SOC increases of the top 5–10 cm. This presents a dilemma in agri-environmental management regarding the appropriate depth for the 1:13 SOC:clay ratio threshold to be applied to achieve acceptable soil health while avoiding demotivating farmers.

In short, it is important that pedological, agronomic and agri-environmental considerations not be confused when using the SVI index, such as in the articles by Poeplau and Don (2023) or Rabot et al. (2024). This is of special importance given current attempts by the soil science community to raise public awareness about soils, to meet stakeholder expectations and to push for soil functions/services to be accounted for in the context of the UN Sustainable Development Goals (SDGs).

## 3 | CONCLUSIONS

The SOC:clay ratio serves as a SVI that relates to soil functions, independently of local SOC distribution, which is influenced by historical cultivation practice. Although the SOC:clay thresholds for assessing structural vulnerability are certainly not applicable across all soil types, they can be tailored by examining the relationship between average structure quality and the SOC:clay ratio in cultivated land. Such a reassessment cannot be based on physical properties proportional to SOC content whose lack of relevance in characterizing the soil structure condition was recognized long ago.

In specific regions, agro-climatic conditions may limit increases in SOC. However, this should not be concluded until the cropping practices have been examined in light of Conservation Agriculture principles and exemplary farms identified. This approach could lead to a temporary adaptation of SOC objectives to achievable targets, which is not a soil health consideration but an agri-environmental management consideration.

On the other hand, the use of SOC level indicators based on observed local distributions of SOC lacks a fundamental basis. Such an approach could potentially be misleading to farmers and stakeholders regarding the context of general SOC decline over time. Furthermore, it may inaccurately classify very poor soil conditions as ‘good’ or ‘very good’. Therefore, we conclude that it should not serve as an alternative to the SOC:clay ratio as an indicator of soil status.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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