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Relevance of the organic carbon to clay ratio as a national soil health indicator

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ABSTRACT

The soil organic carbon (SOC) to clay-sized particles ratio (SOC/clay) has recently been selected as an indicator of the soil organic matter status in managed mineral soils within the framework of the European Soil Monitoring Law proposal. This indicator was initially developed to predict soil structural quality in a local study in Switzerland and was subsequently tested at national scales in England and Wales, and in Germany. In this study, we evaluated if the SOC/clay ratio was relevant to assess the structural quality of soils at the national scale in mainland France. We additionally evaluated its variant, SOC/(silt < 20 μm + clay). We confronted SOC/clay and SOC/(silt < 20 μm + clay) to two indicators of soil structure, the soil bulk density and aggregate stability, and we tested the effect of land use and soil type using information from the French Soil Quality Monitoring Network (RMQS). We showed that the SOC/clay and SOC/(silt < 20 μm + clay) were poor indicators of the soil bulk density and aggregate stability. In our analysis, the SOC content was the best indicator of soil structure. Both land use and soil type had an effect on the SOC/clay value. SOC/clay was found to be strongly affected by soil pH with acidic soils consistently being classified as healthy according to the threshold of 1/13 and alkaline soils often being classified as unhealthy. The domain of applicability of SOC/clay excludes soils involving other SOC stabilization mechanisms than associations with the clay fraction and climate is not taken into account. Based on the RMQS dataset, 63 % of cropland, 81 % of permanent crop and 23 % of grassland soils were below the SOC/clay threshold of 1/13, which would classify them as unhealthy according to the European Soil Monitoring Law. We questioned the relevance of the SOC/clay ratio and its proposed threshold of 1/13 as a soil structure indicator, and more broadly as an indicator of the SOC status of healthy soils for all European pedoclimatic contexts. The Soil Monitoring Law leaves the possibility of using correction factors for specific soil types or climatic conditions, which appears necessary for France, because some pedoclimatic contexts will never allow a satisfactory value to be reached.

1. Introduction

There is an increasing demand for simple indicators to assess soil health, from the field scale for farmers to evaluate the effect of their management practices, to the national scale for countries to report the current status of their soils. In particular, the soil organic carbon (SOC) to clay-sized particles ratio (SOC/clay) has been selected as an indicator of SOC status in managed mineral soils (i.e., soils with SOC content < 20 %) at the European Union level, to be used within the framework of the European Soil Monitoring Law proposal (COM(2023) 416 final). To be considered in a healthy condition, mineral soils must present a SOC/clay greater than 1/13, with the possibility of a correction factor being applied for specific soil types or climatic conditions. Although it is referred to as a “loss of SOC” indicator in the Soil Monitoring Law, the SOC/clay ratio has originally been developed as an indicator of soil structural quality. Because the fine fraction (clay or silt + clay) was observed to contribute to SOC protection either directly via organo-mineral interactions, or indirectly via the formation of aggregates (von

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Lützow et al., 2006), it seems reasonable to explore whether this ratio can be used as an indicator of the SOC status, for example like in Dupla et al. (2021).

The rationale for using the SOC/clay indicator to assess soil structure originates from Dexter et al. (2008) who developed the concept of "complexed organic carbon" (COC). COC is assumed to reflect the fraction of SOC associated with clay-sized particles. This concept implies that SOC is entirely complexed by clay when the SOC content is lower than clay/*n*, with *n* close to 10 for the studied soils (here, clay and SOC contents in mass units). When the SOC content is lower than clay/*n*, a part of the clay fraction is considered not to be associated with carbon and contributes to the measured values of dispersible clay (Dexter et al., 2008; Schjønning et al., 2012). Indeed, Schjønning et al. (2012) and Getahun et al. (2016) found a correlation between the calculated non-complexed clay content and the measured dispersible clay content. High values of dispersible clay denote a low structural stability in water (Czyż and Dexter, 2015). Conversely, when SOC content is higher than clay/*n*, the COC concept implies that a fraction of SOC is not complexed and would occur in the form of particulate organic matter and that soils have reached their minimum level of dispersible clay. In other words, the theory of Dexter et al. (2008) postulates that 10 g clay allow complexing 1 g SOC for the studied soils. Therefore, several authors investigated if a SOC/clay value of 1/10 could be a target value for good soil structure. Johannes et al. (2017a) concluded that SOC/clay ratios of 1/8, 1/10 and 1/13 were appropriate thresholds to distinguish very good, good, moderate and degraded soil structures as determined by a visual evaluation of soil structure (CoreVESS method, Johannes et al., 2017b). The same conclusion was reached by Prout et al. (2021), using an index of soil structural quality based on the shape and size of aggregates and soil texture, although their statistical analysis using boxplots indicated some overlaps between the different classes of soil structural quality. De Jonge et al. (2009) found that soils with SOC/clay $> 1/10$ showed favorable tilth conditions, contrary to soils with SOC/clay $< 1/10$. Dupla et al. (2021) referred to the SOC/clay ratio as the "structure vulnerability indicator" and calculated the amount of SOC necessary to reach the ratio of 1/10. In these studies, an effect of land use has been identified on the proportion of soils classified as degraded, croplands exhibiting a higher proportion of sites with SOC/clay $< 1/13$ as compared to grasslands and forests (Johannes et al., 2017a; Poeplau and Don, 2023; Prout et al., 2021).

The SOC/clay indicator has been used at the national scale in Poland and in Northern France (Dexter et al., 2008), in England and Wales (Prout et al., 2022, 2021), in Germany (Poeplau and Don, 2023), at the regional scale in Switzerland (Dupla et al., 2021; Guillaume et al., 2022; Johannes et al., 2023, 2017a) and in England (Pulley et al., 2023), or at the plot scale in Denmark (de Jonge et al., 2009; Getahun et al., 2016; Schjønning et al., 2012) or in Turkey (Çelik et al., 2020). However, divergent conclusions were drawn about its relevance as an indicator of soil structural quality. In their study at the national scale, Prout et al. (2021) used the threshold values developped in a local study in Switzerland by Johannes et al. (2017a). Prout et al. (2021) validated the threshold values for England and Wales and further suggested that they may apply in similar climate zones across Europe. Conversely, Poeplau and Don (2023) considered that the SOC/clay ratio was not a satisfactory indicator in their national study of croplands and grasslands in Germany, with the example of Chernozems – whose structure is known to be good – mostly classified as having a moderate to degraded structure according to the SOC/clay indicator.

Given all the factors which were identified to control SOC dynamics at different spatial scales (O'Rourke et al., 2015; Wiesmeier et al., 2019), it is necessary to further verify if the SOC/clay indicator is relevant to assess soil structural quality at a national scale in other pedoclimatic contexts. Since SOC may also be associated with the fine silt fraction (von Lützow et al., 2006), this analysis was extended to its variant, the SOC/(silt < 20 µm + clay) ratio (Schjønning et al., 2012). The use of SOC/clay or SOC/(silt < 20 µm + clay), hereafter referred to as SOC indicators, to assess the soil structural quality imply that they show a strong relationship with indicators of soil structure. We tested this hypothesis at the national scale in mainland France by using information from the French Soil Quality Monitoring Network (RMQS). We used two quantitative indicators of soil structure, bulk density and aggregate stability, representing two different structural scales (soil samples of a few hundred cm^3 vs. ten mm^3) with implications on the range of processes involved in soil structure formation and stabilization. Both bulk density and aggregate stability are affected by SOC and clay contents (e.g., Arbor et al., 2023; Le Bissonnais and Arrouays, 1997; Nasta et al., 2020; Regelink et al., 2015). Given the diversity of situations covered by the RMQS and the expected significant differences in soil structure between land uses and soil types, we further tested whether there was an effect of land use and soil type on SOC/clay and SOC/(silt < 20 µm + clay). As the SOC/clay ratio is one of the soil health indicators chosen by the European Commission in the European Soil Monitoring Law, we quantified the proportion of soils that would be in an unhealthy condition in France, according to the proposed threshold of SOC/clay.

2. Material and methods

2.1. The RMQS database

We used topsoil data from the French Soil Quality Monitoring Network (RMQS, https://doi.org/10.15454/QSXKGA). This network represents about 2,200 sites sampled following a 16 × 16 km^2 regular grid across mainland France. At each site, a first set of measurements was made using a composite sample based on 25 individual cores, sampled with a soil auger from 0 to 30 cm, according to an unaligned random sampling design within a 20 × 20 m^2 area (Jolivet et al., 2022). Core samples were then bulked and the resulting composite samples were air-dried and sieved to 2 mm before analysis. Particle-size distribution in five fractions (<2, 2–20, 20–50, 50–200, 200–2,000 µm; pipette method associated with wet sieving, without removing carbonates, NF X31-107), pH in water (1/5 suspension of soil in water, ISO 10390), calcium carbonate content ($CaCO_3$; volumetric method, ISO 10693), SOC content (elemental analysis after dry combustion and correction for $CaCO_3$ content, ISO 10694) and cation exchange capacity (CEC; hexamminecobalt(III) chloride method, NF X31-130) were analyzed, among others (Jolivet et al., 2006). The second set of observations was collected on an adjacent pit, where soil bulk density was measured according to the ring method or the excavation method on three samples distributed vertically between 0 and 30 cm depth (Jolivet et al., 2022). Because the bulk density of the fine earth was not measured, we only used bulk density values of sites with rock fragment content < 20 % in the analysis involving bulk density (1,345 sites). In the following, the land uses of the RMQS sites were simplified into four classes: croplands, permanent crops (i.e., orchards, vineyards, olive groves), grasslands and forests (Fig. 1). A few sites fell outside of these classes and were discarded from the analysis. All the remaining sites could be considered as mineral soils (SOC content < 20 %). In the database, soils of the RMQS are named following the French classification system (Baize and Girard, 2008). In this study, we grouped them into ten classes, differing in terms of SOC stabilization mechanisms. The correspondence in the WRB classification (IUSS Working Group WRB, 2022) is as follows: Al-dominated soils [Podzols, Andosols, Umbrisols except those with qualifier Folic], Ca/Mg-dominated soils [Rendzic Leptosols, Cambisols with qualifiers Calcaric, Hypereutric, Dolomitic or Magnesic], organic matter-rich soils [Histosols, Folic Umbrisols], water-saturated soils [Gleysols, Stagnosols, Planosols], clay-rich soils [Regosols (Clayic), Cambisols (Clayic), Vertisols], sandy or stony soils [Arenosols, soils with qualifier Skeletic], tidal water-affected soils [Tidalic Fluvisols], other Cambisols [Cambisols except those with qualifiers Calcaric, Hypereutric, Dolomitic, Magnesic or Clayic] and Luvisols. Soils with strong human influence [Anthrosols and Technosols] and soils having Solimovic material were excluded from the analysis implying

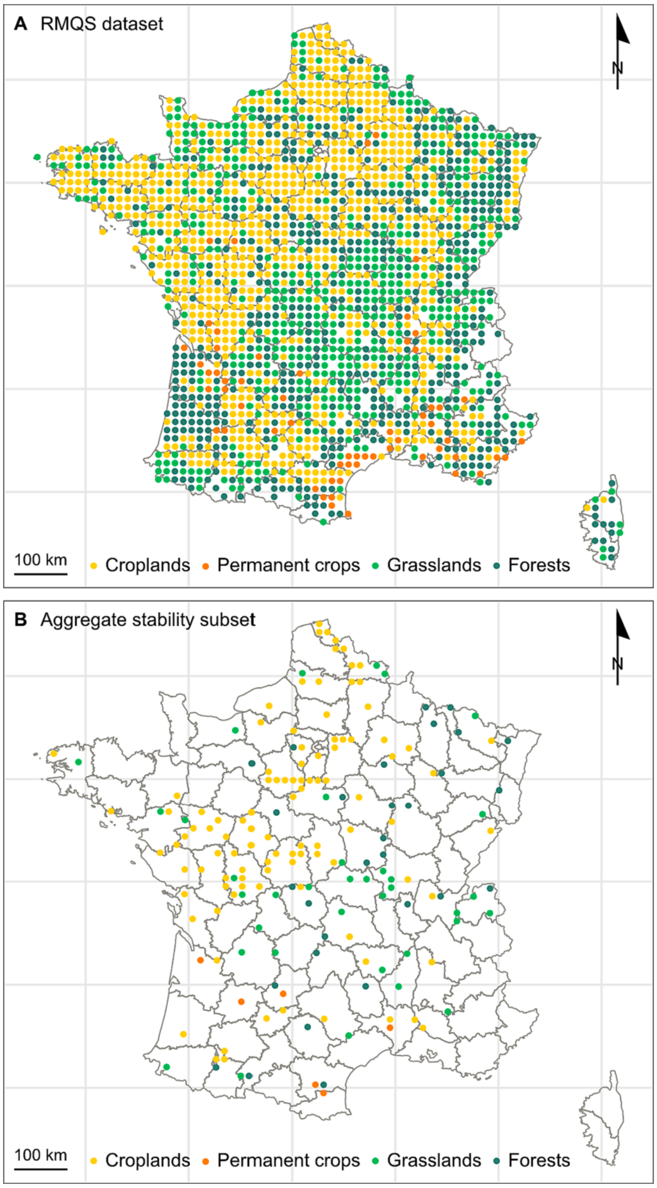

Fig. 1. (A) RMQS sites simplified in four land use classes and (B) RMQS sites with aggregate stability measurements.

grouped soil types.

On a subset of 174 RMQS sites, aggregate stability was measured using the fast wetting method of Le Bissonnais (1996) (ISO 10930) on additional soil samples collected at the surface of the soil profiles (Fig. 1B). The subset included 102 croplands, 6 permanent crops, 36 grasslands and 30 forests. Following this method, air-dried samples were manually broken and manually sieved to keep aggregates of 3 to 5 mm in diameter. Aggregates were dried at 40 °C for 24 h just before starting the aggregate stability test. 5 g of aggregates were immersed in deionized water for 10 min. The fragment size distribution was then measured first using a sieve of 50 μm immersed in ethanol. The > 50 μm fraction was oven-dried and manually dry sieved using 2,000 μm, 1,000 μm, 500 μm, 200 μm, 100 μm and 50 μm sieves. Each size fraction was weighted and the result of the test was expressed as the mean weight diameter (MWD). MWD was calculated by summing the product of the mean diameter of each size class by the relative proportion of aggregates in that size class. The test was replicated three times for each RMQS site and the MWD value was averaged. The larger the MWD, the higher the aggregate stability: very unstable for MWD < 0.4 mm, unstable for MWD between 0.4 and 0.8 mm, medium stability for MWD between 0.8 and 1.3 mm, stable for MWD between 1.3 and 2.0 mm and very stable for MWD > 2.0 mm (Le Bissonnais, 1996).

2.2. *Data analyses*

Four indicators were tested in relation to soil structural properties: the SOC content, clay content, SOC/clay ratio and SOC/(silt < 20 μm + clay) ratio. Simple linear regressions or non-linear regressions were used to highlight potential relationships with soil structural properties for each land use class. We evaluated regression quality using the root-mean-square error (RMSE, eq. 1):

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2} \qquad (1)$$

where y_i and $\hat{y}_i$ are measured and predicted values for site i and n is the number of observations. For simple linear regressions, we also used the coefficient of determination (r^2). Fits were only shown in the figures when $r^2 > 0.55$ and RMSE < 1 for linear regressions and when a trend was sufficiently marked to choose an appropriate function for non-linear regressions. Outlier detection was used to better understand the domain of applicability of the SOC indicators and was performed for linear relationships on each land use class. Outlier detection used the Cook's distance method of the R package "performance" (Lüdecke et al., 2021). When detected, outliers were not removed from the analyses. The effect of the four land uses and soil types on soil properties and SOC indicators were assessed by using the nonparametric test of Kruskal-Wallis, followed by Dunn's multiple comparisons with Bonferroni correction, at the $p = 0.001$ level. Only grouped soil types with more than 20 sites were included in the Kruskal-Wallis test. All statistical analyses were performed using the R software (R Core Team, 2022).

3. Results and discussion

3.1. *Link between the SOC indicators tested and soil structure indicators*

3.1.1. *Bulk density*

There were no significant relationship between SOC/clay or SOC/(silt < 20 μm + clay) and bulk density for sites with rock fragment content < 20 % in croplands and forests (Fig. 2A and B). For grasslands, points were distributed in a vertical fashion for SOC/clay < 1/13 or SOC/(silt < 20 μm + clay) < 1/20 (Fig. 2A and B). For higher values of SOC/clay or SOC/(silt < 20 μm + clay), the distribution became more horizontal and the dispersion increased. A function of the form $y = 1/(a \times x) + b$ could be fitted for grasslands, with a RMSE of 0.28 using SOC/clay as the explanatory variable and a RMSE of 0.25 using SOC/(silt < 20 μm + clay). A fair decreasing linear relationship was found with clay content in croplands, grasslands and forests (Fig. 2C). Bulk density was better described by SOC content, where a function of the form $y = -a \times \ln(x) + b$ could be fitted for croplands, grasslands and forests (Fig. 2D). Using SOC content as the explanatory variable, the RMSE was 0.16 for forests and 0.12 for croplands and grasslands. It has to be noted that in this study, we did not attempt to find the best possible pedotransfer function to predict bulk density, which might depend on other soil properties and textural class.

The thresholds of 1/8, 1/10 and 1/13 suggested by Johannes et al. (2017a) and the threshold of 1/20 suggested by Schjønning et al. (2012) were represented as vertical dotted lines in Fig. 2A and B. These thresholds did not appear to be effective in linking SOC/clay nor SOC/(silt < 20 μm + clay) to bulk density. Indeed, the distribution being very vertical around these thresholds for each land use, the bulk densities spanned for SOC/clay = 1/8 were similar to those spanned for SOC/clay = 1/13.

In their study, Dexter et al. (2008) used a subset of the RMQS dataset corresponding to topsoils of croplands and grasslands in Northern

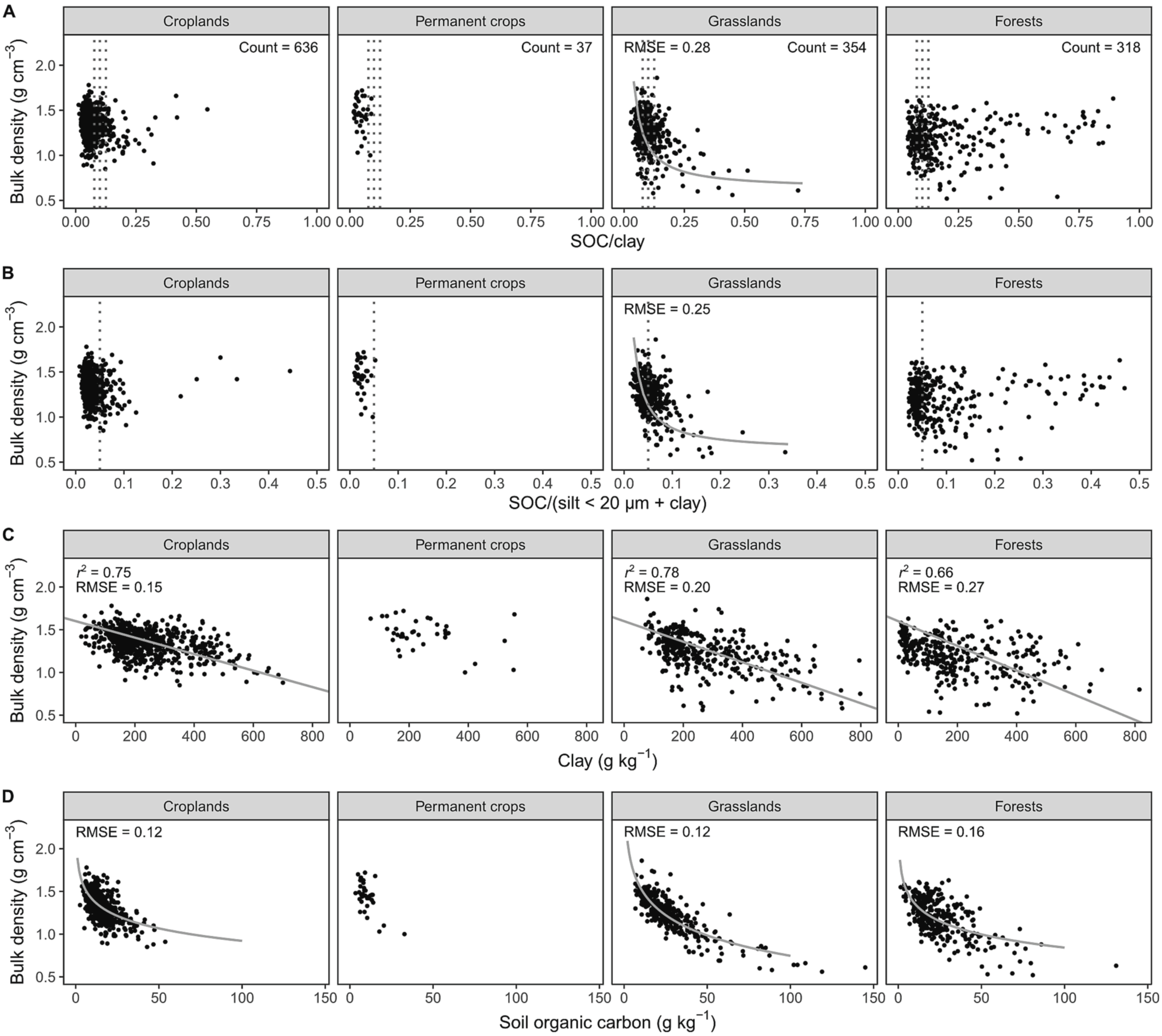

Fig. 2. Bulk density as function of (A) soil organic carbon to clay ratio, (B) soil organic carbon to silt < 20 µm + clay ratio, (C) clay content and (D) soil organic carbon content, for topsoils of the RMQS dataset with rock fragment content < 20 %. Functions plotted in blue correspond to (A and B) $y = 1/(a \times x) + b$, (C) $y = a \times x + b$ and (D) $y = -a \times \ln(x) + b$. Vertical dotted lines represent the thresholds of 1/8, 1/10 and 1/13 suggested in Johannes et al. (2017a) and the threshold of 1/20 in Schjønning et al. (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

France. They found that the inverse of bulk density was better explained by SOC content for croplands because of their low levels of SOC. The inverse of bulk density was better explained by clay content for grasslands because of their greater SOC contents. Our results did not support this finding since bulk density appeared to be explained by both the SOC and clay contents when considering the whole mainland France (Fig. 2C and D). Johannes et al. (2023, 2017a), for soils with a large range of clay contents, also found that SOC content was a better explanatory variable of soil bulk density and of some other physical properties (i.e., gravimetric water content and air content at −100 hPa) than SOC/clay.

3.1.2. *Aggregate stability*

A linear relationship was found between aggregate stability (MWD) and SOC/clay and SOC/(silt < 20 µm + clay) in croplands and permanent crops and in grasslands (Fig. 3A and B). The quality of the regression was better when considering only SOC content or clay content for croplands and permanent crops ($r^2 = 0.78$, RMSE = 0.41 for both, Fig. 3C and D). All indicators seemed less efficient for use in grasslands and forests than in croplands and permanent crops, meaning that the link with MWD could only be valid for croplands and permanent crops (Fig. 3). A higher content of particulate organic matter in forests and grasslands may explain this observation. According to Guillaume et al. (2022), the fact that the amount of SOC in particulate organic matter does not increase proportionally with the clay content may be a limitation of using the SOC/clay ratio as an indicator of soil physical quality in organic carbon-rich soils. Moreover, other soil properties than SOC and clay contents would have to be taken into account to better model MWD. Clay mineralogy, the content, type and concentration of cations, and sesquioxide and $CaCO_3$ contents are also known to affect aggregate stability (Le Bissonnais, 1996).

The thresholds of 1/8, 1/10 and 1/13 suggested by Johannes et al. (2017a) and the threshold of 1/20 suggested by Schjønning et al. (2012)

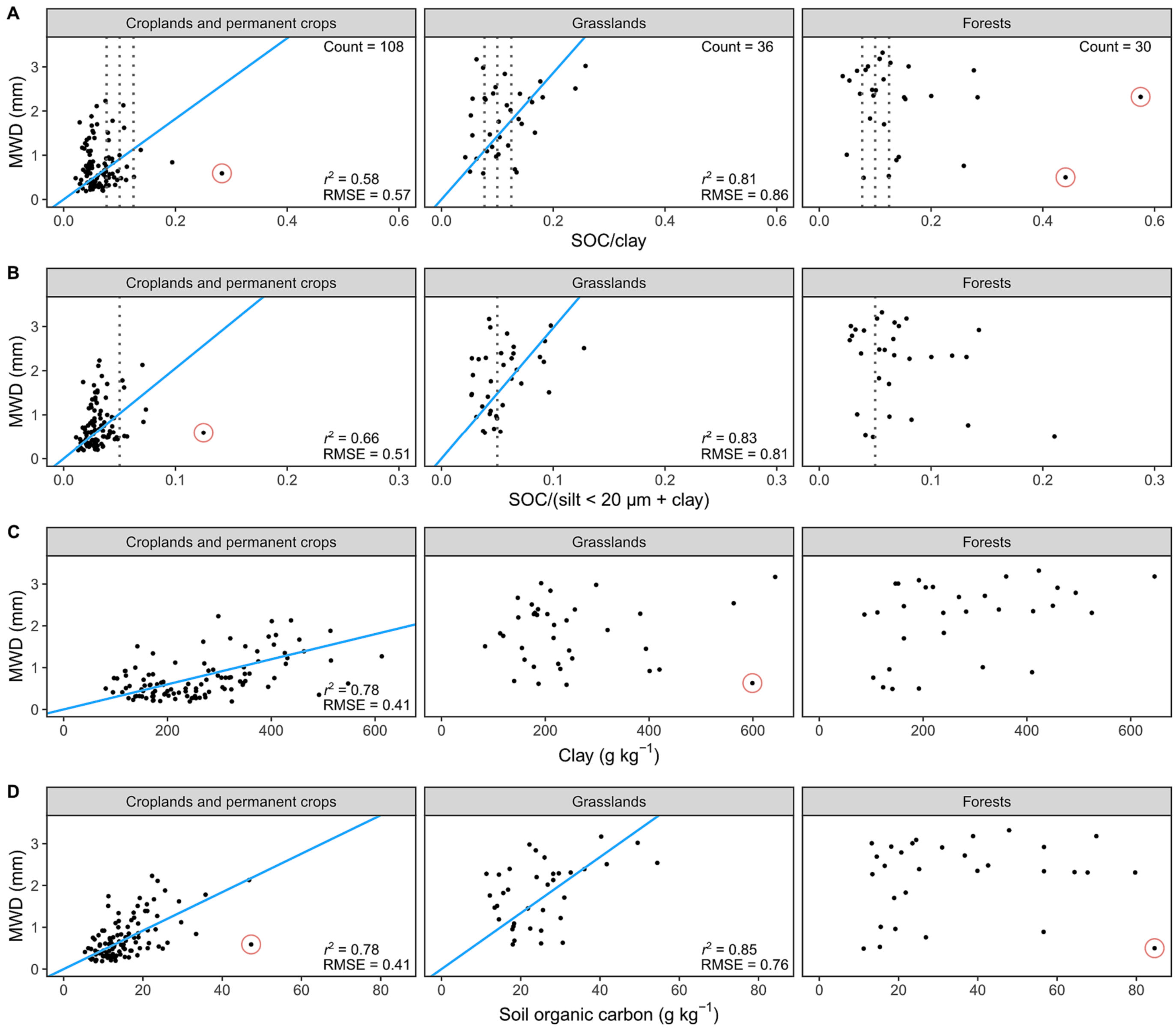

Fig. 3. Mean weight diameter (MWD) as function of (A) soil organic carbon to clay ratio, (B) soil organic carbon to silt < 20 μm + clay ratio, (C) clay content and (D) soil organic carbon content, in the topsoil of the RMQS dataset. Solid blue lines represent linear regressions. Outliers are indicated by a circle. Vertical dotted lines represent the thresholds of 1/8, 1/10 and 1/13 suggested in Johannes et al. (2017a) and the threshold of 1/20 in Schjønning et al. (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

were represented as vertical dotted lines in Fig. 3A and B. These thresholds did not appear satisfying to discriminate different values of MWD. This observation is in line with the large overlaps found in the studies of Johannes et al. (2017a) and Prout et al. (2021) when representing their qualitative soil structural quality assessments as boxplots.

The same RMQS sites were identified as outliers for SOC/clay and SOC/(silt < 20 μm + clay) (Fig. 3). One site under cropland is a Cambisol (IUSS Working Group WRB, 2022) with a silty texture and a high SOC content (SOC = 47.3 g kg^{-1}, clay = 167 g kg^{-1}, silt = 548 g kg^{-1}, pH = 5.9). Two additional outliers are very sandy forest soils, one being classified as a Podzol and the other one as an Umbrisols (Hyperdystric) (IUSS Working Group WRB, 2022). They have a high SOC content relative to their clay content and a pH in water of 4.2. Two of these sites were also identified as outliers for SOC content with the Cook's distance method, one in croplands and another one in forests (Fig. 3).

3.1.3. *Soil structure indicators*

There is no universally accepted way to characterize soil structure (Díaz-Zorita et al., 2002). In the original study of Johannes et al. (2017a), the SOC/clay ratio was compared with a semi-quantitative indicator of the soil structural quality, the CoreVESS score (Johannes et al., 2017b). The CoreVESS method is an adaptation for the laboratory of the Visual Evaluation of Soil Structure (VESS) field method (Ball et al., 2007; Guimarães et al., 2011). CoreVESS is applied to smaller soil samples than VESS. Therefore, only the evaluation criteria of the VESS method that could be observed on soil cylinders of approximately 150 cm^3 were kept in CoreVESS. This method has not been widely used yet but appeared to be appropriate to detect the degradation of soil structural porosity (Johannes et al., 2017b; Lin et al., 2022). In our national scale study, we used two available quantitative indicators of soil structure, bulk density and aggregate stability (measured using a fast wetting method). According to the literature, the CoreVESS method seems to be related to these two indicators of soil structure. Indeed, an increasing linear relationship was consistently found between the CoreVESS score and bulk density (Cornelis et al., 2019; Johannes et al., 2017b; Lin et al., 2022; Mutuku et al., 2021). A negative relationship was also found with the MWD, but in pedoclimatic contexts different than France (Cornelis et al., 2019; Mutuku et al., 2021). For this reason, we think that using bulk density and MWD to assess the relevance of SOC/clay and SOC/(silt < 20 µm + clay) was a reliable approach. In our study, bulk density and MWD were found to be related to SOC and clay contents (Fig. 2C and D and Fig. 3C and D), which was consistent with previous studies about aggregate stability (Le Bissonnais and Arrouays, 1997; Regelink et al., 2015) and bulk density (see pedotransfer functions cited in Arbor et al., 2023; Nasta et al., 2020). In particular, the relationship between bulk density and SOC content was non-linear and the relationship with clay content was linear (Fig. 2C and D). In the literature, a fair positive linear relationship was found between the CoreVESS score and SOC content across the CoreVESS range (Cornelis et al., 2019) or only for scores ranging from 1 to 3 (i.e., high structural quality) (Johannes et al., 2017b). A weak negative relationship (Lin et al., 2022) or no relationship (Johannes et al., 2017b, 2023) was found with clay content. Therefore, dividing the SOC content by the clay content may have little influence on the results when SOC/clay is confronted to the CoreVESS score as compared to SOC content alone. On the contrary, this division strongly affects the results when looking for relationships between SOC/clay and bulk density, since bulk density is related to SOC content by a non-linear relationship and to clay content by a linear relationship.

Bulk density varies over time depending on agricultural field operations and depends on the soil water content during sampling. In the RMQS dataset, bulk density was measured when the soil water content was close to field capacity and when the soil has naturally compacted after cultivation operations (Jolivet et al., 2022). In this respect, the CoreVESS protocol is more rigorous, because it takes into account volume changes in swell-shrinking soils by first equilibrating free to swell samples at a given matric potential. Aggregate stability tests also have their limitations, the main being that the results are highly sensitive to the protocol used (Díaz-Zorita et al., 2002). In the RMQS dataset, this drawback was taken into account by following an ISO protocol for the MWD determination. Using a different aggregate stability test could have given different results in terms of MWD because different mechanisms of aggregate breakdown, such as slaking, differential swelling or raindrop impact, could be involved depending on the initial soil water content, rate of wetting and energy applied (Le Bissonnais, 1996). In the fast wetting method used in this study, immersion in water of dry aggregates mimics a heavy rain and favors aggregate breakdown by slaking, i.e., aggregate breakdown caused by the compression of entrapped air during wetting (Le Bissonnais, 1996).

We found that SOC/clay and SOC/(silt < 20 µm + clay) were not good indicators of the soil bulk density and aggregate stability, while the SOC content was a much better predictor. It leads us to question the use of the SOC/clay ratio as one of the indicators of soil health in managed ecosystems, as proposed in the Soil Monitoring Law proposal.

3.2. *Current situation in France*

3.2.1. *Effect of land use on the SOC indicators tested and on soil properties*

Descriptive statistics are presented in Table 1 for each land use to show the range of variation of different soil properties, SOC/clay and

Table 1

Overview of soil properties for four land uses in the topsoil of the RMQS dataset and its aggregate stability subset (SOC: soil organic carbon content, CEC: cation exchange capacity, MWD: mean weight diameter). Different letters indicate significant differences among the four land uses.

		RMQS dataset				Aggregate stability subset			
		Croplands	Permanent crops	Grasslands	Forests	Croplands	Permanent crops	Grasslands	Forests
	Count	878	59	521	581	102	6	36	30
SOC (g kg^{-1})	Mean	17^{a}	12^{b}	29^{b}	34^{b}	16^{a}	10^{a}	25^{b}	36^{b}
	Median	15	9	25	27	14	8	24	26
	Min.	3	3	7	1	5	7	11	11
	Max.	58	39	145	159	47	21	54	85
Clay (g kg^{-1})	Mean	244^{a}	252^{ab}	262^{a}	228^{b}	257^{a}	286^{a}	252^{a}	278^{a}
	Median	217	223	214	189	242	298	213	240
	Min.	19	56	62	2	81	125	84	87
	Max.	700	591	798	815	613	463	643	646
SOC/clay	Mean	0.079^{a}	0.054^{b}	0.126^{c}	0.231^{d}	0.067^{a}	0.036^{a}	0.112^{b}	0.150^{b}
	Median	0.067	0.045	0.107	0.139	0.058	0.036	0.102	0.114
	Min.	0.012	0.012	0.028	0.037	0.029	0.021	0.043	0.042
	Max	0.546	0.162	0.721	9.000	0.283	0.052	0.258	0.575
SOC/(silt + clay)	Mean	0.038^{a}	0.029^{a}	0.063^{b}	0.122^{c}	0.032^{a}	0.018^{a}	0.055^{b}	0.079^{b}
	Median	0.032	0.023	0.054	0.070	0.028	0.017	0.049	0.063
	Min.	0.008	0.009	0.014	0.022	0.012	0.011	0.027	0.027
	Max.	0.444	0.087	0.334	6.000	0.125	0.028	0.128	0.310
pH water	Mean	7.0^{a}	7.6^{a}	6.3^{b}	5.6^{c}	7.1^{a}	7.7^{a}	6.2^{ab}	5.6^{b}
	Median	7.0	8.1	5.9	4.9	7.3	8.3	5.9	4.9
	Min.	4.5	4.9	4.5	3.7	5.1	6.0	4.9	4.0
	Max.	8.6	8.7	8.6	8.5	8.3	8.6	8.3	8.0
CEC (cmol^{+} kg^{-1})	Mean	14.0^{a}	14.6^{a}	14.5^{a}	13.4^{b}	15.2^{a}	14.2^{a}	12.8^{a}	15.4^{a}
	Median	11.8	13.1	10.0	6.3	14.0	14.1	9.4	7.2
	Min.	1.0	3.6	0.8	0.2	2.6	3.9	3.5	2.1
	Max.	59.6	39.3	63.5	70.1	41.1	24.2	40.3	54.1
$CaCO_3$ (g kg^{-1})	Mean	72^{a}	111^{a}	35^{b}	34^{b}	58^{a}	178^{a}	40^{a}	36^{a}
	Median	1.0	23.5	0.5	0.5	1.4	189	0.5	0.5
	Min.	0	0	0	0	0	0	0	0
	Max.	866	451	706	739	866	416	646	531
Bulk density (g cm^{-3})	Mean	1.4^{a}	1.5^{a}	1.3^{b}	1.2^{b}	1.4^{a}	1.6^{a}	1.3^{ab}	1.1^{b}
	Median	1.4	1.5	1.3	1.2	1.4	1.6	1.3	1.1
	Min.	0.8	1.0	0.4	0.5	0.8	1.4	0.9	0.7
	Max.	2.0	2.0	2.0	1.9	1.8	1.7	1.7	1.6
MWD (mm)	Mean					0.7^{a}	0.5^{a}	1.8^{b}	2.2^{b}
	Median					0.6	0.4	1.9	2.4
	Min.					0.2	0.2	0.6	0.5
	Max.					2.2	1.4	3.2	3.3

SOC/(silt < 20 μm + clay) in the RMQS dataset. We observed significant differences at $p < 0.001$ between all land uses in the indicators SOC/clay and SOC/(silt < 20 μm + clay), except for SOC/(silt < 20 μm + clay) in croplands and permanent crops.

We used the thresholds of SOC/clay of 1/8, 1/10 and 1/13 suggested by Johannes et al. (2017a) to visualize SOC content as a function of clay content for the four land uses (Fig. 4). The majority of sites in croplands and permanent crops had a SOC/clay ratio < 1/13 (Fig. 4). A majority of forest sites had a SOC/clay > 1/8. The grassland sites were more evenly distributed between the different classes of SOC/clay. A majority of sites in croplands and permanent crops presented a SOC/(silt < 20 μm + clay) ratio < 1/20 (Fig. 4). Conversely, a majority of forest sites had a SOC/(silt < 20 μm + clay) > 1/20. The grassland sites were more evenly distributed.

63 % of cropland, 81 % of permanent crop, 23 % of grassland and 13 % of forest soils showed a SOC/clay < 1/13, so their soil structure would be classified as degraded. The proportion of degraded cropland soils was much higher than in other national-scale studies. In England and Wales, croplands also exhibited a higher proportion of sites with SOC/clay < 1/13, but these sites represented only 38.2 % of the studied sites (Prout et al., 2021). For ley grass, 15 % of the sites had a SOC/clay < 1/13, 6.6 % for permanent grass and 5.6 % for forests (Prout et al., 2021). In Germany, 37 % of cropland and 14 % of grassland soils were found to have a SOC/clay < 1/13 (Poeplau and Don, 2023). Our data show that grassland and forest soils have a smaller proportion of sites with SOC/clay < 1/13 than croplands. According to Prout et al. (2021), this trend supports the use of SOC/clay = 1/13 as an indicative threshold for soil degradation, as grassland and forest soils are generally close to semi-natural systems.

3.2.2. Effect of soil type on the SOC indicators tested

The Kruskal-Wallis test showed a significant difference on SOC/clay and SOC/(silt < 20 μm + clay) depending on our grouped soil types ($p < 0.001$). A summary of the post-hoc Dunn's multiple-comparison test is given in Table 2 for SOC/clay. Distinct groups were found for each land use, from a tendency to high SOC/clay ratios in Al-dominated soils or Leptosols, to low SOC/clay ratios in Ca/Mg-dominated soils. Results were different depending on the land use considered (Table 2). It shows that there is an effect of both land use and soil type on the SOC/clay value.

We represented the SOC content as a function of clay content with the thresholds of 1/8, 1/10 and 1/13 suggested by Johannes et al. (2017a) for each of the grouped soil types and land uses in Fig. 5. The majority of sites classified as Al-dominated soils and Leptosols had a SOC/clay ratio > 1/8 in all land uses (Fig. 5). Podzols were also found to have SOC/clay > 1/8 in the national scale studies of England and Wales (Prout et al., 2021) and Germany (Poeplau and Don, 2023). Interactions of SOC with aluminum and iron contributes to SOC stabilization in Podzols (von Lützow et al., 2006), leading to high SOC content for a given clay content. It is known that, in Andosols, the dominance of highly reactive short-range-order minerals such as allophane also lead to store high amounts of SOC (Kögel-Knabner and Amelung, 2021). Because of high agricultural constraints Al-dominated soils and Leptosols were in majority not cultivated. SOC/clay was < 1/13 in croplands and permanent crops for only 8 % of Al-dominated soils and 13 %

Table 2
Summary of the Dunn's multiple-comparison test for Kruskal-Wallis analysis of variance on ranks. Groups of soil types followed by the same letter are not significantly different at the $p = 0.001$ level with respect to their soil organic carbon to clay ratio.

	Croplands, permanent crops	Grasslands	Forests
Al-dominated soils	a	ab	a
Leptosols	abc	a	ab
Other Cambisols	ab	ab	bc
Water-saturated soils	bc	abc	bcd
Luvisols	c	bc	cd
Ca/Mg-dominated soils	d	c	d

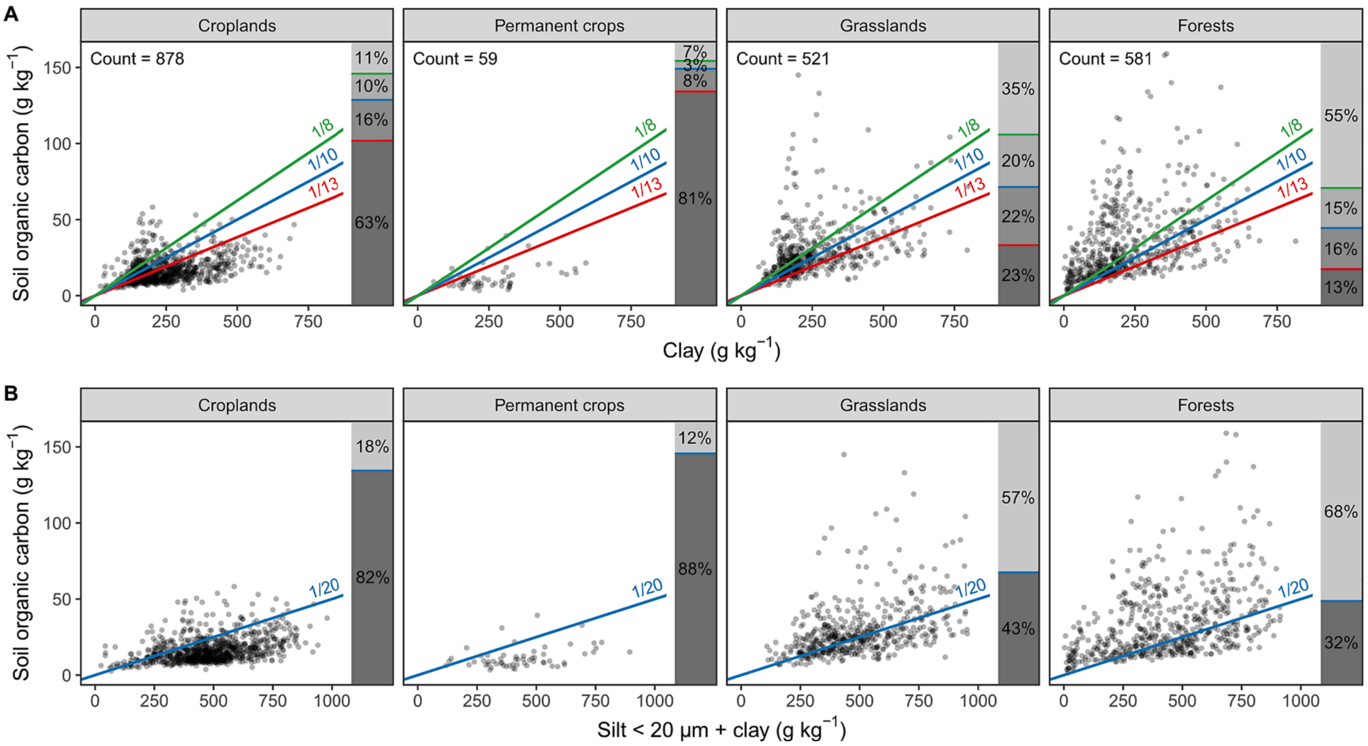

Fig. 4. Soil organic carbon content as a function of (A) clay content and (B) silt < 20 μm + clay content in the topsoil of the RMQS dataset for different land uses. The thresholds of 1/8, 1/10 and 1/13 are suggested in Johannes et al. (2017a) and the threshold of 1/20 in Schjønning et al. (2012). On the right side of each plot, the percentage of sites in each soil structural quality class is given, from the best soil structural quality at the top to the worst at the bottom.

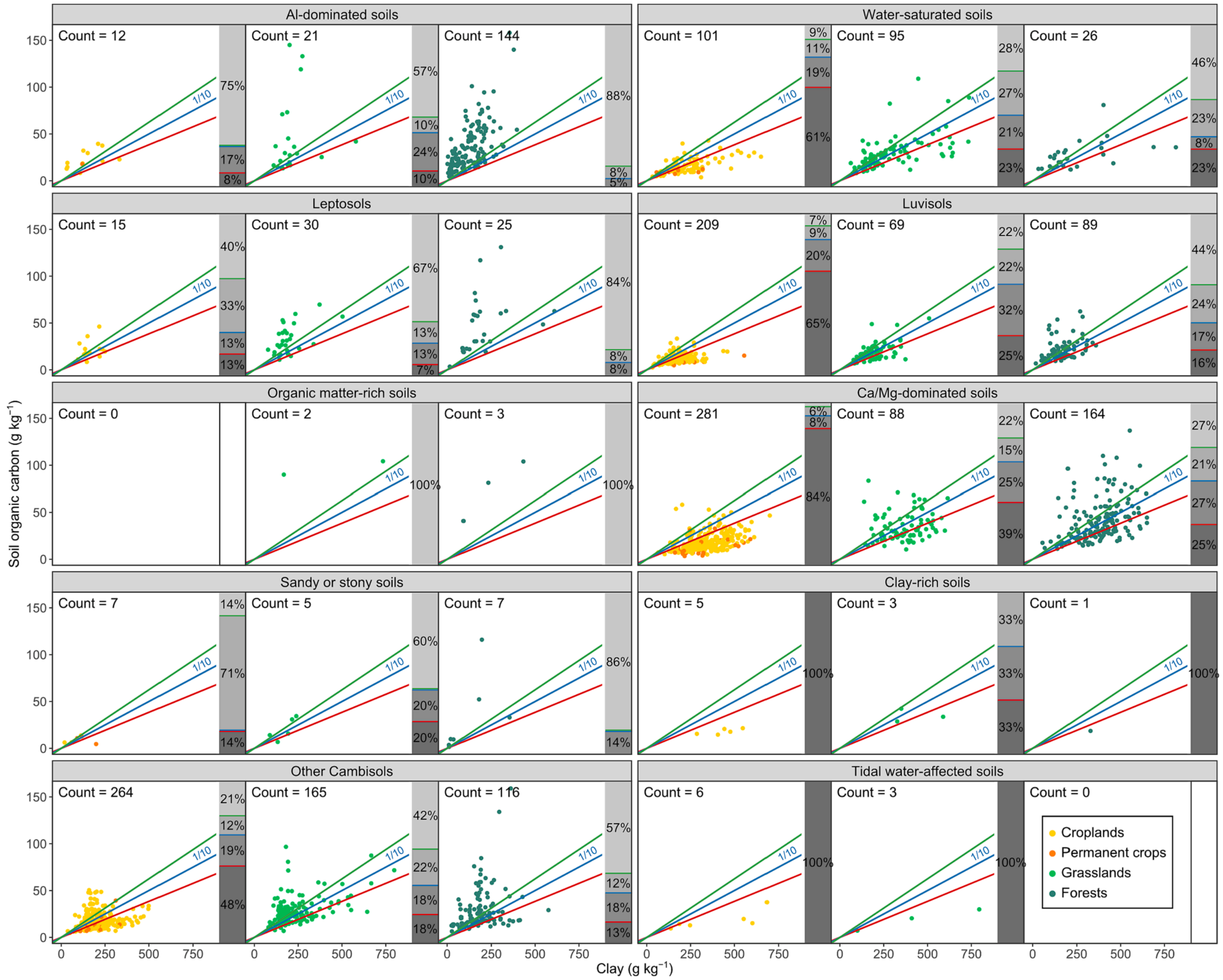

Fig. 5. Soil organic carbon content as a function of clay content in the topsoil of the RMQS dataset for different soil types and land uses. The thresholds of 1/8, 1/10 and 1/13 are suggested in Johannes et al. (2017a). On the right side of each plot, the percentage of sites in each soil structural quality class is given, from the best soil structural quality at the top to the worst at the bottom.

of Leptosols.

A high proportion of sites with SOC/clay > 1/8 was also found in organic matter-rich soils and sandy or stony soils, but only a few sites represented these classes in our dataset (Fig. 5). In the soil types grouped in organic-matter rich soils (i.e., Histosols and Folic Umbrisols), an external driver is responsible for the low mineralization and SOC accumulation (e.g., climate, waterlogging), leading to high SOC/clay ratios.

The sites were more evenly distributed between the different SOC/clay classes for Cambisols, water-saturated soils, Luvisols and Ca/Mg-dominated soils (Fig. 5). These soil types were more often cultivated than the previous ones, and croplands and permanent crops tended to have the lowest SOC/clay ratios (SOC/clay < 1/13 in croplands and permanent crops for 48 % of Cambisols, 61 % of water-saturated soils, 65 % of Luvisols and 84 % of Ca/Mg-dominated soils). This observation highlights a confounding effect between soil type and land use. Cambisols are derived from a variety of parent materials, therefore spanning a wide variety of soil properties such as pH or composition of clay-sized minerals (Kögel-Knabner and Amelung, 2021). It may explain the wide range of SOC/clay ratios observed in Cambisols. Water-saturated soils also span a wide variety of soil properties. SOC content has been observed to increase with the level of waterlogging (Amendola et al., 2018; Meersmans et al., 2008; Poeplau et al., 2020). In the water-saturated soil class, we could observe that some grassland and forest sites had some of the highest clay contents of the dataset and had SOC/clay < 1/13 (Fig. 5).

A majority of sites classified as clay-rich soils and tidal water-affected soils had a SOC/clay < 1/13, but only a few sites represented these classes (Fig. 5). 100 % of clay-rich soils and tidal water-affected soils under croplands and permanent crops had a SOC/clay < 1/13. Clay-rich Vertisols also showed SOC/clay < 1/13 in Germany (Poeplau and Don, 2023). Poeplau and Don (2023) considered that it would take an immense effort in terms of carbon input to move these clay-rich soils from a degraded class to a moderate class as defined by the SOC/clay ratio. Salinity in salt-affected soils is usually responsible for poor plant growth leading to low carbon inputs into the soil and low SOC contents (Wong et al., 2010). In addition, the presence of sodium ions may cause clay dispersion, resulting in SOC losses (Wong et al., 2010). In the Soil Monitoring law, the 1/13 threshold was chosen to be a target value to achieve because it distinguished managed and semi-natural systems in the study of Prout et al. (2021). We however showed that the 1/13 threshold does not allow this distinction for every type of soil.

One of the main soil properties discriminating different soil types is soil pH. There is also a known control of pH on SOC stabilization (Kögel-Knabner and Amelung, 2021; Rowley et al., 2018), which is partly responsible for the differences observed by comparing the acidic Al-dominated soils to the alkaline Ca/Mg-dominated soils in Fig. 5. Therefore, we looked in more detail at the variation of SOC/clay with soil pH (Fig. 6). The majority of sampling sites had a SOC/clay > 1/8 for pH lower than 5, corresponding to a very good soil structure according to the thresholds proposed by Johannes et al. (2017a). These sites included Podzols, Cambisols (Hyperdystric) or Umbrisols (Hyperdystric), Luvisols and Fluvisols or Fluvic Cambisols developed on sandy or silty materials (WRB classification, IUSS Working Group WRB, 2022). The great majority was under forest land use (Fig. 6). In the coarse soil textures of these RMQS sites, when recorded from the soil profile, the soil structure was single grained. It usually leads to classify soil structure as poor. Prout et al. (2021) also observed a tendency for high SOC/clay ratios in acidic soils and a lower effect of soil pH in the range 5.5 to 7.

For pH > 8 (and ≤ 8.7, the maximum pH value found), the range of SOC/clay values was smaller than in the rest of the pH range (Fig. 6). The mean and median clay contents of these sites were larger than in the whole dataset. SOC/clay was the lowest (<1/40) for some RMQS sites classified as Cambisols (Calcaric) or Renzic Leptosols (IUSS Working Group WRB, 2022) under agricultural land use and a climate characterized by a high annual average temperature in Southwest France. In addition to clay contents higher than in the whole dataset, they showed lower mean and median carbon contents than the whole dataset. RMQS sites with SOC/clay > 1/8, supposed to have a good structural quality according to the SOC/clay ratio, were very rare for pH > 8.2.

3.2.2. Map of healthy and unhealthy soils

Based on the RMQS dataset, 63 % of cropland, 81 % of permanent crop and 23 % of grassland soils were below the threshold of SOC/clay of 1/13 proposed in the European Soil Monitoring Law (Fig. 4). The “one out – all out” principle chosen in this law proposal implies that this single failing criterion is sufficient to classify these soils as unhealthy. We sought to observe the geographical trends that would emerge from the application of a SOC/clay threshold of 1/13 on the French managed soils (Fig. 7). If Prout et al. (2021) found that soils with SOC/clay < 1/13 were not located in a particular region in England and Wales, we found known geographical patterns in France. The trends observed in our study, by analyzing the effect of land use, soil type and soil pH on SOC/clay, are clearly visible spatially at the national scale (Fig. 7A and B). Climate also seems to have an additional impact on the results, through the altitude and latitude.

For example, some soils classified in a healthy condition are located in the Brittany region and Massif Central (Fig. 7C). Soils of Brittany are silty, with low clay contents. They are developed from an eroded crystalline basement, leading mainly to Cambisols with acid soil pH (Fig. 7B). Soils are used for croplands and grasslands (Fig. 7A). This region is also known to produce and use the largest quantities of organic fertilizers in France, due to a developed livestock production (Loyon, 2017). The climate is marked by an oceanic influence with medium to high precipitations (Joly et al., 2021). Massif Central corresponds to low to medium elevation mountains, mainly covered by grasslands (Fig. 7A). It is also an eroded crystalline basement with some volcanic rocks responsible for the presence of Andosols (Al-dominated soils, Fig. 7B). Soil textures are coarse. Massif Central shows a mountain climate with low temperatures and high precipitations (Joly et al., 2021).

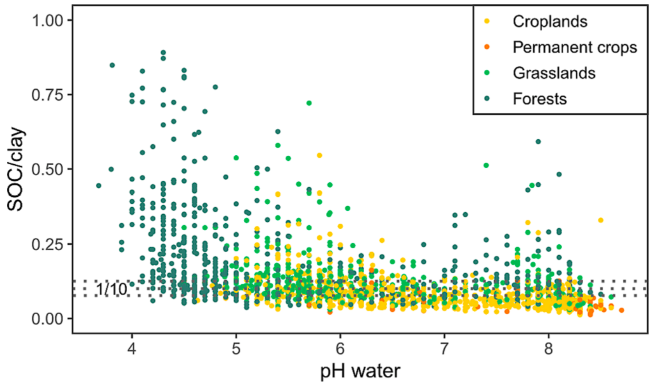

Fig. 6. Soil organic carbon to clay ratio (SOC/clay) as function of soil pH, in the topsoil of the RMQS dataset. Horizontal dotted lines represent the thresholds suggested in Johannes et al. (2017a).

On the contrary, we can cite the example of some soils classified as unhealthy, located in the coast of Languedoc-Roussillon and the Charentes regions (Fig. 7C). In Languedoc-Roussillon, soils are mainly developed from limestones and quaternary alluvial deposits leading to alkaline pH (Ca/Mg-dominated soils, Fig. 7B). They are highly cultivated as vineyards (Fig. 7A). This permanent crop usually returns low amounts of SOC to the soil. Climate is Mediterranean, with high temperatures and low precipitations (Joly et al., 2021). The Charentes region is located in the northern part of the sedimentary basin of Aquitaine. Soils are cultivated (Fig. 7A), with a clayey texture and developed from carbonate materials (Ca/Mg-dominated soils, Fig. 7B). The climate is marked by an oceanic influence, with medium to high precipitations (Joly et al., 2021).

We have cited here extreme examples, combining several favorable (Brittany, Massif Central) or unfavorable factors (Languedoc-Roussillon, Charentes) for the SOC/clay indicator. These factors are not all related to soil texture or management as taken into account by the SOC/clay indicator. Climate, pH and mineralogy also affect the SOC/clay value. All these factors also define agricultural constraints which were responsible for the historical land use and management of soils in France. The fact that geographical patterns are visible at this national scale supports the idea of defining threshold values for assessing soil health by pedoclimatic context, which we could refer to as “soil districts” in a European legislative context. The definition of soil districts is, however, still vague. For their definition, a trade-off will have to be made between the pedoclimatic homogeneity of soil districts and the number of sampling points necessary to define robust reference values.

In the national scale study of Germany, Poeplau and Don (2023) considered that the SOC/clay indicator was insensitive to changes in SOC content in both coarse- and fine-textured soils. A problem in clay-rich soils was also reported by Çelik et al. (2020) in Turkey. In a field study in croplands with clay contents of 50 %, they found a SOC/clay < 1/13 although the VESS score classified soil structure as good. In our study, only 2 % of the cropland sites with a clay content ≥ 35 % were classified in a healthy condition, and they were not found further South than the Charentes region (Fig. 7C). We did not find healthy soils in croplands for clay contents ≥ 50 %.

Our study also underlined that the normalization of SOC content by the fine fraction content provided an oversimplified view of the links between SOC and soil structure. As shown when plotting SOC/clay as function of soil pH (Fig. 6), mechanisms such as sorption on aluminum species cannot be taken into account using the SOC/clay indicator. This mechanism is however dominant in some soil types (Kögel-Knabner and Amelung, 2021; Rasmussen et al., 2018). This is a major problem when one wants to apply the SOC/clay indicator for a wide range of pedoclimatic contexts as they exist at a national or European level. In the case of France, removing soils for which other factors of SOC dynamics than those related to the crystalline minerals found in the fine fraction are involved would lead to exclude at least Al-dominated soils, organic matter-rich soils, tidal water-affected soils and soils with pH ≤ 5. These soils represent only 6 % of the managed mineral soils in the RMQS dataset. Removing these few sites from our analysis of the link between SOC indicators and soil structure indicators for managed soils would not modify our conclusions, i.e., SOC is a better indicator of soil structure than SOC/clay or SOC/(silt < 20 μm + clay).

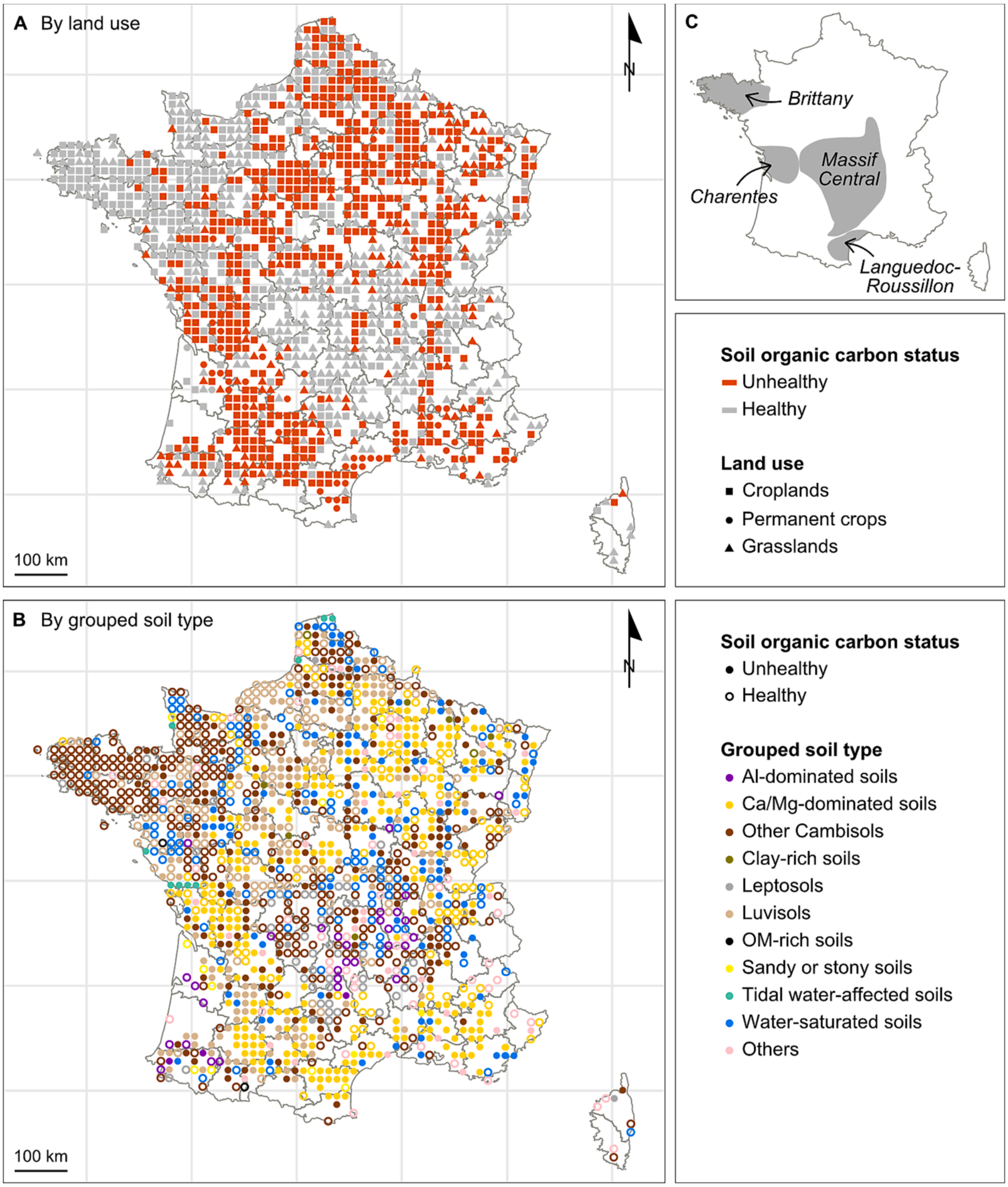

Fig. 7. Map of the RMQS sites classified as unhealthy because of a SOC/clay value lower than 1/13 in the topsoil, symbolized by (A) land use and (B) grouped soil type. Four natural or administrative regions mentioned in the text are represented in (C).

It is unclear whether the high percentage of highly alkaline soils in an unhealthy condition is realistic (81 % of the managed RMQS sites with pH $\geq$ 8, Fig. 6). These soils are highly represented in France, since 23 % of the managed RMQS sites have a pH $\geq$ 8. In these soils, some other SOC stabilization mechanisms are supposed to be involved (Rowley et al., 2018) but in France, many confounding factors also affect their carbon inputs into the soil and SOC mineralization. These confounding factors make it difficult to draw a conclusion about the relevance of SOC/clay in the case of soil pH $\geq$ 8. A large part of managed alkaline soils is under croplands or permanent crops (85 %), a large part is found under a climate showing high annual average temperatures in Southern France (22 %) and a large part is clayey (35 % with a clay content $\geq$ 35 %). In addition, it cannot be excluded that the use of a particle size analysis without removing carbonates and leading to overestimates of the fine fraction content could have influenced the resulting SOC/clay class of alkaline soils. Additional investigations would be required.

The Soil Monitoring Law leaves the possibility of applying a correction factor for specific soil types and climatic conditions. It seems clear that an adaptation of the threshold is required for France, because it will be nearly impossible to reach the threshold of 1/13 for some soils under agricultural use, for example under a Mediterranean climate or for clayey soil textures. As mentioned earlier, the role of clay particles on SOC content is well known. However, climate, through its effect on primary productivity and decomposition, is also a strong driver of SOC. The results of Chen et al. (2019) for France and Pacini et al. (2023) for Europe both suggest that, along with soil properties, the maximum attainable SOC content is strongly driven by climate. These results suggest that the SOC/clay threshold should take into account climatic zones.

3.3. Explaining divergent conclusions about the SOC/clay indicator

Previous studies on the SOC/clay indicator have drawn divergent conclusions about its relevance when confronted with soil structural indicators, some authors being in favor of the use of SOC/clay (Johannes et al., 2017a; Prout et al., 2021) and others not (Poeplau and Don, 2023). As presented earlier, CoreVESS is not very sensitive to clay content (Johannes et al., 2023, 2017b; Lin et al., 2022), contrary to bulk density and aggregate stability. We also believe that the use of qualitative physical indicators, although very useful for field applications, to be compared with SOC/clay was partly responsible for these divergent conclusions. When qualitative indicators of soil structure were used to investigate their link with SOC/clay, such as the CoreVESS score or an index based on the shape and size of aggregates and soil texture, the observed trends were considered satisfactory by Johannes et al. (2017a) and Prout et al. (2021). However, when quantitative indicators of soil structure were used, such as the inverse of bulk density or the gravimetric water content and air content at a given matric potential, the relationships were unsatisfying (Poeplau and Don, 2023) or no better than the relationship with SOC content (Johannes et al., 2017a). The use of quantitative indicators of soil structure in our study allowed using scatter plot representations instead of the boxplots necessarily used in Johannes et al. (2017a) and Prout et al. (2021). If the median values of SOC/clay presented in the boxplots appeared well discriminated for the different levels of the qualitative structural measure, boxplots also showed large overlaps that could indicate some more complex relationships. The continuous variables used in our study allowed visualizing these more complex relationships, such as inverse or logarithmic relationships shown in Fig. 2, and to highlight the low sensitivity of the 1/8, 1/10 and 1/13 thresholds in the case of France. A second explanation for the inconsistent conclusions about the SOC/clay indicator is linked to the use of an indicator designed and first tested in a restricted pedoclimatic environment to be applied throughout Europe. While the use of locally developed indicators should not be condemned, we recommend vigilance regarding the use of thresholds defined in other studies on datasets with wider ranges of variation in soil properties. Prout et al. (2021) implicitly defined a domain of applicability of the SOC/clay ratio, because they removed peat soils and sites identified as outliers in the SOC/clay distribution from their study. Their proposal for a soil degradation threshold of 1/13 was however taken up by the European Commission. In the same way, Dupla et al. (2021) excluded drained peatlands, sandy soils and heavy clay soils and removed outliers in the SOC/clay distribution. The thresholds proposed by Johannes et al. (2017a) were established for a single soil group (Cambi-Luvisols according to the WRB classification), by purpose, to limit the variability in the factors of SOC dynamics. In their study, soil pH ranged from 5 to 8.

4. Conclusion

In this study, we intended (i) to test the relevance of the SOC/clay and SOC/(silt < 20 μm + clay) ratios to assess the structural quality of soils and (ii) to quantify the proportion of soils that would be considered as unhealthy in France, using the threshold of SOC/clay chosen in the European Soil Monitoring Law proposal. We used information from the French Soil Quality Monitoring Network representing quantitative measurements of 1,345 bulk densities and 174 aggregate stability tests. We showed that SOC/clay and SOC/(silt < 20 μm + clay) were poor indicators of the soil bulk density and aggregate stability. The SOC content was a much better indicator of soil structure. By normalizing the SOC content by the fine fraction content, these indicators provide an oversimplified view of the links between SOC and soil structure. Both land use and soil type had an effect on the SOC/clay value. In particular, SOC/clay was found to be strongly affected by soil pH, with acidic soils consistently being classified as healthy according to the threshold of 1/13 and alkaline soils often being classified as unhealthy. This bias of the indicator, if used with a fixed threshold of 1/13, also prevents its use as an indicator of the SOC status for the wide range of pedoclimatic contexts of Europe. Additional investigations are however required to explain the results for alkaline soils. Based on the RMQS dataset, 63 % of cropland, 81 % of permanent crop and 23 % of grassland soils were below the threshold of 1/13, which would lead to classify these soils as unhealthy. The Soil Monitoring Law leaves the possibility of using correction factors for specific soil types or climatic conditions, which appears necessary for France, because some pedoclimatic contexts will never allow a satisfactory value to be reached. A pan-European study of the correlation of SOC/clay and additional SOC indicators with several quantitative and visual soil structure variables appears necessary, to determine their domain of validity and identify, whenever necessary, relevant threshold values for the diversity of European pedoclimatic conditions.

CRediT authorship contribution statement

Eva Rabot: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Nicolas P.A. Saby:** Formal analysis, Writing – review & editing. **Manuel P. Martin:** Writing – review & editing. **Pierre Barré:** Writing – review & editing. **Claire Chenu:** Writing – review & editing. **Isabelle Cousin:** Writing – review & editing. **Dominique Arrouays:** Writing – review & editing. **Denis Angers:** Writing – review & editing. **Antonio Bispo:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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