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Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter?

Alice Johannes[a,b,*], Adrien Matter[a], Rainer Schulin[b], Peter Weisskopf[c], Philippe C. Baveye[d], Pascal Boivin[a]

[a] University of Applied Sciences of Western Switzerland hepia, Soils and Substrates group, Institute Land-Nature-Environment, route de Presinge 150, 1254 Jussy Geneva, Switzerland
[b] ETH Zürich, Institute of Terrestrial Ecosystems, Universitätstrasse 16, 8092 Zürich, Switzerland
[c] Swiss Federal Research Station Agroscope, Soil Fertility and Soil Protection group, Department of Natural Resources & Agriculture, Reckenholzstrasse 191, CH-8046 Zurich, Switzerland
[d] UMR ECOSYS, AgroParisTech-INRA, Université Paris-Saclay, Avenue Lucien Brétignières, Thiverval-Grignon 78850, France

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ABSTRACT

Most soil structure-related physical properties are correlated to soil organic carbon (SOC) content. Texture, mineralogy, and SOC:clay ratio are also acknowledged to affect physical properties, however there is no consensus or general conclusions in this respect. Against this background, the present study aims at determining objectives for the management of SOC in terms of structural quality of agricultural soils. The large area in which 161 free-to-swell undisturbed samples were obtained for this research represents a major part of the Swiss agricultural land and belongs to one broad soil group (Cambi-Luvisols). The structural quality was scored visually, and bulk volumes (inverse of bulk density) were measured at standard matric potentials. To define the effect of SOC without interference of soil mechanical degradation, soils with good structural quality scores were considered first in studying the relationship between SOC and soil pore volumes. Results suggest that the relationship is always linear, irrespective of the clay content of the soils. No optimum of SOC corresponding to a fraction of the clay content is found, contrary to the theory of "complexed organic carbon" (Dexter et al., 2008). However, the SOC:clay ratio decreases with decreasing soil structure quality. The SOC:clay ratio of 1:8 is the average for a very good structure quality. A SOC:clay ratio of 1:10 is the limit between good and medium structural quality, thus it constitutes a reasonable goal for soil management by farmers. A SOC:clay ratio of 1:8 or smaller leads to a high probability of poor structural state. These ratios can be used as criteria for soil structural quality and SOC management, and in that context, the concept of complexed organic carbon appears relevant.

1. Introduction

The content of soil organic matter (SOM) in a given soil results from the integrated effects of many factors like site conditions, biological activity, and soil management (Kay, 1998). SOM content is correlated to a number of soil physical properties, like soil bulk volume, moisture retention curve, fluid transfer properties, and mechanical resistance of the soil to stresses. This can be quantified via numerous parameters, most of which have been shown to be largely correlated to SOM. This is true for soil aggregate stability (e.g., Abiven et al., 2009; Six et al., 2004), mechanical properties (Keller and Dexter, 2012; Soane, 1990), or penetration resistance (e.g., Stock and Downes, 2008). The most documented is probably the relationship between SOM, or soil organic carbon (SOC), and soil bulk density (e.g., Saini, 1966). Continuous increase in soil porosity with SOC was reported in many cases. Studies that included a broad range of SOC values (from 0 to > 50%) usually found a semi-logarithmic relationship, thus decreasing effect of SOC on porosity or bulk density (BD) at large SOC content (e.g. Jeffrey, 1970). Studies based on a limited range of low SOC contents even found a linear relation, thus proportional increase, between porosity and SOC (e.g. Saini, 1966).

Because in many soils, a significant portion of the SOC is bound to clay minerals, several authors have considered clay or clay + fine silt content as covariables when analysing the effect of soil constituents on soil physical properties. Together with SOC, texture is generally assumed to influence the physical properties (Kay, 1998). Clay mineralogy was shown

* Corresponding author at: University of Applied Sciences of Western Switzerland hepia, Soils and Substrates group, Institute Land-Nature-Environment, route de Presinge 150, 1254 Jussy Geneva, Switzerland.
E-mail address: Alice.Johannes@hesge.ch (A. Johannes).

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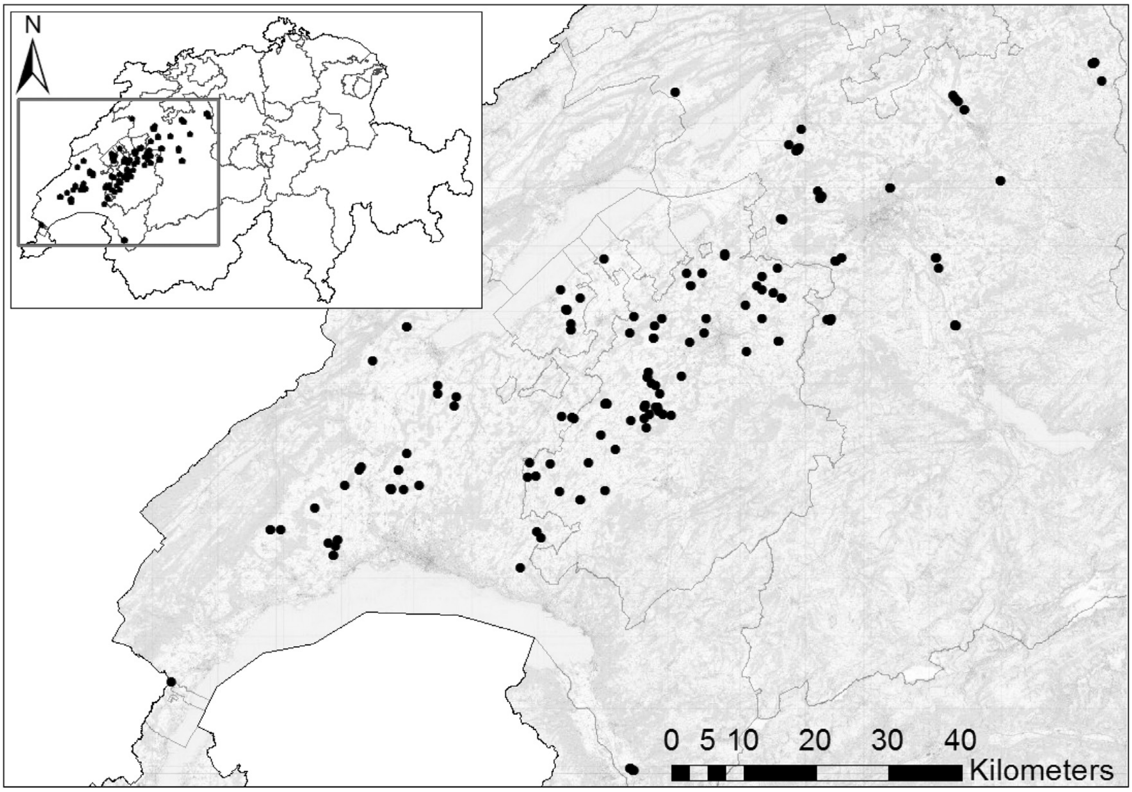

Fig. 1. Map of the soil sampling locations in Western Switzerland.

to influence the SOC content of soils with allophanic minerals, but not for those containing 1:1 and 2:1 phyllosilicates (Feller and Beare, 1997; Fernandez-Ugalde et al., 2016). The same linear relation between water content at pF2.5 and SOC, however, was found for the soils with all these mineral types according to Feller and Beare (1997). These authors pointed out that with increasing clay content, a larger SOC content was necessary to achieve the same level of aggregate stability.

Triggered by these observations, Dexter et al. (2008) analysed the role of the clay:SOC ratio in the relation between bulk density (BD) and SOC using soil databases from Poland and France that included soils of several taxonomic orders. They introduced the concept of "Complexed Organic Carbon" (COC) as the fraction of the SOC bound to clay, and found highest coefficient of determination of the linear relation between COC and soil volume (1/BD) for clay:COC = 10, thus interpreted as the saturation of the clay surface by SOC. They found the same optimum ratio for clay dispersibility and considered that the fraction of SOC corresponding to a tenth of the clay content was the maximum COC controlling the structure-related physical properties of soils. In particular, they concluded that structural porosity was no longer increasing with SOC above 10% of clay content, and that the optimum SOC content of a soil would thus be 10% of the clay content. They showed that the clay:SOC ratio 10 was separating the permanent pasture soils from the cropped soils in their database. Maximum correlation between 1/BD and SOC, however, does not mean optimum or desirable values of soil physical quality. In further tests of this approach, Schjonning et al. (2012) and Getahun et al. (2016) found that non-complexed clay (with a clay:SOC ratio of 10) was a better predictor of dispersible clay than total clay content, while aggregate strength was shown to be better explained by clay content alone.

These different analyses raise a number of issues. The main concern is that soil structural quality was not described in these various articles, which means that the used databases might include data of soils with different levels of structural degradation at the time of sampling, as is often the case in cropped soils. Other factors than SOC, e.g., mechanical stresses, influence the soil physical properties, which should not interfere with the assessment of the effect of SOC. Moreover, even when a specific sub order is considered, soil management, climate, and parent materials may have differed strongly in the different articles. Also, the techniques used to determine the physical properties were not described in detail. In particular for bulk density, a standardized matric potential should be applied prior to the volume measurement to eliminate the effect of the swelling state (Goutal et al., 2012).

This rapid overview of the literature on the connections between SOM or SOC and various physical characteristics of soils, taking into account or not the effect of the clay:SOC ratio, suggests that there might be an optimum or desirable range of SOM, but as pointed out by Loveland and Webb (2003), the evidence is "equivocal at best". SOM may be essential for a number of agricultural and environmental aspects, but in the field, it is managed by farmers. In this general context, the main objective of this research was to determine the SOC content that should be targeted in the management of an agricultural soil from a single soil group developed on the same parent materials, and to determine if clay content should be taken into account to identify this optimal SOC content. We focused on soil pore volumes and worked at large scale. We used the Visual Evaluation of Soil Structure (VESS, Ball et al., 2007) adapted to soil samples (Johannes et al., 2016) to make distinction between soils with degraded soil structure and soil with "good structure", thus possibly not impacted by mechanical stresses. On these later, the relationships between SOC or SOC:clay ratio and soil volume (1/BD), and the relevance of the concept of clay saturation by SOC proposed by Dexter et al. (2008) were analysed. The relationships between soil structure quality and the SOC:clay ratio were then discussed. Throughout this article, the description will be in terms of SOC only (not of SOM), to simplify the narrative.

Table 1
Soil characteristics.

	SOC (%)	pH	CEC ($cmol_c$ kg^{-1})	Clay < 2 μm (%)	Fine silt 2–20 μm (%)	Coarse silt 20–50 μm (%)	Silt 2–50 μm (%)	Fine sand 50–200 μm (%)	Coarse sand 0.2–2 mm (%)	Sand 0.05–2 mm (%)
Mean	1.9	6.6	13.7	20.5	22.2	16.2	38.3	24.2	16.5	40.7
Median	1.8	6.7	13.8	20.1	21.8	15.0	37.4	24.3	16.2	41.7
SD	0.6	0.7	4.9	5.1	4.9	4.6	8.4	5.3	8.5	11.9
Min.	0.8	5.0	5.3	9.9	10.6	7.4	20.3	11.0	2.1	14.4
Max.	3.9	8.0	26.3	34.3	34.7	28.1	57.7	39.4	41.4	66.7

SD: standard deviation, SOC: soil organic carbon, CEC: cation exchange capacity.

Table 2
Number of observation in each score.

CoreVESS score	1	1.5	2	2.5	3	3.5	4	4.5	5
Number of observations	10	10	36	25	33	17	16	10	4

2. Materials and methods

2.1. Sampling and analysis

The investigated soils are classified as “Braunerde” soils according to the Swiss soil map (Office fédéral de topographie, 1984). They correspond to an intermediate Cambi-Luvisol group in the World Reference Base for soil resources (IUSS Working Group WRB, 2006) and to Inceptisols according to the USDA taxonomy (Soil Survey Staff, 1999). Only soils developed on mixed moraine – molasses bedrocks were considered. A total of 161 locations were selected to represent agricultural soils with a large range of structural quality, including permanent pasture, conventional plough tillage, and no-till practices. When looking for soils without structure degradation, we discarded sites with signs of stresses like wheel tracks, surface sealing or erosion.

The sampled area covered approximately 6000 km^2 and represented a major part of the farmed soils on the Swiss Plateau (Fig. 1). Detailed soil properties are presented in Table 1.

At each location, two undisturbed soil samples were collected at 5–10 cm depth close to each other using a custom-made cylindrical corer. The corer allowed easy removal without mechanical disturbance of the sample from the cylinder so that sample quality could be checked immediately after sampling. Removal from the corer was also required to allow unconfined swelling of the soil during saturation in the laboratory. This is important since the soils were collected at different water content, thus different swelling state, which jeopardizes volume comparisons (Goutal et al., 2012). Physico-chemical analyses were performed on the first sample and the structural quality of the soil was assessed on the replicate sample using CoreVESS scoring (Johannes et al., 2016).

The samples were kept at 4 °C before analysis. They were first equilibrated at − 10 hPa matric potential in a sand box. After weighing to determine the water content at − 10 hPa, their volume was measured using the plastic bag method (Boivin et al., 1990). After air drying, weight and volume were measured again. Finally, the samples were oven-dried at 105 °C until equilibrium, weighted and sieved to 2 mm. The weight and volume of the coarse (> 2 mm) fraction were measured and removed from the sample volume and weight, to calculate the physical properties of the < 2 mm fabric, namely gravimetric water content at − 10 hPa ($W_{-10\ hPa}$), specific volume (bulk volume per g of dry mass) at − 10 hPa ($V_{-10\ hPa}$), specific (per g of dry mass) air content at − 10 hPa ($Air_{-10\ hPA}$), and specific volume at air dry state (V_{dry}). $Air_{-10\ hPA}$ was calculated as $V_{-10\ hPa}$ - $W_{-10\ hPa}$ - 1/ρ, with ρ the particle density. $Air_{-10\ hPa}$ and $W_{-10\ hPa}$ correspond to the > 150 μm and < 150 μm pores in equivalent radius, respectively, according to Jurin-Laplace's law. The < 2 mm fraction was analysed for SOC with the method of Walkley and Black (1934) and for texture with the traditional pipette method. The replicate samples were scored with CoreVESS a method adapted from VESS (Ball et al., 2007; Guimarães et al., 2011) to soil cores, and analysed for SOC and clay content as well. For details, consult Johannes et al. (2016). In brief, the scores (Sq) range from 1 (“very good”) to 5 (“poor”). Scores of 1 and 2 represent good structure, a Sq of 3 is a moderate structure quality, and Sq values of 4 and 5 describe poor structures. When there was doubt between two scores, half points were attributed. Before scoring, samples were equilibrated to − 100 hPa to ensure comparable scoring conditions; samples were scored without knowing their origin for more objectivity. The number of observations in each score is presented in Table 2. To avoid interaction between physical stress and SOC effect, the sample properties with replicate sample scores < 3 were used to analyse the relationships between SOC and physical properties, and to test the complexed organic carbon concept.

2.2. Relationships between SOC and physical properties

Three different models (linear, semi-logarithmic, and broken-stick) were fitted to the relationships between SOC or SOC:clay ratio and the physical properties of the samples with CoreVESS < 3, with the R software (version 3.1.0). The semi-logarithmic and broken-stick models were selected to account for the decreasing effect of SOC on structural properties at large SOC contents, with or without threshold, respectively.

Broken-stick regression graphs and statistics (Toms and Lesperance, 2003) were fitted using the “segmented” package (Muggeo, 2015) (version 0.5–1.4) of the R software. A simple piecewise-regression model, which joins two straight lines at the breakpoint was used:

$$yi = \begin{cases} \beta_0 + \beta_1 x_i + e_i & for\ x_i \leq \alpha \\ \beta_0 + \beta_1 x_i + \beta_2 (x_i - \alpha) + e_i & for\ x_i > \alpha \end{cases}$$

where y_i is the value for the ith observation, x_i is the corresponding value for the independent variable, α is the breakpoint and e_i are residual errors. The first slope is β_1 and the second slope is $\beta_1 + \beta_2$, so β_2 can be interpreted as the difference between slopes. The statistical significance of the breakpoint was assessed using a Davies test (Davies, 2002), which tests for the difference in slope parameters in a piecewise regression.

2.3. Test of the complexed organic carbon concept

We applied, on the soil samples with CoreVESS < 3, the same procedure as Dexter et al., 2008, which we recall hereafter. It is based on the assumption that the physical properties are determined by the part of SOC complexed to the clay particles, and that above a maximum SOC:clay ratio the clay is saturated. Hence, they calculated the correlation between the bulk density and the Complexed Organic Carbon (COC), a fraction of the SOC that does not exceed 1/n of the clay content (Eq. 1) to find n corresponding to the maximum correlation coefficient.

$$COC = IF\left[SOC < \frac{clay}{n}\right] THEN\,[SOC]\,ELSE\left[\frac{clay}{n}\right] \quad \text{Eq. 1}$$

Note that the number of samples with $SOC < \frac{clay}{n}$ and thus with COC = SOC increases as n decreases. In a second part of their paper dedicated to clay dispersibility, Dexter et al. (2008) omitted all the samples with SOC $< \frac{clay}{n}$ from their analysis, defining:

$$COC = IF\left[SOC < \frac{clay}{n}\right] THEN\ [not\ available]\ ELSE\left[\frac{clay}{n}\right] \quad \text{Eq. 2}$$

In the case of Eq. 1, one should expect a correlation coefficient converging to a final value with decreasing n since the smaller n the less the data set changes. In the case of Eq. 2, the number of considered data decreases, and the remaining samples should be the sandier ones, in which a small n is more frequently observed. We used both Eqs. 1 and 2 to plot the correlation coefficient between the physical properties as a function of n. We refer to COC_1 and COC_2 when Eqs. 1 or 2 were used, respectively.

3. Results and discussion

In the description of results, we shall first focus on the samples with good structure (CoreVESS < 3) to examine the relationships between SOC and porosities, and test the complexed organic carbon concept. Then we considered samples of all the structural qualities to determine the relationships between CoreVESS scores and the SOC:clay ratio.

3.1. Relationships between SOC, SOC:clay and porosities

Linear, logarithmic and broken-stick regressions were fit to the experimental data of SOC, SOC:clay ratio and the physical properties $V_{-10\ hPa}$, V_{dry}, $W_{-10\ hPa}$, and $Air_{-10\ hPa}$ obtained at the 87 locations with good structural quality (Sq < 3) (Table 3). The relationships between SOC and physical properties are always better determined than those between the SOC:clay ratio and physical properties. The values of R^2 range from 0.37 to 0.79. A slightly smaller R^2 was obtained with the BD to SOC relationship (not shown) instead of volume (1/BD) to SOC. The break point of the broken stick model is never significant, which means that there is no threshold in the SOC values or the SOC:clay ratios above which the effect of SOC decreased. The R^2 of the linear model (Fig. 2) is larger or equal to the R^2 of the other models. It describes best the relation between SOC or SOC:clay and the physical properties of non-degraded soils (Sq < 3). The relationships between porosities and SOC appear proportional, up to the highest value observed in our study. According to this, the general rule is “the more SOC the better the physical properties”, whatever the clay content. These observations are in good agreement with those of Heuscher et al. (2005) and Manrique and Jones (1991) who found that clay and silt are poor predictors of the bulk density of Inceptisols, which are close to Cambi-Luvisols, whereas SOC was a good predictor.

3.2. Application of the “complexed organic carbon” concept

According to Dexter et al. (2008), COC determines the physical properties of soils. The correlation coefficients between the specific volume (1/BD) of the dry soil and COC_1 or COC_2 as a function of the clay:SOC ratio n are presented in Fig. 3a and b, respectively, for the 87 soils in good structural state (Sq < 3). In both cases, the correlation coefficient continuously increased up to a maximum that is reached by n = 6 to 7 corresponding to SOC:clay ratios of 0.14–0.16, that is when COC is equal to SOC and total SOC is, therefore, taken into account (Fig. 3a). This ratio can be considered as the observed maximum, difficult to exceed in the field. Fig. 3a shows that total SOC must be taken into account to fully explain the measured physical properties.

When only the samples with SOC > COC_2 are considered (Fig. 3b), the number of samples included in the analysis decreases with decreasing n, and the average texture of the samples becomes sandier. This procedure, thus lead to an increasing bias with respect to the representation of the entire sample population. Irrespectively of this, though ranges of SOC and clay content in our study were larger than in

Table 3
Parameters of the linear, logarithmic and broken-stick models for several physical soil properties (specific volume at − 10 hPa ($V_{-10\ hPa}$), specific volume of dry soil (V_{dry}), water content at − 10 hPa ($W_{-10\ hPa}$) and specific air content at − 10 hPa ($A_{-10\ hPa}$)) as a function of soil organic carbon (SOC) content or SOC:clay ratio.

Predictor	Model		Equation	R^2	Adj. R^2
SOC	Linear	$V_{-10\ hPa}$	$0.574^{***} + 0.113^{***}$ SOC	0.788	0.786
		V_{dry}	$0.593^{***} + 0.064^{***}$ SOC	0.632	0.627
		$W_{-10\ hPa}$	$0.197^{***} + 0.079^{***}$ SOC	0.724	0.720
		$A_{-10\ hPa}$	$0.000 + 0.034^{***}$ SOC	0.404	0.396
	Logarithmic	$V_{-10\ hPa}$	$0.641^{***} + 0.249^{***}$ log (SOC)	0.775	0.772
		V_{dry}	$0.632^{***} + 0.149^{***}$ log (SOC)	0.634	0.629
		$W_{-10\ hPa}$	$0.241^{***} + 0.179^{***}$ log (SOC)	0.748	0.744
		$A_{-10\ hPa}$	$0.0226^{**} + 0.070^{***}$ log (SOC)	0.353	0.345
	Broken-stick	$V_{-10\ hPa}$	0.470^{***} + 0.190 SOC - 0.081 (SOC - 1.43) for SOC > 1.43	0.792	0.784
		V_{dry}	0.470^{***} + 0.159 SOC - 0.097 (SOC - 1.41) for SOC > 1.40	0.644	0.631
		$W_{-10\ hPa}$	$0.160^{***} + 0.101^{***}$ SOC - 0.056 (SOC - 2.66) for SOC > 2.66	0.746	0.737
		$A_{-10\ hPa}$	0.029 + 0.017 SOC + 0.039 (SOC - 2.57) for SOC > 2.57	0.442	0.421
SOC:clay ratio	Linear	$V_{-10\ hPa}$	$0.638^{***} + 1.627^{***}$ratio	0.365	0.358
		V_{dry}	$0.605^{***} + 1.197^{***}$ ratio	0.453	0.447
		$W_{-10\ hPa}$	$0.225^{***} + 1.301^{***}$ ratio	0.437	0.430
		$W_{-10\ hPa}$	$0.037^{**} + 0.322^{**}$ ratio	0.082	0.071
	Logarithmic	$V_{-10\ hPa}$	$1.219^{***} + 0.178^{***}$ log (ratio)	0.368	0.360
		V_{dry}	$1.036^{***} + 0.132^{***}$ log (ratio)	0.467	0.461
		$W_{-10\ hPa}$	$0.698^{***} + 0.146^{***}$ log (ratio)	0.467	0.461
		$W_{-10\ hPa}$	$0.143^{***} + 0.031^{*}$ log (ratio)	0.065	0.054
	Broken-stick	$V_{-10\ hPa}$	$0.601^{***} + 2.012^{***}$ ratio - 2.321 (ratio - 0.157) for ratio > 0.157	0.401	0.379
		V_{dry}	$0.579^{***} + 1.472^{***}$ ratio - 1.414 (ratio - 0.156) for ratio > 0.156	0.490	0.471
		$W_{-10\ hPa}$	$0.193^{***} + 1.623^{***}$ ratio - 1.981 (ratio - 0.157) for ratio > 0.157	0.487	0.468
		$W_{-10\ hPa}$	0.097^{*} − 0.436 ratio + 0.988 (ratio - 0.093) for ratio > 0.093	0.128	0.095

V: Specific volume ($cm^3\ g^{-1}$); W: Gravimetric water content ($g\ g^{-1}$); A: Gravimetric air content ($cm^3\ g^{-1}$); SOC: Soil organic carbon (%).
Only the second equation of the broken-stick model is shown here. None of the breakpoints were significant.
* Indicates significance level at $p < 0.05$.
** Indicates significance level at $p < 0.01$.
*** Indicates significance level at $p < 0.001$; adj. R^2: adjusted R^2.

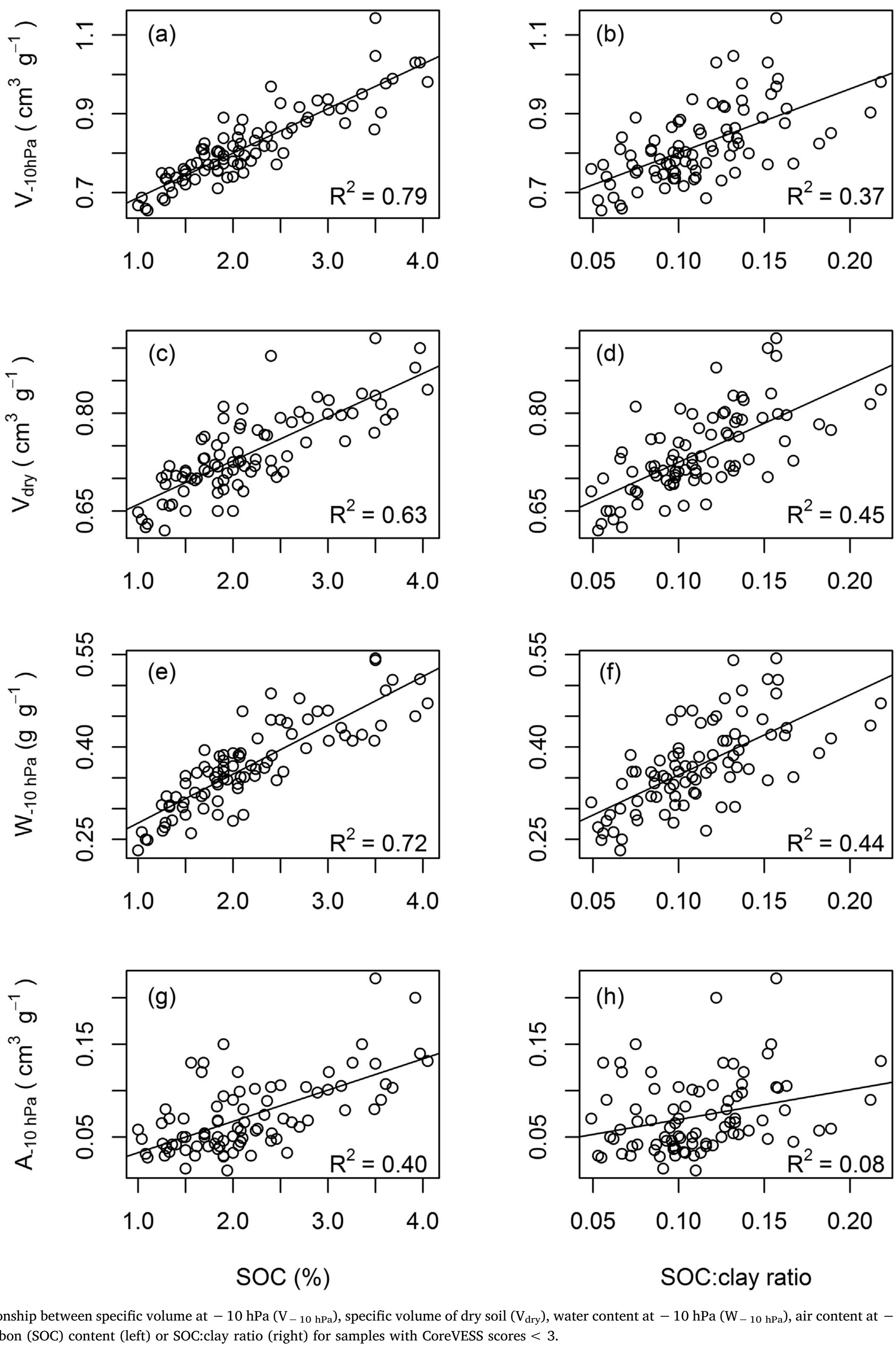

Fig. 2. Linear relationship between specific volume at − 10 hPa ($V_{-10\ hPa}$), specific volume of dry soil (V_{dry}), water content at − 10 hPa ($W_{-10\ hPa}$), air content at − 10 hPa ($Air_{-10\ hPa}$), and soil organic carbon (SOC) content (left) or SOC:clay ratio (right) for samples with CoreVESS scores < 3.

the databases used by Dexter et al. (2008), none of the methods showed an optimum of the correlation between COC and structural soil properties, in contrast to the findings of these authors. This means that our results do not support the hypothesis that complexed organic carbon controls the specific soil volume or the soil bulk density. Our data show instead that total SOC controls physical properties regardless of clay content. Similar results were obtained with the other physical parameters $V_{-10\ hPa}$, $Air_{-10\ hPa}$ and $W_{-10\ hPa}$ (not shown). The main differences between the two studies are that we (i) worked with a single soil group, (ii) selected only samples with good structure, (iii) used a specific sampling and volume measurement procedure, in particular with free to swell samples equilibrated at standard matric potential, and (iv) chose a sample population with a larger range of SOC and clay content.

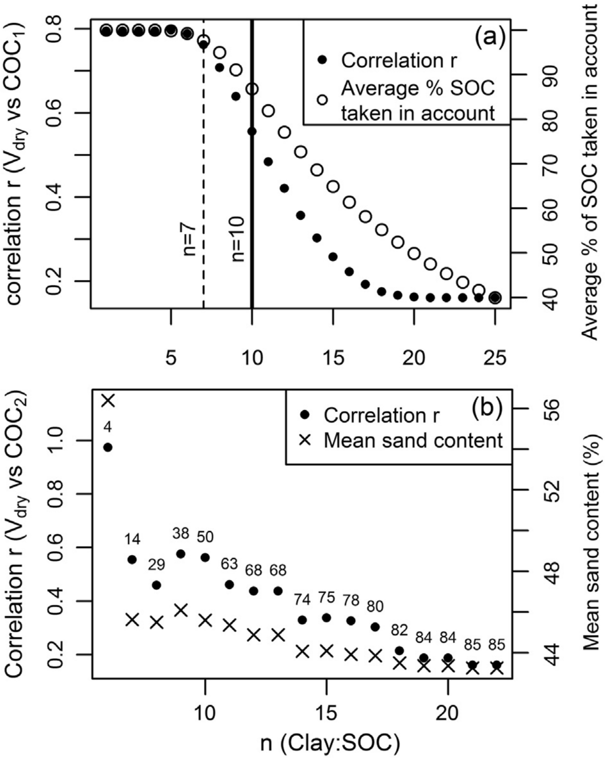

Fig. 3. (a) Correlation coefficient (r) between the specific volume of dry soil (V_{dry}) and complexed organic carbon (COC_1) calculated following Dexter et al. (2008), expressed as a function of n (clay:SOC, Eq. 1; black dots). The right ordinate corresponds to the average percentage of SOC present as COC (open circles). (b) Correlation coefficient (r) between the specific volume of dry soil (V_{dry}) and COC_2 calculated with Eq. 2, as a function of n (clay:SOC), as black dots, above which the number of observations is given. The right ordinate corresponds to mean sand content represented in the diagram by the symbol "x". Samples with CoreVESS scores < 3.

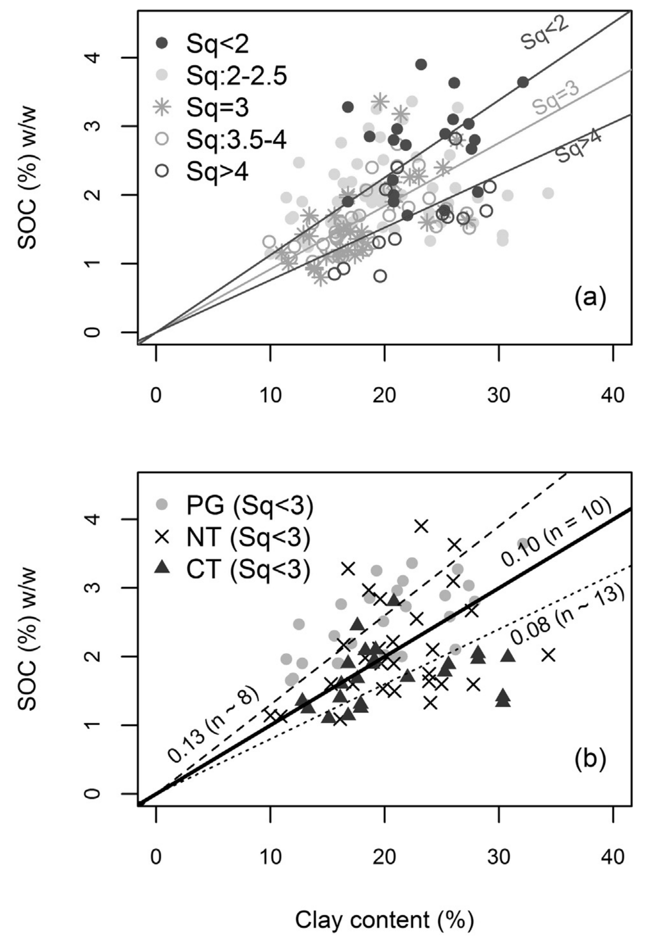

Fig. 4. Soil organic carbon content (SOC) as a function of clay content (a) for different CoreVESS scores (Sq) and (b) for different soil management practices (PG: permanent grass, NT: no-till, CT: conventional tillage) within soils of good structural state (Sq < 3). The dashed line indicates a SOC:clay ratio of 1:8, the full line a SOC:clay ratio of 1:10, and the dotted line a SOC:clay ratio of 1:13.

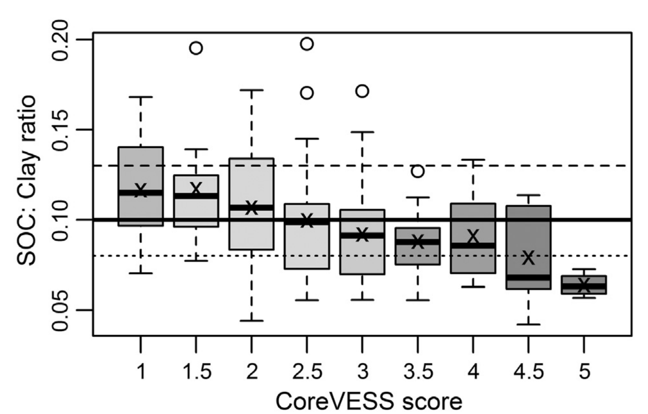

Fig. 5. Boxplots of soil organic carbon (SOC) to clay ratio for different CoreVESS scores. Boxplots show mean values (cross), median values (solid horizontal line), 50th percentile values (box outline), minimum and maximum values (whiskers) and outliers (open circles). The dashed line indicates a SOC:clay ratio of 1:8, the full line a SOC:clay ratio of 1:10, and the dotted line a SOC:clay ratio of 1:13.

3.3. SOC:clay ratio and structure quality

If the pore volumes are proportional to SOC alone for soils with good structural quality, is there a relation between SOC:clay and soil structure quality in general? In other words, if the clay saturation by SOC at a good structural state is not explaining the physical properties, does this parameter account for the structural state?

Fig. 4a suggest that the average SOC:clay ratio is decreasing with increasing score. The linear regression lines with no intercept for Sq < 2 (very good structure), Sq = 3 (medium structure) and Sq > 4 (very poor structure) correspond to SOC:clay ratios (significant slopes) of 0.12, 0.09 and 0.08, respectively. The "good structure" domain (Sq < 3) corresponds to average SOC:clay ratios larger than 0.10 (Figs. 4a and 5). Therefore, on average, the larger the clay content, the larger the SOC content must be to observe given structure quality, especially a good one. This is in agreement with the findings of Feller and Beare (1997) who showed that at larger clay content a larger SOC content was required to reach a given aggregate stability level, and suggested that the concept of clay saturation is relevant for soil structural quality.

3.4. SOC content criteria

Fig. 4b presents the SOC values as a function of clay content for the good structured soils (Sq < 3), distinguishing between the different soil management practices. The distribution of the permanent grass and tilled soils is close to that reported by Dexter et al. (2008). In the area with a SOC:clay ratio larger than 1:10 (Fig. 4b, full line), mainly samples from permanent grass can be found, but also some from no-tillage and conventional tillage. Conventional tillage samples, however, hardly overshoot the 1:10 ratio compared to permanent grass and no-till, their highest ratio being 1:8 (Fig. 4b, dashed line). Therefore, a SOC:clay ratio of 1:10 seems to be a reasonable target to obtain a good structure whatever the soil management. The ratio of 1:8 is the mean ratio of the very good structured samples (Sq = 1, Fig. 5), and we consider it as a "top value". Conversely, the regression line for the

Table 4
Expected structure quality as a function of the SOC:clay ratio.

SOC:clay	Expected structural quality	CoreVESS[a]
> 1:8	Very good	< 2
1:10 < SOC:clay < 1:8	Good	2–3
1:13 < SOC:clay < 1:10	Improvement suggested SOC:clay of 1:10	3–4
< 1:13	Bad	> 4

[a] Johannes et al., 2016.

relationship between SOC and clay for CoreVESS Sq > 4 samples shown in Fig. 4a corresponds to a SOC:clay ratio of 1:13 (see Fig. 4b). At this SOC:clay ratio, 63% of the samples show degraded (Sq > 3) or moderate (Sq = 3) structure. This 1:13 ratio can be considered as a "minimum value" below which the structure is likely to be degraded. Most of these samples are from conventionally-tilled fields (55%), but a considerable fraction also is from fields under NT (33%). The proposed SOC:clay criterions are summarized in Table 4.

As can be seen in Figs. 4 and 5, a high SOC:clay ratio is not sufficient to have a good structure, since a soil with a large SOC content can be mechanically compacted. On the other hand, the smaller the SOC content, the more the soil can be affected by mechanical stresses (Goutal-Pousse et al., 2016; Schäffer et al., 2008). It is, therefore, logical to find an increasing VESS score with decreasing SOC, though the structure degradation can also be due to low SOC (Kay, 1998; Kay and Munkholm, 2004). On the contrary, some samples with small SOC:clay ratio received a good score. An important factor in this context is local heterogeneity, which is particularly high in tilled soils, resulting in large scoring heterogeneity at the local scale (Johannes et al., 2016). These uncertainties, however, are likely to be averaged out due to the large number of data used to calculate the SOC:clay ratios for the different scores, and the proposed SOC:clay criteria are, therefore, relevant. This is supported by the good partition between permanent pasture and tillage obtained with the 1:10 ratio. Based on a large survey of arable soil properties the criteria represent realistic goals for application. The present results were established on samples collected in the 5–10 cm layer and apply to the topsoil. Below the plough layer, because SOC content drops dramatically, changes in clay content would most likely become the leading parameter controlling the physical properties.

Our results were obtained from samples from Cambi-Luvisols developed on mixed moraine-molasses bedrocks. This is a wide group covering a large area of Europe. Moreover, apart from the methodological improvements that may explain some of the discussed discrepancies with the literature, our results are generally in line with previously reported observations, in particular regarding the importance of a SOC:clay ratio of 1:10 and the relation between SOC and physical properties. They may apply, therefore, to a much larger range of soils, which should be tested.

4. Conclusions

For soils showing no evidence of physical stress or structure degradation, the linear relation between SOC and soil pore volume (or 1/BD) means that a SOC increase will result in a proportional increase of soil porosity regardless of how much SOC is complexed to clay. Contrarily to Dexter et al. (2008), we found no optimum in the correlation between the physical properties and a COC fraction of the SOC proportional to the clay content. The largest correlations were observed when the SOC content was fully taken into account indicating that total SOC controls physical properties rather than COC.

The SOC:clay ratio, however, appears to be a relevant criteria when considering soil structure quality. Soils with visually evaluated good structure quality have higher SOC:clay ratios than soils of poor structural quality, and the different structure quality scores correspond in average to different SOC:clay ratios. This allows the establishment of criteria for SOC management. We proposed a ratio of 1:8 as a field optimum for good structure quality, and 1:10 as a reasonable goal for farmers, reachable even with tillage. Finally, 1:13 is a ratio below which the structure quality is most likely unacceptable and needs improvement. Nevertheless, the 1:8 and 1:10 SOC:clay ratios do not guarantee a good soil structure, since mechanical damage may occur regardless of SOC content. These results support the idea that complexed organic carbon is a relevant concept for soil structural quality, and that clay content has to be taken into account in the definition of objectives for SOC content.

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