Searching the critical soil organic carbon threshold for satisfactory tilth conditions – test of the Dexter clay:carbon hypothesis

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Summary

The concern for deteriorating soil structure at low soil organic matter (SOM) contents calls for better knowledge of SOM interaction with soil minerals as well as guidelines for soil conservation. We measured clay dispersibility in a field with a textural gradient. Our results support the concept of differentiating soil content of clay in a complexed and non-complexed part although our data did not point out an exact clay/OC ratio threshold. Our results also indicated that labile fractions of SOM may play an important role in soil physical behavior. We revisited literature data and found evidence that soil content of fines (<2 or <20 µm) is a major determinant of soil specific surface area (SA). We noted that soil SA coverage with SOM changed dramatically at a specific ratio of either clay (<2 µm) or clay+silt (<20 µm) with soil OC. This is an indirect support of the recently suggested quantification of the soil mineral 'saturation' hypothesis. More studies are needed on the causal relationships. We conclude that clay/OC~10 or (clay+silt$_{20\mu m}$)/OC~20 are corresponding indices reflecting shift in soil physical behavior.

Introduction

There is a general concern that low soil organic matter (SOM) contents may deteriorate soil physical properties. Loveland and Webb (2003) reviewed the literature but failed to identify a critical lower threshold of SOM for sustained soil functions. A group of scientists gathered for the same task during the European Union work on a Soil Thematic Strategy suggested target SOM values for all the hundreds of combinations of climate and soil types (van Camp et al., 2004). Such an approach reflects that the state of knowledge of SOM interaction with mineral particles is rather poor. It is further a very ineffective strategy for soil conservation. Dexter et al. (2008) recently showed that SOM effects on soil physical properties can be related to the clay-size soil fraction. Work on Polish and French data sets indicated that organic carbon (OC) was complexed with clay for n=clay/OC ratios higher than n=10, which was often observed for arable soils. For pasture soils, clay/OC ratios were typically below 10. Such soils have often been considered as having passed their ‘capacity factor’ for carbon sequestration (Hassink, 1997). Dexter et al. (2008) defined complexed clay (CC) as CC=(nOC) if (nOC<clay) else CC=clay, while non-complexed clay (NCC) in turn was defined as NCC=(clay-CC) if (clay-CC)>0 else NCC=0. In this paper we examine, whether the clay/OC = 10 ‘saturation’ threshold fits with observed data for soil physical behaviour in Denmark. We further put the concept into perspective by evaluating the relation between soil mineral fines and soil surface area.

Materials and Methods

Cubes (~700 cm^3) of minimally disturbed soil were collected in the plough layer of a loamy field with a textural gradient at Flakkebjerg, Denmark. We sampled in experimental plots managed either with i) organic manures, crop rotation including grass leys (labeled O2), ii) organic manures, annual crops (O4), or iii) mineral fertilizers, annual crops (C4). Sampling took place in a winter wheat crop in the spring each of the three years 2007, 2008 and 2009. Subsamples were taken from the cubes and clay dispersibility measured by a low-energy input method including end-over-end shaking in water for 2 minutes (Schjønning et al., 2002). Further, soil was air-dried and 1-2 mm aggregates isolated from the fragmented soil. Clay dispersibility was then measured on collections of aggregates either at air-dry condition or re-saturated and drained to -100 hPa matric potential.

Results and discussion

New data for clay dispersibility

In Fig. 1 we plotted clay dispersibility against NCC (n=10) for three years of measurement in experimental plots at the Flakkebjerg field with a clay gradient. We note that clay dispersibility was dependent of year of measurement. This may be due to different management conditions in the period up to sampling (e.g. water contents at tillage) (Watts et al., 1996). This additional dimension in evaluation of soil structural stability is very important but not the subject of this study. We further note that we never observed levels of dispersed clay higher than the NCC (the 1:1 line in the Figure). We found a significant increase in dispersed clay with increase in NCC. However, the regression lines did not meet origo for any of the years. By recalculation of NCC with different values of n, we found optimized probability of non-significant intercept for n equal to 5.0, <3, and 8.5 for 2007, 2008 and 2009, respectively (calculations not shown). This supports the concept with distinction between complexed and non-complexed clay. On the other hand, the results also indicate that comprehensive data sets are needed to settle the most correct value of n=clay/OC.

In Table 1, we have tabulated the ratio between the clay dispersed from the air-dried aggregates and from those at -100 hPa matric potential. Data for 2007 is lacking because aggregates were not available in sufficient quantities. A low ratio indicates a high degree of cementation of clay particles at dry conditions (aggregates behaving as 'burned bricks' rather than biologically stabilized aggregates). In both years, the highest ratio was observed for the treatment with organic manures and crop rotation including leys, while the lowest was observed for the treatment with mineral fertilizer and arable cropping. The treatment-induced differences in NCC calculated from SOM were negligible (data not shown). The results in Table 2 thus reflect pools of labile organic matter that need to be taken into account when evaluating soil structural stability.

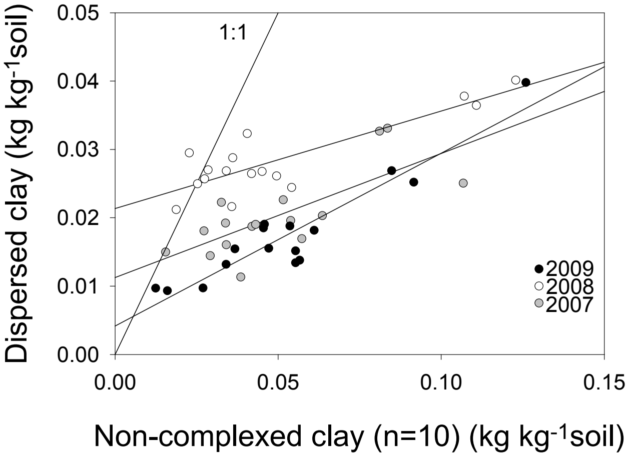

Fig. 1. Clay dispersibility in a low-energy test for experimental plots at a field with a textural gradient. Non-complexed clay calculated assuming clay 'saturation' for clay/OC=10.

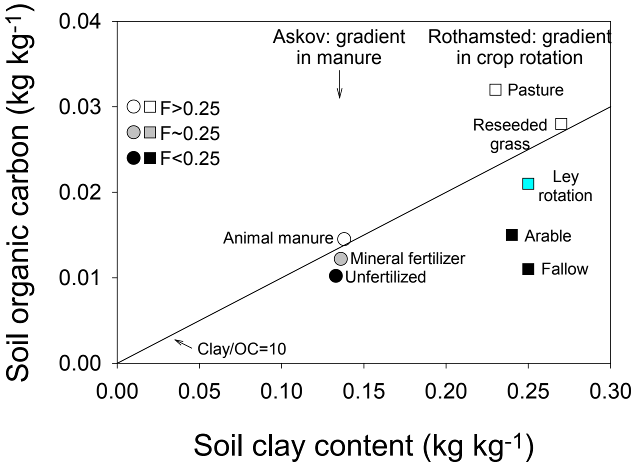

Fig. 2. Soil content of clay and OC for two management-induced gradients in OC. Index of soil friability, F, calculated from tensile strength of dry aggregates and transformed to comparable expressions as suggested by Dexter (2004). F~0.25 corresponds to 'acceptable' friability. Data from Watts & Dexter (1997) and Munkholm et al. (2002).

Table 1. The ratio between dispersed clay from dry and wet 1-2 mm aggregates when shaken in water for two minutes. Numbers of replicate plots for each treatment are 6, 6 and 4 for the O2, O4 and C4 treatments, respectively. Figures followed by the same letter within a specific year are not significantly different (P=0.05).

Crop rotation	Sampling year	
	2008	2009
Organic manure, incl. grass ley (O2)	0.95a	0.64a
Organic manure, annual crops (O4)	0.93a	0.61a
Mineral fertilizes, annual crops (C4)	0.87a	0.57b

The clay/OC ratio and soil friability

Fig. 2 shows results from two long-term experiments with either different fertilization (Askov, Denmark; Munkholm et al., 2002) or crop rotation (Rothamsted, England; Watts & Dexter, 1997). We note that crop rotation (Rothamsted) has induced greater differences in SOM than fertilization strategy (Askov). The line in the Figure is equivalent to n=10 as suggested by Dexter et al. (2008) as a clay 'saturation' threshold. The Rothamsted treatment with the highest SOM content had permanent pasture, while all other treatments were managed in arable cropping. The low clay/OC ratio of the pasture soil supports the idea that such soils may display SOM not complexed to minerals (Hassink, 1997; Dexter et al., 2008).

Soil friability is a measure of a soil's tendency to crumble to smaller fragments under the action of an applied stress. This tilth property is important e.g. for creation of suitable seedbeds and have been shown to relate to clay dispersibility. Soil friability can be quantified from the tensile strength of aggregates by different approaches, and Dexter (2004) showed that the threshold between 'poor' and 'good' tilth can be expressed by an index F=0.25, where F is Dexter's F3 or ½F1 value,- please consult Dexter (2004) for details. From Fig. 1 we note satisfactory tilth conditions (F>0.25) at the Askov treatment with animal manure, while friability for the arable treatment at Rothamsted with nearly the same SOM content was 'poor' (F<0.25). Such an observation is exactly the source for confusion as evidenced by the Loveland and Webb (2003) paper. However, taking the clay content into account – as quantified by the Dexter-n ratio between clay and SOM – the trend in data makes sense.

Soil organic matter and soil surface area

The scientific basis for expressing soils' ability to complex organic matter simply by soil clay content needs verification. Several studies have found SOM also in the silt and even the sand size organo-mineral particle fractions (Christensen, 1992). Further, the clay mineralogical composition is different among soils, which may compromise the Dexter idea of clay/OC=10 as a general threshold for clay 'saturation'. We re-analyzed some data for specific surface area (SA) determined by the Ethylene Glycol Monoethyl Ether (EGME) method. The data reported by Petersen et al. (1996) was supplemented by new measurements performed by the same laboratory but including soils with different mineralogy and geographical origin (de Jonge, L.W., unpublished data). Multiple regressions showed that only soils' content of clay and SOM contributed significantly to SA. Further, clay accounted for nearly all the variation (analyses not shown). However, we also noted that across the soils studied, the fraction of silt (2-20 µm) correlated strongly with the fraction of clay (R^2 =0.83, RMSE=0.039). This means that we cannot unambiguously identify the causal dependency between the mineral fractions and the SA.

In Fig. 3 we have calculated the amount of SOM per unit SA and plotted it against the clay/OC or the (clay+silt)/OC ratio for the data set just discussed. Interestingly, we found a close fit to a hyperbolic type relation for both drivers. The degree of fit to a hyperbolic relation reflects, whether SA is determined by the mineral fraction in question. Linear regression of log-transformed data indicated that the <20 μm fraction explained nearly the same variation in SA data as the <2 μm fraction (see equations in the Figures). Assuming a SOM density of 1 g cm^{-3}, the SOM equivalent layer thickness can be calculated to range from ~0.1 to 6 nanometer for the soils studied (right-hand ordinate axis in the Figures). We note that the Dexter clay/OC ratio of n=10 corresponds to approximately 1 nanometer equivalent SOM coverage of EGME-accessible surfaces. Interestingly, our data show that the layer thickness increases dramatically where the clay/OC ratio gets below 10. We found a linear relation between the (clay+silt)/OC (y) and the clay/OC ratio (x): $y=1.85*x$, $R^2=0.97$. Accordingly, the increase in soil SA coverage with SOM increases when the (clay+silt)/OC ratio decreases below ~18.5 (or approximately 20) (Fig. 3b). We interpret the results as an indirect support of Dexter et al.'s hypothesis of a soil 'saturation' threshold for SOM. SA data from soils with independently varying contents of clay and silt is needed to evaluate, whether the clay/OC=10 threshold should be regarded only an empirical index or whether it actually reflects causal relations. Nevertheless, the concept seems valuable and useful in soil conservation contexts even when regarded only an index.

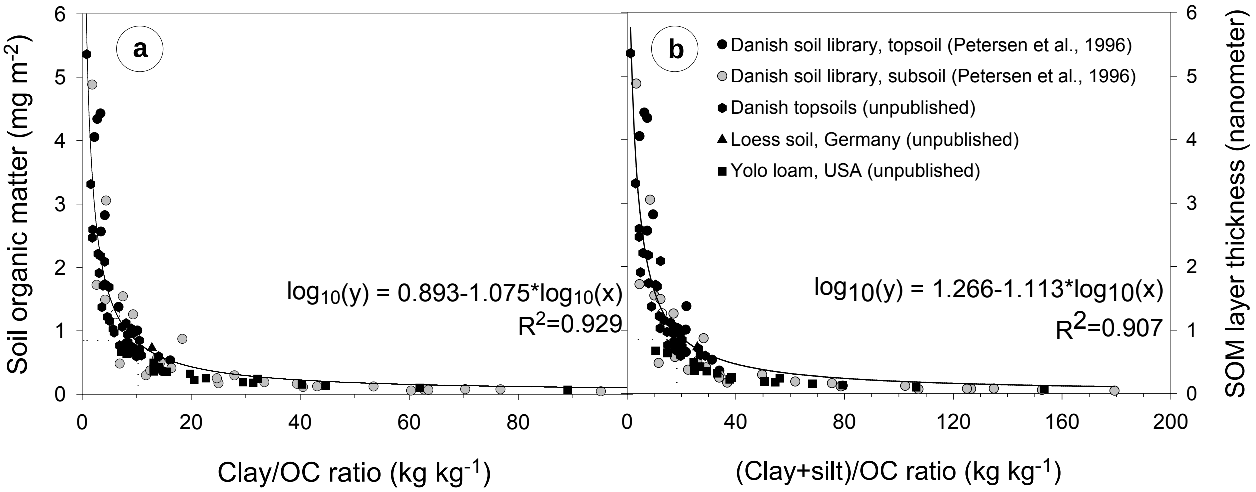

Fig. 3. SOM relative to the specific SA plotted against (a) the clay/OC ratio or (b) the (clay+silt$_{<20\ \mu m}$)/OC ratio for a range of soils.

Conclusions

Three years of clay dispersibility measurements in a field with a textural gradient supported the concept of clay 'saturation' with organic matter although our data did not unambiguously point out n=10 as the clay/OC threshold. Manure applications and crop rotations seem to affect clay dispersibility through pools of labile organic matter that are negligible in quantity as compared to the inherent SOM. Data from the literature showed that soil SA related to soil clay (< 2 µm) as well as to clay+silt (<20 µm) particle fractions. Soil SA coverage with SOM increased markedly for clay/OC ratios below 10 or for (clay+silt)/OC ratios below 20. Soil friability quantified at two long-term field experiments further indicated that soil tilth may become non-optimal for values of clay/OC>10, which may also be expressed by a (clay+silt$_{<20\mu m}$)/OC ratio >20. There is an urgent need for further studies of the causal relations giving rise to these valuable thresholds for soil quality.

Acknowledgements

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