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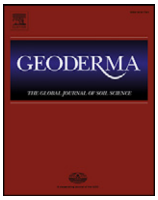

The influence of clay-to-carbon ratio on soil physical properties in a humid sandy loam soil with contrasting tillage and residue management

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ABSTRACT

Tillage and residue management influence soil organic carbon (SOC) and lead to changes in soil physical behaviour and functioning. We examined the effect of the clay-to-carbon ratio on soil physical properties in a humid sandy loam soil with contrasting tillage and residue management. Soil was sampled at the 0–10, 10–20 and 25–30 cm depths of a sandy loam soil at Flakkebjerg, Denmark in 2013. We used the experimental plots of a long-term field experiment with mouldboard ploughing (MP) and direct drilling (DD) treatments. The residue management included straw removal (−S) and straw retention (+S). We measured SOC, clay dispersibility and tensile strength of air-dried 8–16 mm aggregates in either natural or remoulded condition. Soil friability, soil workability and specific rupture energy were calculated from the tensile strength measurements. SOC was higher in DD at 0–10 cm than MP at 0–10 cm and DD and MP soil at 10–20 cm, while MP was higher than DD at 10–20 cm depth ($p < 0.05$). However, there was no difference in the effect of the contrasting tillage managements on carbon sequestration when an equivalent soil mass and the entire topsoil layer were considered. In the top 10 cm soil, DD decreased clay dispersibility ($p = 0.09$) and increased soil friability ($p < 0.05$) compared with the MP soil. Direct drilling with straw removal (DD − S) resulted in higher workability compared with mouldboard ploughing with straw removal (MP − S) ($p < 0.05$). We defined non-complexed clay as NCC = clay − 10 × SOC according to Dexter et al. (2008). NCC was a better predictor of dispersible clay than total clay and SOC at all depths in natural aggregates, while tensile strength and derived parameters were generally better explained by the total amount of clay in remoulded aggregates. Remoulded aggregates had higher tensile strength and rupture energy but lower friability and workability than natural aggregates. A linear regression of total clay and SOC explained better ($R^2 = 0.79$) the variation in tensile strength of remoulded aggregates than models including the clay-to-carbon ratio. Our results indicate that the degree of clay saturation with carbon has a significant influence on clay dispersibility in natural aggregates, while soil aggregate strength expressions of remoulded aggregates are better explained by soil clay content.

1. Introduction

Soil organic carbon (SOC) decline is assumed to impose a threat to soil quality (Johnston et al., 2009; Schjønning et al., 2009). A low SOC content may deteriorate soil structure, including aggregate stability (Elmholt et al., 2008). Abid and Lal (2009) observed a negative correlation between aggregate tensile strength and SOC. Watts and Dexter (1998) and Guimarães et al. (2009) found a positive correlation between soil friability and SOC. Dexter and Czyz (2000) and Czyż et al. (2002) demonstrated a reduction of clay dispersibility with increasing SOC. Furthermore, Arthur et al. (2014) reported that workability in illitic soils was positively related to the SOC content.

Intensive tillage and traffic applied to soil with low SOC content under wet conditions makes the soil vulnerable to clay dispersion (Schjønning et al., 2012; Watts and Dexter, 1997). Upon drying, the dispersed clay forms an internal crust and cement (Kay and Dexter, 1992), which ultimately develops mechanically strong soil aggregates. These may require a higher energy input to initiate fragmentation (Kay and Munkholm, 2004) with a likely adverse effect on friability (Kay and Dexter, 1992) and workability. The overall outcome may be that the soil becomes more difficult to work.

The dynamics of SOC are affected differently with different tillage practices. A long-held general assumption is that direct drilling (DD) increases SOC compared with mouldboard ploughing (MP) (Baker et al., 2007; Conant et al., 2007; West and Post, 2002). This, however, was not apparent when the comparison considered the whole Ap soil horizon and equivalent soil mass (Angers and Carter, 1996; Angers et al., 1993b). The effect of DD was here limited to alteration of SOC location and in a build-up of SOC near the soil surface (Angers et al., 1997; Baker et al., 2007). The DD's induced stratified SOC increase near the surface were expected to bring about an important subsequent effect on a range of processes (e.g. soil less vulnerable to slaking (Angers et al., 1993a), reduced surface runoff and erosion (Soane et al., 2012)

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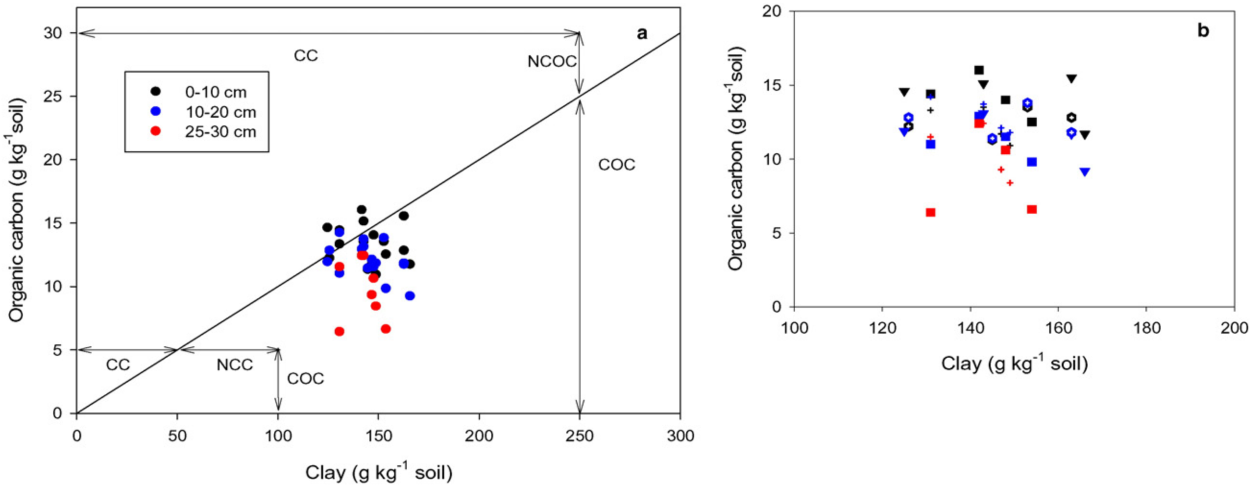

Fig. 1. The clay and organic carbon contents of soil from the experimental plots for 0–10, 10–20 and 25–30 cm depths. The straight lines indicate the suggested condition for clay saturation by OC: n = clay/OC = 10 (Dexter et al., 2008) (left). The clay and organic carbon content of soil for each experimental treatments and soil depth (right). DD + S (Square), MP + S (plus), MP − S (hex, x hair) and DD − S (downward-pointing triangle). Colour differences indicate different soil depths similar to Fig. 1a. Please consult text for explanation of clay and OC fractions.

and improve soil structural stability (Carter, 1992)). A higher SOC concentration for MP than for DD was, on the other hand, found at 10–20 cm depth (Baker et al., 2007; Powlson et al., 2011; Powlson et al., 2014; Riley, 2014; Schjønning and Thomsen, 2013).

The aforementioned paragraphs confirm the strong relations that exist between SOC, soil and crop management, and soil physical properties. There has been an attempt to define the critical lower threshold level of SOC for British soils to ensure soil functioning, but this was not successful (Loveland and Webb, 2003). This reveals that the interaction of SOM and soil mineral particles is not fully understood, indicating the difficulty in using the approach in soil conservation and management (Schjønning et al., 2012). However, based on the work of Hassink (1997), Dexter et al. (2008) proposed a clay-to-carbon ratio of about 10 as a transition point for a shift in soil physical properties. They underlined that the change in soil physical properties is driven more by the relative contents of SOC and soil minerals than total SOC. In this paper, therefore, we examined the cumulative effect of tillage and residue management on SOC and its impacts on soil physical properties in a humid sandy loam soil. We further compared soil strength, rupture energy, soil friability and workability for remoulded and natural aggregates to test the effects of the clay-to-carbon saturation concept suggested by Dexter et al. (2008). We hypothesised that the relative contents of SOC and soil minerals was a better driver of soil physical properties considered in this study than total clay and SOC. We also expected a stratification of carbon in the soil layer for DD and that this would influence the soil physical properties.

2. Materials and methods

2.1. Experimental site

The experimental site was established in 2002, which was eleven years prior to the start of our investigation at Flakkebjerg (55°19′N, 11°23′E), Denmark. The soil derives from moraine deposits of the last glaciation. It is a freely-drained sandy loam and according to the WRB (FAO) classification system is a Glossic phaeozem (Krogh and Greve, 1999). In the 0–25 cm layer, the soil consists of 27% coarse sand (200–2000 μm), 43% fine sand (20–200 μm), 14% silt (2–20 μm), 15% clay (<2 μm), about 2% organic matter (Munkholm et al., 2008) and a pH of 6.3. The mean annual precipitation and temperature at Flakkebjerg (1961–90) are 558 mm and 7.7 °C, respectively (Olesen, 1993). The potential evapotranspiration of the area is 586 mm (Olesen, 1991).

2.2. Experimental design and treatments

The design was a split-plot in four replications comprising two factors – straw management and tillage. The main plot consisted of straw removal (−S) and retention (+S) treatments. The tillage system included direct drilling (DD) and mouldboard ploughing (MP) as subplots. In this study, the four treatment combinations were labelled as DD − S, MP − S, DD + S and MP + S. From 2003, the cropping sequence was winter wheat (*Triticum aestivum* L.) with under sown perennial rye grass (*Lolium perenne* L.), spring barley (*Hordeum vulgare* L.) with under sown perennial rye grass, pea (*Pisum sativum* L.), winter wheat, winter wheat, winter barley (*H. vulgare* L.) with in-sown fodder radish (*Raphanus sativus* L.), oat (*Avena sativa* L.), winter wheat and spring barley accompanied by in-sown fodder radish. The fodder radish was spread out in the field 14 days prior to the harvest of the main crop (Hansen et al., 2015).The experimental fields had been under arable farming including mouldboard ploughing for decades before the initiation of the investigation (Hansen et al., 2010). The MP plots were ploughed to a depth of about 20 cm before sowing of the main crops. The DD plots had not been tilled since autumn 2002, except for disturbances during seeding (5–8 cm). A chisel coulter drill (Horsch Airseeder CO 4) was used for DD and a traditional seed drill for MP.

2.3. Soil sampling and measurements

2.3.1. Soil sampling

Soil sampling took place in a winter wheat (*T. aestivum* L.) crop in the fourth week of November, 2013. The MP and DD plots had been

Table 1
Treatment effects on soil organic carbon content of each soil depth.

Depth cm	Soil organic carbon concentration (g kg^{-1} soil)							
					Straw		Tillage	
	DD + S	MP + S	DD − S	MP − S	+S	−S	DD	MP
0–10	14.2	12.3	14.2	12.4	13.3	13.3	14.2^{c}	12.4^{ab}
10–20	11.3	12.9	11.4	12.4	12.1	11.9	11.3^{a}	12.7^{b}
25–30					9.7		9.0	10.4

Interactions between treatments were not significant ($p > 0.05$). The main effects of tillage and straw management were tested. For the upper two soil depths the autoregressive, AR (1) correlation structure was used to test differences across soil layers. Different lower case letters indicate statistical significance at $p < 0.05$.