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Adopting soil organic carbon management practices in soils of varying quality: Implications and perspectives in Europe

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A B S T R A C T

Soil organic carbon (SOC) content can greatly affect soil quality by determining and maintaining important soil physical conditions, properties and soil functions. Management practices that maintain or enhance SOC affect soil quality and may favour the capacity of soils to sequester further organic carbon. Nevertheless, the effectiveness of these measures depends upon both the soil characteristics and the current SOC content.

This study defines an indicator of soil potential stability *(n-potential)* allowing the most effective practices in terms of soil stability and capacity to store organic carbon to be selected. By relating the clay content to SOC content, the *n-potential* indicates the "potential" presence of non-complexed clay (NCC) in soils, enabling the soil stability and its capacity to store carbon (C) to be inferred. In this work, we classify soils of European regions based on five *n-potential* categories (i.e. >20; 15–20; 10–15; 5–10; <5). By relating the information provided by the *n-potential* to the specific texture of the analysed soils, priority actions (i.e. protecting the existing soil stability or promoting soil aggregate formation) that should be adopted are identified. Our findings show that the selection of the appropriate SOC management practices can greatly contribute improving soils of European regions in terms of quality and capacity to store organic carbon.

The *n-potential* contributes to the understanding of the physical consequences on soils arising from implementation of SOC management practices. This can guide the development of policies promoting the application of such practices, and can help farmers to select the practices that are most effective in maintaining or increasing of SOC content and soil stability.

1. Introduction

Soil organic carbon (SOC) plays crucial roles in determining and maintaining important soil physical conditions and soil functions (Dexter et al., 2008; Schjønning et al., 2012). SOC, which occurs as soil organic matter (SOM), influences the fluxes of key plant nutrients and thus the agronomic productivity of soils (Dexter et al., 2008; Whitbread, 1995; Lal, 2006; Smith et al., 2016). Soil carbon also greatly influences soil structure and related properties (e.g. water retention, bulk density, friability, tillage) by contributing to the formation of stable aggregates (Dexter et al., 2008; Lefroy et al., 1995). A decline of SOC content, through loss of organic matter, implies a decline of soil quality, i.e. the capacity of a soil to function (Karlen et al., 1997). Several of its key properties would therefore be altered, with adverse effects on crop productivity and with a reduction in the soil's capacity to protect C from mineralization.

Soil management practices may significantly influence the capacity of the soil to sequester SOC. On the other hand, the carbon accumulated in soil arising from specific practices, can be lost more rapidly because of land-use change (Smith, 2005; Smith, 2008). In order to obtain the greatest potential soil carbon sequestration, the established carbon sinks need to be protected (e.g. by maintaining

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native plant cover or continued best management) from significant disturbance over time (Smith, 2004). Alvarez et al. (2014) show that no-tillage practice increases the total carbon and nitrogen amount when compared with other tillage systems (e.g. reduced tillage), though other studies have suggested smaller effects (Powlson et al., 2014).

As a general rule, SOC management practices are targeted to enhance and/or to maintain soil C, but their effectiveness depends upon both the soil characteristics (i.e. soil quality) and the current SOC content. Indeed, the adoption of a practice that enhances organic carbon content could result in an unintended consequence in a soil already saturated with C, since the added C would be lost (Dexter et al., 2008; Freibauer et al., 2004; Hassink, 1997).

Under these circumstances, a question arises: which kind of information might be helpful to select the most effective SOC management practices in terms of soil stability and carbon storage? To address this question, we identified the actions that should be taken as a priority to protect existing soil aggregates, to promote the genesis of new soil aggregates or to achieve both objectives. To address this aim, we defined the soil potential stability indicator *(n-potential),* which is given by the ratio between the soil texture (i.e. clay content) and the SOC content. This indicator allows soils to be classified in quality terms, which we assume to be related to the potential presence of non-complexed clay (NCC).

In Section 2, an overview of the management practices that affect SOC is provided. Section 3 describes the potential stability indicator "*n-potential*" and discusses its rationale. In Section 4, findings obtained by mapping soils across Europe in terms of clay content, SOC content and quality according the *n-potential* indicator, are discussed. Sections 5 provides a conclusion to the manuscript.

2. SOC management practices

By changing soil physical and chemical characteristics, agricultural management practices greatly affect soil properties, functionality and quality (Kuotsu et al., 2014; Okadaa et al., 2014; Silva et al., 2014). Das et al. (2014) state that the major causes of soil degradation are attributable to intensive tillage-based production, along with practices such as residue removal, inadequate fertilization and limited use of manure. In this respect, many authors underline the advantage of SOC management practices (Smith et al., 2015). For instance, cover crops can prevent erosion, enrich the soil with organic matter and fulfil functions such as nitrogen fixation (Barthès et al., 2004; De Baets et al., 2011; Poeplau et al., 2015). No-tillage and reduced tillage management practices can affect the decomposition rate of soil organic matter and thus the availability of nutrients, by favouring the relative abundance of specific soil microorganisms over others (Frey et al., 1999). Moreover, some previous studies have revealed that the combination of practices can enhance the beneficial effects on soil compared to individual practices: e.g., crop residue retention amplifies the positive effects on water retention, soil physical conditions and microbial activity of no-tillage practices (Varela et al., 2014; Silva et al., 2014).

Several authors have discussed the effects of SOC management practices on the capacity of soils to sequester and store organic carbon (Smith et al., 2000; Díaz-Zorita and Grove, 2002; Flynn et al., 2007; Trigalet et al., 2014). Diaz-Zorita and Grove (2002) argue that the adoption of conservation tillage practices may promote "surface accumulation of C because of reduced mineralization". Practices based on the reduction of tillage intensity may induce an increase in SOC (Arrouays et al., 2002).

The carbon stock–enhancing effect of SOC management practices can occur because of either increased carbon input or reduced soil disturbance, or through a combination of the two (Freibauer et al., 2004). In this work, we distinguish between (i) those practices that reduce soil disturbance, from (ii) practices that, instead, promote increased soil carbon stocks (Freibauer et al., 2004). Table 1 summarizes the effects on SOC content due to the adoption of the SOC management practices.

2.1. Reducing soil disturbance

2.1.1. Zero or no tillage

In terms of soil disturbance, zero-tillage (ZT; also known as no-tillage) is an increasingly applied conservation practice. It consists of cultivating crops while adopting agricultural practices that leave the soil undisturbed. The only soil disturbance occurring under zero-tillage is related to the movement of the agricultural machines generally used for weeding, seeding and harvest. Most authors refer to ZT as to a system (Carter and Rennie, 1982; Frey et al., 1999; Das et al., 2014), which is applied over a period far longer than a specific crop cycle and includes other practices such as crop rotation and cover crops. The drastic reduction of the pressure on soil due to the adoption of the ZT system brings different benefits to the soil, especially over long periods, such as: increased fraction and stability of macro-aggregates and improvement of water infiltration (Franzluebbers, 2002); reduction of erosion (De Freitas and Landers, 2014); greater aeration (Batey, 2009); improved soil moisture and reduction of bulk density (Jin et al., 2011) in the topsoil. In wetter, heavier soils however, zero tillage can hamper crop emergence and soil workability (Smith et al., 1998), so is not suitable for all soils and bioclimatic regions. ZT can protect organic matter from high temperature and thus reduce mineralization (Alvarez et al., 2014) and has positive effects on soil chemical characteristics, (e.g. cation exchange capacity and organic matter content; Wu et al., 2015).

2.1.2. Reduced tillage

In this work, we refer to reduced tillage (RT) to cover all those practices which, regardless of whether the practices are inversion (e.g. mouldboard plough) or non-inversion tillage-based (e.g. chisel), significantly reduce soil disturbance by: shallower depth of tillage; reduced frequency of passes over the soil or by tilling only specific field portions (e.g. strip and ridge tillage). RT practices improve soil structure by favouring soil aggregation and SOC stabilization (Sheehy et al., 2015; Kabiri et al., 2015). Alliaume et al. (2014) note that, when combined with mulching and manure, RT can favour moisture conservation, further reducing runoff and soil erosion because of the greater quantity of water intercepted and stored.

2.1.3. Direct drilling

By cultivating a narrow band of soil where seeds are placed and then covered by a rear roller or a harrow, direct drilling (DD; also known as no-till seeding) allows the main crop to be sown into the previous crop stubble on an untilled soil (Morris et al., 2010). Because of the significant reduction of soil disturbance and the presence of crop residue, it ensures the protection of soil particles against water and air erosion to a much greater degree than under conventional seeding (inversion-tillage based). When soil is left undisturbed from sowing to harvest, DD is, in all respects, a zero tillage practice and its effects on soils are similar to those due to ZT (Arrouays et al., 2002).

2.2. Enhancing C-input

2.2.1. Cover crops: catch crops and green manure

The cultivation of cover crops (CCs) ensures soil cover in periods in which no crop cultivation is scheduled in an annual cropping