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

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Abstract

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.

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 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 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 addess 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; Okada *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; Diaz-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

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).

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 (Sheedy *et al.*, 2005; 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.

Direct drilling

By cCultivating 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

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 system. De Baets *et al.* (2011) list several physical and chemical functions associated with cover crops, ranging from nitrogen fixation and carbon sequestration to improved soil aggregation and the prevention of wind and water erosion. The impact of cover crops on the development of soil microorganisms and fauna, as well as on the prevention of contaminant leaching to groundwater is further recognised. Based on the specific soil functions affected by cover crops, Dabney *et al.* (2010) divide cover crops into catch crops and green manure.

Catch crops are grown with the specific aim of preventing leaching nitrogen losses (Cicek *et al.*, 2015; Constantin *et al.*, 2010) by taking up available nitrogen in the soil. Catch crops can be sown after the main crop harvest (usually in conventional systems) or after animal manure application (usually in organic systems). However, timely sowing would maximize their root growth and thus their effectiveness at catching leached nutrients (Dabney *et al.*, 2010).

Green manure is instead a cover crop that fulfils both the fertilizing function, by improving the nutrition of the consecutive crop (Dabney *et al.*, 2010) and the soil amendment function, affecting soil physical conditions (Alliaume *et al.*, 2014). To this ends, green manure crops can be ploughed into soil or left as a mulch to decay on the soil surface (Varela *et al.*, 2014). Similarly to catch crops, the effectiveness of this practice is highly affected by the management and the timeliness with which specific cropping operations are carried out (e.g. sowing season and mowing period).

Crop rotation

Because of the nature of the selected crops (e.g. legumes, cereals, grassland) and/or of the management practices adopted, the succession of different crops in a specified order on the same fields (i.e. Crop rotations, CR) greatly affect physical and chemical soil characteristics (Angus *et al.*, 2015; Lal, 2004). For instance, groundwater storage is favoured when the rotation is under a no-tillage system (Gozubuyuk *et al.*, 2015) and when specific crops and techniques are adopted (e.g. corn after cotton better than corn after rice; Dakhlalla *et al.*, 2016); thereby, nitrogen leaching can significantly be reduced to low levels through a proper combination of few crops (e.g. barley with Italian ryegrass rather than with pea and grasslands; Eriksen *et al.*, 2015).

Residue management

Return of residues to the soil rather than residue removal or the application of animal manure and sludge, have the potential to quickly increase soil carbon levels. Residue management directly affects the increase and/or the maintenance of soil organic matter, which in turn will affect chemical (e.g. pH, cation exchange capacity, nutrients cycling) and physical soil properties (e.g. soil particle aggregation, soil moisture content and soil temperature; Turnel *et al.*, 2015). When residues are not incorporated into the soil through tillage, they physically protect soil against water and wind erosion (Turnel *et al.*, 2015), further favouring water retention (Verhulst *et al.*, 2011).

3. Materials and methods

In order to identify and discuss the consequences on soil stability and capacity to store organic carbon arising from the implementation of the management practices, we adopted the logical scheme depicted in Fig. 1. Firstly, we defined the *n-potential* indicator by relating the clay content to the SOC content. Then, based on five *n-potential* categories, the soils of the European Regions were classified with regard to their potential stability. By analysing the varying soil texture classes that may occur within each *n-potential* category, a set of considerations can be made in terms of soil stability and the potential capacity to store organic carbon (i.e. enhancing knowledge). This enhanced knowledge allows both a better understanding of the effects on soil when the different type of SOC management practices are adopted and to identify priority actions, namely (i) to protect the existing soil aggregates, (ii) to promote the genesis of new soil aggregates, or (iii) the combination of the two previous options. Finally, the overall information deriving from the latter step, provides a solid basis for selecting the most effective SOC management practices in terms of soil stability and soil carbon storage.

3.1. The potential stability indicator as soil quality indicator

In order to appreciate the capacity of a soil to function, i.e. soil quality (Karlen *et al.*, 1997), a number of indicators related to soil chemical, physical and biological properties have been proposed (Paz Ferreiro and Fu, 2013; Reeves, 1997). Schoenholtz *et al.* (2000) suggest the use of a range of chemical (e.g. SOC, fertility, pH) and physical (e.g. texture, bulk density, erosion potential) soil properties as static (i.e. point in time) and dynamic (i.e. processes related) indicators of soil quality. Because of its impact on several soil functions, SOM is recognized as a key factor in determining soil quality and thus is considered the most significant single indicator of soil quality and productivity (Reeves, 1997). Arshad and Cohen (1992) propose aggregate stability as an indicator of soil quality, since the presence of stable aggregates positively affects agricultural productivity, and significantly contributes to preservation of environmental quality (Amézketa, 1999). Along these lines, in this work we apply the potential stability indicator (i.e. *n-potential*) as an indicator of soil quality. It relates a soil physical attribute, namely soil texture, with a soil chemical condition amenable to retention of organic carbon. The underlying reason is that this indicator can provide information about the potential presence of non-complexed clay in the soil that can affect different soil properties.

3.1.1. The rationale of the potential stability indicator (n-potential)

Soil stability is defined as the "ability of a soil to retain the heterogeneous arrangement of solid and void space when specific stresses occur" (Amézketa, 1999). The presence of stable aggregates and pores between aggregates, contributes greatly to water movement and water retention, soil aeration and soil biological activity, thus influencing key soil functions. Soil stability is inherently connected to the content of SOC and to the interactions that SOC establishes with the fine mineral particles (i.e. clay and silt: Hassink, 1997; Reeves, 1997; Dexter *et al.*, 2008, Hoyle *et al.*, 2011). In this regard, various authors have provided compelling literature on the maximum amounts of C that become associated with the clay and silt fraction of soil (Hassink, 1997; Hoyle *et al.*, 2011), that account for the "capacity factor" (Amézketa, 1999; Carter *et al.*, 2003; Dexter *et al.*, 2008). To identify the maximum amount of C that can be complexed with clay only, Dexter et al (2008) suggest the use of factor *n* defined as the ratio of the total clay content to the amount of clay that can be complexed by 1 g of organic carbon, Their reasoning is summarised as:

$$\mathrm{Cmax} = \mathrm{clay}/\mathrm{n}$$

Within the aforesaid context, Dexter *et al.* (2008) concluded that 1 g of carbon is complexed with 10 g of clay, giving an n = 10, namely the saturation level. This implies that carbon contents greater than the capacity factor ($n < 10$) result in an amount of carbon that is non-complexed (NCOC) and thus more exposed to decomposition. In contrast, amounts of carbon under the capacity factor have a value of n > 10 and have non-complexed clay (NCC) present, which will be more easily dispersed in water than the complexed clay (CC) (Amézketa, 1999; Dexter *et al.*, 2008). The presence of dispersed clay particles in soil results in a soil that is a structureless mass (Dexter, 2004), thereby affecting soil physical properties. For instance, the decline of soil friability (i.e. an increase of the tensile strength) is due to the increase of NCC and to its cementing action (Watts and Dexter, 1998) affecting aspects such as the soil workability, and soil water and air circulation. Kay and Dexter (1992) state that the increase in tensile strength depends upon the amount of clay dispersed in soil. Indeed, dispersed clay favours soil compaction (i.e. cemented crusts) rather than flocculation with damaging consequences on tilth properties, water content and water and air transport (Schjonning *et al.*, 2009).

An inverse relationship exists between the amount of NCC and SOC content (Dexter, 2004). In fact, though SOC is distributed among different sized aggregates, it actively contributes to aggregate formation by binding clay particles in micro-aggregates (Malamoud *et al.*, 2009; Amezketa, 1999). Angers and Carter (1996) suggested that C is associated with water-stable aggregates and that the labile organic fractions bind micro-aggregates into macro-aggregates. SOC in macro-aggregates is in forms that are relatively labile and thus easily subject to potential decomposition (Angers and Carter, 1996) and only the C in micro-aggregates can be considered "protected" (Carter *et al.*, 2003).

Under these circumstances, we relate soil texture, more specifically the clay content, with the amount of organic carbon in soil, to calculate the soil potential stability indicator (i.e. *n-potential* = clay/SOC). Since its calculation takes into account the total organic carbon (SOC) rather than the fraction of organic carbon that is associated with fine particles (i.e. the light fraction according to the scheme proposed by Carter at al., 2003), we label the *n* indicator with the term "*potential*". Indeed, though the NCC is a function of the clay and SOC quantities in soil (Malamoud *et al.*, 2009), we can speculate upon the soil quality status by hypothesizing the NCC presence, since only part of the total SOC will be involved in clay complexation.

For a better understanding of the consequences related to different *n-potential* values, in our analysis we refer to two *n-potential* range values: ≥ 10 and < 10. Various *n-potential* categories, which represent different combinations of clay content and SOC content, are then taken into consideration within each range value. Table 2 provides an overview of different *n-potential* values.

3.2. Input data

Percentage of organic carbon content and clay content were derived from the LUCAS (Land Use/Cover Area frame statistical Survey) soil survey (Toth *et al.*, 2013; see Figure 3) and were used for calculating the soil potential stability indicator. LUCAS is a harmonised survey across all EU Member States to gather information on land cover and land use. Estimates of the area occupied by different land use or land cover types are computed on the basis of observations taken at more than 250,000 sample points throughout the EU. In 2009, the European Commission extended the periodic LUCAS survey to sample and analyse the main properties of topsoil in 23 Member States of the EU. This topsoil survey represents the first attempt to build a consistent spatial database of soil cover across the EU based on standard sampling and analytical procedures, with the analysis of all soil samples being carried out in a single laboratory. Approximately 22,000 points were selected from the main LUCAS grid for the collection of soil samples. A new monitoring survey is currently ongoing (2015-2016), the results of which can be expected in the next few years. The benefit of LUCAS data is that it is recently observed data and there is a clear link to land use. For our analysis we only used the LUCAS data from arable soils, including all crops apart from grassland. Fig. 2 shows the distribution of the LUCAS data for clay (1a) and SOC (1b). The lighter textured sandy soils are mainly found in northern Europe, whereas heavy clay soils are mainly found in the Mediterranean areas. The organic carbon content is, in general, highest in the north-western part of Europe, while most Mediterranean countries, but also Poland, have low organic carbon values.

For each individual LUCAS sample point, the *n-potential* indicator was calculated as the ratio between the percentage of clay and the percentage of SOC.

4. Results and discussion

4.1. The "n-potential" in European soils

European soils, classified according to the *n-potential* categories, are depicted in the map of Fig. 3. For the sake of understanding of the implications linked to *n-potential*, in the following discussion we refer to the "relative SOC", i.e. the SOC content compared to the total amount of clay.

Soils falling within the category *n-potential* > 20 share the same characteristic: the relative SOC is very low, which implies that most of the existing clay is not complexed (NCC). Though in these soils the primary need seems to be the increasing of SOC, different actions have to be suggested depending on the type of soil. In soils that range from sandy-loamy to silty-loamy, a low clay content (= 10-20%) suggests that, despite the very low SOC content (< 1%), the amount of free clay (i.e. NCC) may be fairly limited if compared to other soil particle size fractions (i.e. silt and sand), further resulting in a restricted potential to store additional C. Under these conditions (e.g. Southern Spain). The priority in these soils is to protect the existing (few) soil (macro and micro) aggregates, which can be met by reducing as much as possible soil disturbance through the adoption of no-till practices. This implies that the adoption of a subsequent practices to increase SOC must be carried out under no-till systems (e.g., crop residues must be left to spontaneously decay on soil surface). Promoting the genesis of new stable aggregates becomes the overriding objective as NCC increases, due to greater clay content.. This condition occurs for soils ranging from sandy-clay-loam to silty clayey (Central Italy with clay ranging from 30 to 40%), being exceptionally clayey (e.g. Central Eastern Italy) with clay content higher than 40%. Although, these soils are rather unstable, they have a very high potential to store C. Thus, despite reasonable SOC content (1.5 to 2.5% corresponding to 2.5-4.31% SOM), practices such as green manure ploughed in the soil, to quickly increase SOC content and CCs are suggested, which will reduce wind and water erosion through continuous soil cover, and will may favour stabilization processes. Within this category (i.e. *n-potential* > 20) an intermediate situation is represented by those soils whose low relative SOC is coupled with clay content of 20 to 30% (soils ranging from sandy-clay-loam to silty-clay-loam; e.g. South Western France). Under these conditions, both types of SOC management practices need to be adopted simultaneously, both to preserve the existent low soil stability and to promote the complexation of the free clay which, given the medium-high proportion of clay in the soil texture (up to 30%), can negatively affect soil characteristics. The same consideration applies when in these soil types (i.e. from sandy-clay-loam to silty-clay-loam) the *n-potential* is 15-20, and the relative SOC is still limited (< 1.5%; e.g. North Eastern France). Nevertheless, in these soils, a higher relative SOC (1.5 to 2.5%) guarantees more stability, and safeguarding the current soil aggregates becomes the priority (e.g. Central Western Germany). On the contrary, increased clay content (30 to 40%; North Eastern Hungary) raises the probability that the NCC may have an adverse effect on soil characteristics: practices favouring the aggregation of the free clay through C inputs should be applied.

When *n-potential* ranges between 10 and 15, it indicates that a significant amount of the existing SOC is engaged in clay complexation (relative SOC higher than in the previous categories) resulting in a limited presence of NCC. Under these conditions, the most preferable action is to protect the current soil stability. Nevertheless, in soils ranging from sandy-clay-loam to silty clayey (i.e. clay is 30 to 40%), because of their higher clay content, carbon input-based practices that could lead towards the saturation level (i.e. the highest level of clay complexation), may be applied in combination with no-tillage or minimum-tillage practices, despite the already relatively content of SOC (up to 3.5%). This, in turn, would allow the considerable C store capacity of such soils to be fully exploited. Soils with an *n-potential* equal to 5-10 show a high relative SOC content. Indeed, in these soils, clay, the content of which does not exceed the 30%, is coupled with a SOC content ranging between 1.5% and 7%. In these circumstances, the modest free clay has a negligible influence on soil characteristics and functions, regardless the soil texture. Therefore, only practices to reduce soil disturbance will be effective, while practices to increase SOC will be ineffective. The latter, indeed, would enrich soils with organic carbon that if not complexed to free clay will be unstable and will be exposed to degradation processes and loss. This is even more true for soils ranging from sandy-loamy to silty-loamy with an *n-potential* <5. In these soils, clay is at most 20% (e.g. North Eastern the Netherlands), while SOC content may exceed 7% (i.e. very high relative SOC content). In this case, it can be assumed that the NCC is absent (or extremely limited) and that existing soil stability cannot be undermined. Moreover, it can be assumed that the already limited capacity to store C of such soils is saturated. This is the case for soils ranging from sandy to silty, where less than 10% of clay is coupled with more than 7% of SOC (e.g. Northern Finland).

At this point, it is important to underline that, over the medium and long term, farmers are required to be dynamic and farsighted in selecting the SOC management practices. Indeed, regardless the soil texture and the priority action to be implemented, when soil stability is achieved, preservation of stability of the soil aggregates becomes the paramount objective for farmers who want to protect the quality and the soils' capacity to store organic carbon. Thus, farmers would benefit from integration of either RT or ZT systems in their own farming system.

4.2. SOC management in European Regions

Relating the identified priority actions (on the basis of *n-potential* and the relative SOC) to the level of implementation of each SOC management practice in the EU 27 regions (Fig. 4), it appears that in most soils there is a great potential for improving or maintaining soil quality, and to fully exploit their capacity to store organic carbon. Currently, most of the EU-27 regions show a limited adoption of SOC management practices (Sánchez *et al.*, 2016, Sánchez *et al.*, 2013). Moreover, the extent to which farmers are aware of practices that contribute to improved soil carbon (Ingram *et al.* 2014), and the regional understanding of the effective choices and costs (Sánchez *et al.* 2014), varies considerably across the European regions. While in Fig. 4 the implementation rates of each SOC management practices in European Regions are depicted, Fig. 5 illustrates the average values of the level of implementation of the SOC management practices of European regions aggregated in four areas along the lines of Sánchez *et al.*, 2016 and Sánchez *et al.*, 2013: Atlantic, Boreal, Continental and Mediterranean.

In the countries of the Mediterranean area (Fig. 5), where *n-potential* > 20 is the most frequent category, both type of practices that reduce soil disturbance and favour the soil aggregate stabilization are seldom used. For instance, in Southern Spain, though the adoption of no-till practices is required, conventional tillage is implemented over more than 80% of arable land compared to reduced tillage that reaches, at most, 20% and zero tillage, which represents only 7% (Fig. 4). A similar situation occurs in Central Eastern Italy where clay-rich soils could be enriched with organic carbon, but both residue management and cover crops are adopted on less than the 20% of land, while conventional practices are adopted on the 60% of the arable land, and up to 20% of land is left bare (Fig. 4). The provision of C-input would allow these soil types to attain their full capacity for C storage, which is the highest among soils in Europe, but is also the least exploited. Ploughing crop residues or green manure into the soil can be counted among conventional practices, but these are the quickest and probably the most effective measures to favour soil particle aggregation, thereby retaining a greater proportion of organic carbon within the soil.

In the Central European countries, that mostly fall within the Atlantic and the Continental areas (Fig. 5), there is a better equilibrium between the clay and the SOC content (*n-potential* falls mostly in the categories 15-20 and 10-15), so practices aiming at the maintenance of the existing soil stability are needed. Nevertheless, in these countries, ZT has received little consideration, not exceeding the 4% of the arable land. Instead, RT is widely applied by farmers; an average value of more than 20% of the arable land is coupled with peaks higher than 40% (e.g. Northern France and Northern Germany) and 60% (e.g. Central Germany).

A better situation can be found among some of the countries of the Boreal area, where there is the highest concentration of soils with *n-potential* <10. Indeed, in these countries, the relative SOC is particularly high, suggesting an established soil stability, especially when *n-potential* <5. Farmers from these Northern regions seem to act in favour of the maintenance of the quality and stability of their soils. Indeed, these areas record, across Europe, the lowest implementation levels of conventional practices (in some regions it is even lower than 20%), which are most responsible for continuous soil disturbance. Moreover, practices that help to protect existing soil aggregates benefit from a broader consensus in regions of the Boreal area than in other European regions: e.g. RT in some cases occurs on up to 40% of land and ZT exceeds 10% (e.g. Southern Finland). In contrast, measures to increase C-inputs, such as RM (most of the Regions are under the average value of 13%) and CCs (2% of the arable land on average), are not widely adopted. Indeed, for these kinds of soils, there is a limited capacity to store C du to both the low clay content and the high relative SOC which is much lower than soils located in Central and Southern Europe: therefore, the added organic carbon would be exposed to degradation and will thus be lost.

Our findings are consistent with the outcomes of Lugato *et al.* (2014a) who assessed SOC stocks by simulating the conversion from arable land to different alternative management practices (e.g. cover crops, reduced tillage, residue management) in European regions. According to their work, an increase in C stock may occur by: (i) converting to practices that reduce soil disturbance (such as grassland and RT) in agricultural soils of Central Europe (with *n-potential* by 10-20) and Northern Europe (with *n-potential* < 10); (ii) adopting practices that increase C-input (e.g. crop residue incorporation) in soils of Mediterranean regions (with a *n-potential* > 20); (iii) the combination of RT and straw incorporation in those agricultural soils where there is a high content of clay and SOC.

4.3. Policy implications

Many European regions are at risk of soil disturbance and soil loss due to both low SOC stock in the topsoil and low levels of implementation of SOC management, especially in the Mediterranean area. Recent evidence-based studies (e.g., Lugato *et al.*, 2014b and the results presented in this paper) suggest clear regional opportunities to improve stocks of soil organic carbon. At the same time, there is recognition that both the incentives and offsetting schemes do not fully capture the actions needed to fully implement SOC farm management practices.

The knowledge-based approach depicted in Fig. 6, illustrates a broader range of considerations to policy development, including evidence-based scenarios, physical constraints (e.g. soil texture, SOC, soil stability) and farm management changes (i.e. SOC management practices adoption) that were described in earlier sections. Nevertheless, a major limitation to policy development is the lack of understanding of the physical constraints. While information provided by the *n-potential* indicator can greatly help to overcome such knowledge shortage (about physical constraints), the inclusion of demonstration and pilot projects, as foreseen by the Rural Development Plans, may facilitate adoption of SOC management practices by farmers. There are major advantages in progressing with this bottom-up approach that demonstrates the effects as physical effects first, and then looks at the economic impacts of these effects.

Finally, in most cases, effective policy development may include combining information from detailed analyses and the wider communication of a number of existing leading studies, which combine the scientific and economic aspects of the alternative SOC management practices (e.g. Macleod *et al.*, 2010; Moran *et al.*, 2011; Alexander *et al.*, 2015).

5. Conclusions

Knowledge of the implications derived from the adoption of management practices in different soil qualities can help farmers to select practices that are the most appropriate and effective to protect or improve soil stability and enhance SOC content for their own soils.

The indicator *n-potential* enabled us, firstly, to classify soils of the European Regions by taking into consideration simultaneously the clay and the SOC content and ranking them according their potential quality (i.e. the hypothetical presence of NCC). Then, by comparing the *n-potential* values to both the specific soil texture and the relative SOC, the overall objective, namely to protect the existing soil-aggregates and/or to enhance the SOC content, and consequently the most suitable SOC management practices, were identified. Our findings show that soils within European regions have room for improvement in terms of their quality and their capacity to store organic carbon. In particular, the unstable soils of Southern Europe have a great potential to store C, while moving towards the Northern regions of Europe, soils are more stable but with a very limited capacity to store additional C. However, from South to North Europe much must be done in identifying those management practices that, respecting the varied nature of the European soils, can contribute towards the improvement and the maintenance of soil quality.

We conclude that information provided by *n-potential* may lead towards the implementation of targeted policy measures, instead of blanket measures, by enriching the policy development processes with a clear and greater understanding of the physical consequences on soils (of different types) due to the implementation of SOC management practices. This greater knowledge and understanding can greatly help farmers to select, within the targeted measures, the most appropriate SOC management practices for their own soils. To this end, farmers must integrate the indications provided by the *n-potential* with information that goes beyond soil dynamics alone, such as the existing cropping systems, the compatibility of crops to the new practices and soil types, the available technology and particularly the economic feasibility, which heavily affects final farmers' choices. Further research is desirable, to explore such agronomic and economic aspects in order to design a complete knowledge-base on SOC management practices, for selecting the most effective practices to improve soil stability and the capacity of soils to store organic carbon.

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Figures

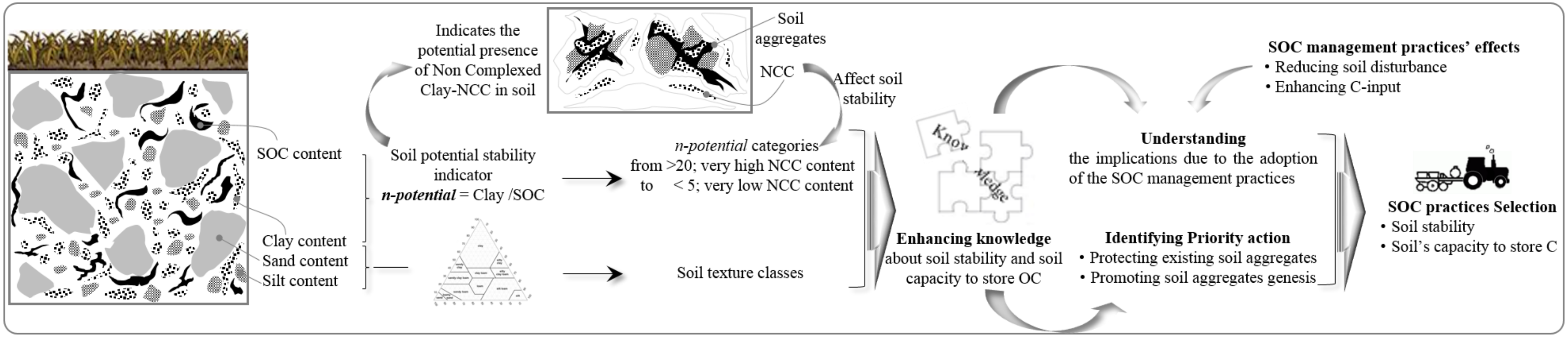

Fig. 1. Logic scheme. By using data about SOC and clay content, the *n-potential* indicator is calculated. Based on five *n-potential* categories, soils of the European Regions are classified based on their potential stability. Soil texture classes are identified within each *n-potential* category. Based on *n-potential* and the specific soil texture class, specific considerations can be made in terms of soil stability and capacity to store OC, enhancing our knowledge about soils. This enhanced knowledge allows us to improve the understanding of the effects of SOC management practices and to identify those actions that have to be taken in order not either improve o, at least, to not impair the existing soil stability. The overall information that flows at the end of our logic scheme is the basis for selecting the most appropriate SOC management practices in soils of varying quality.

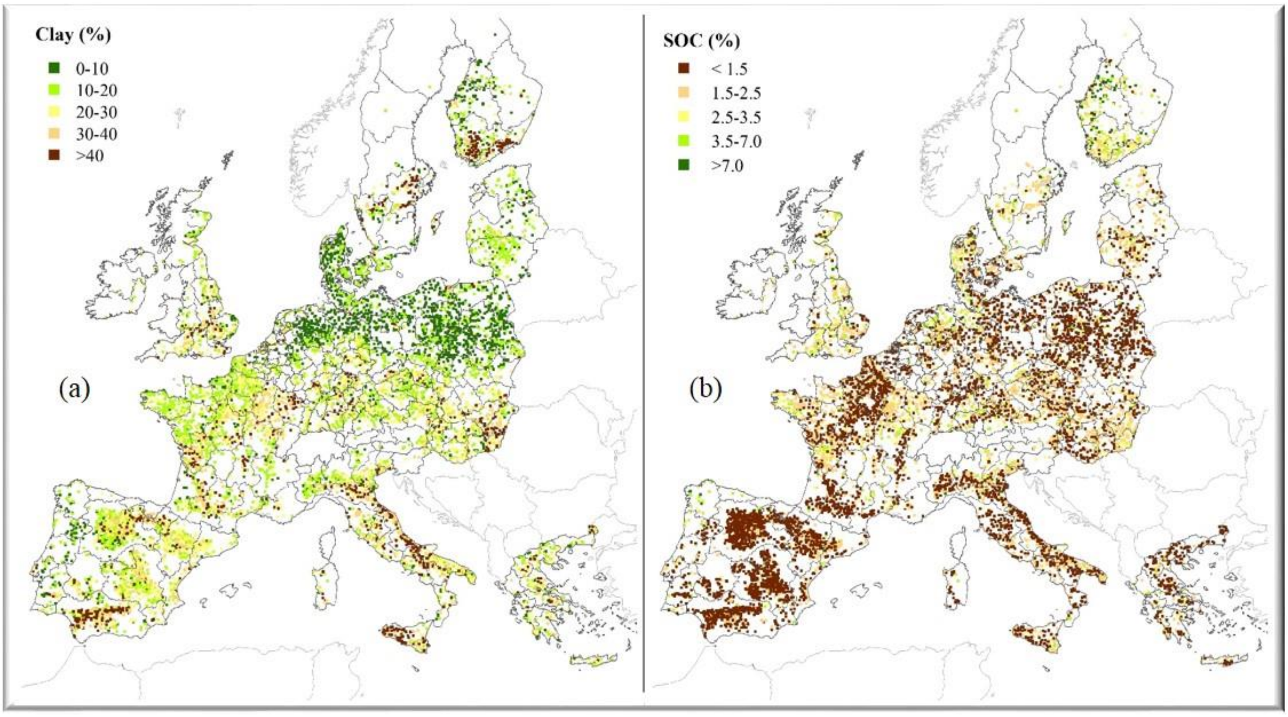

Fig. 2. Clay content (a) and SOC (b) content (in %) in European regions.

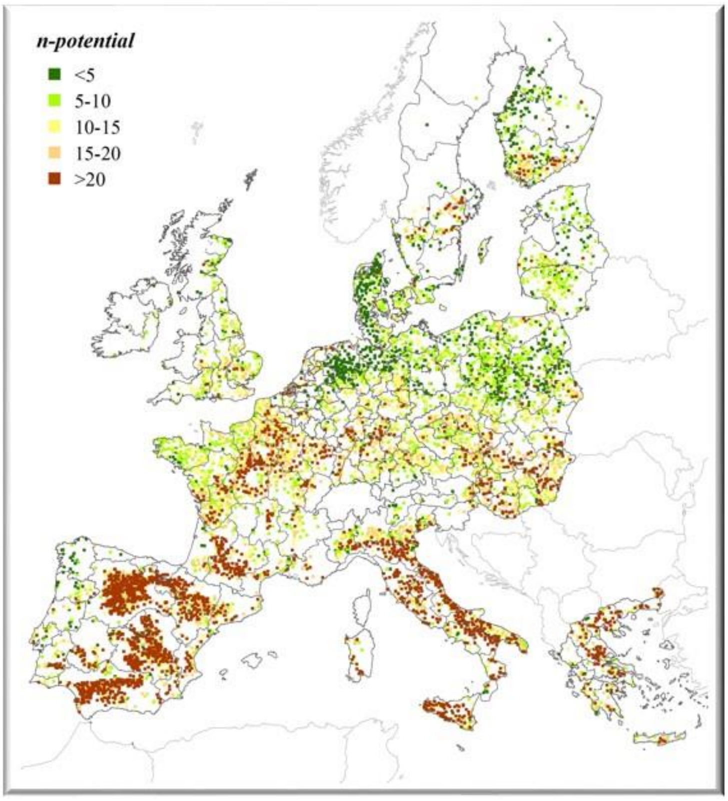

Fig. 3. The indicator *n-potential* in soils of the European regions.

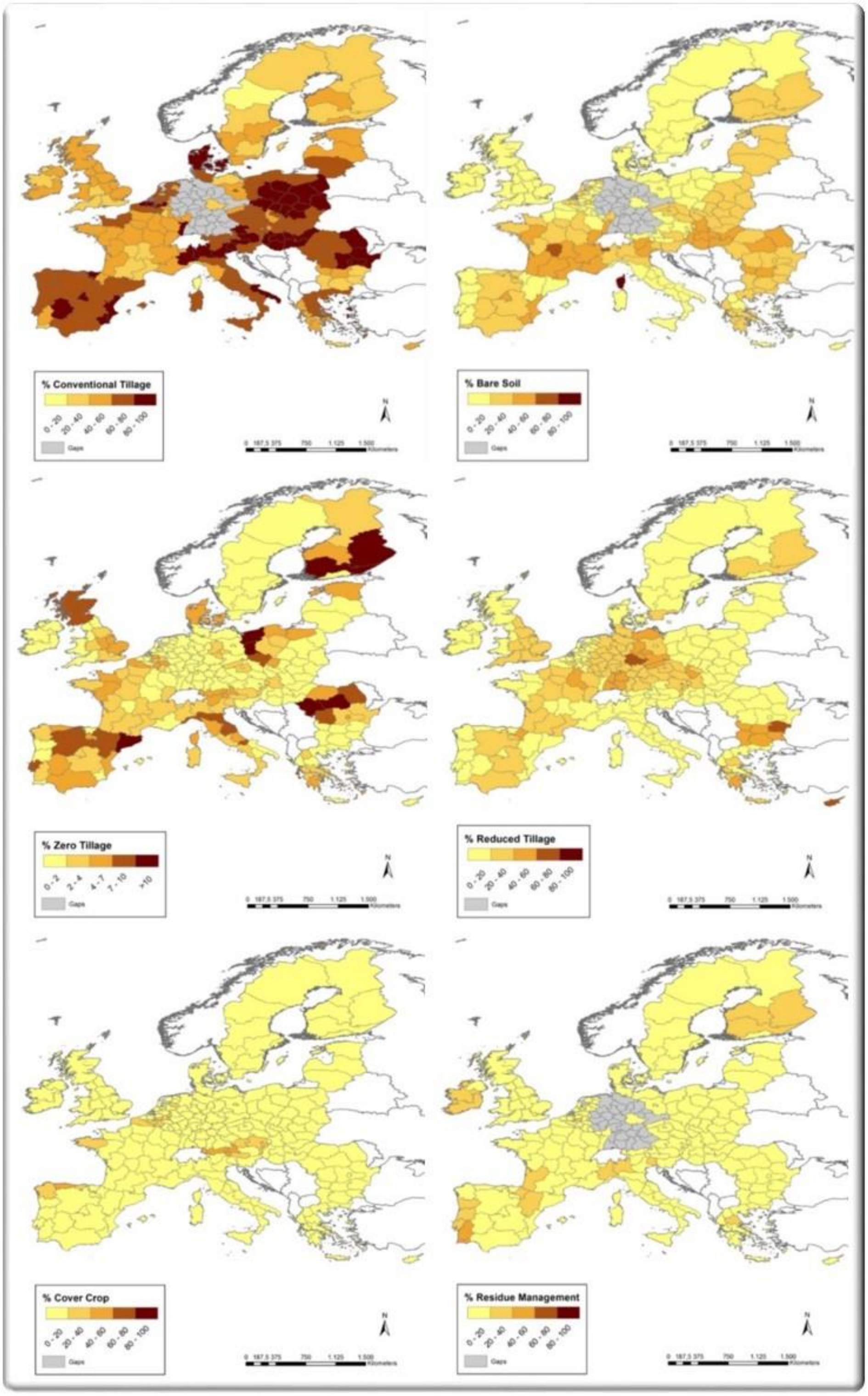

Fig. 4. Land under SOC management practices compared to the total area of arable land in European regions (from Sánchez *et al.*, 2013).

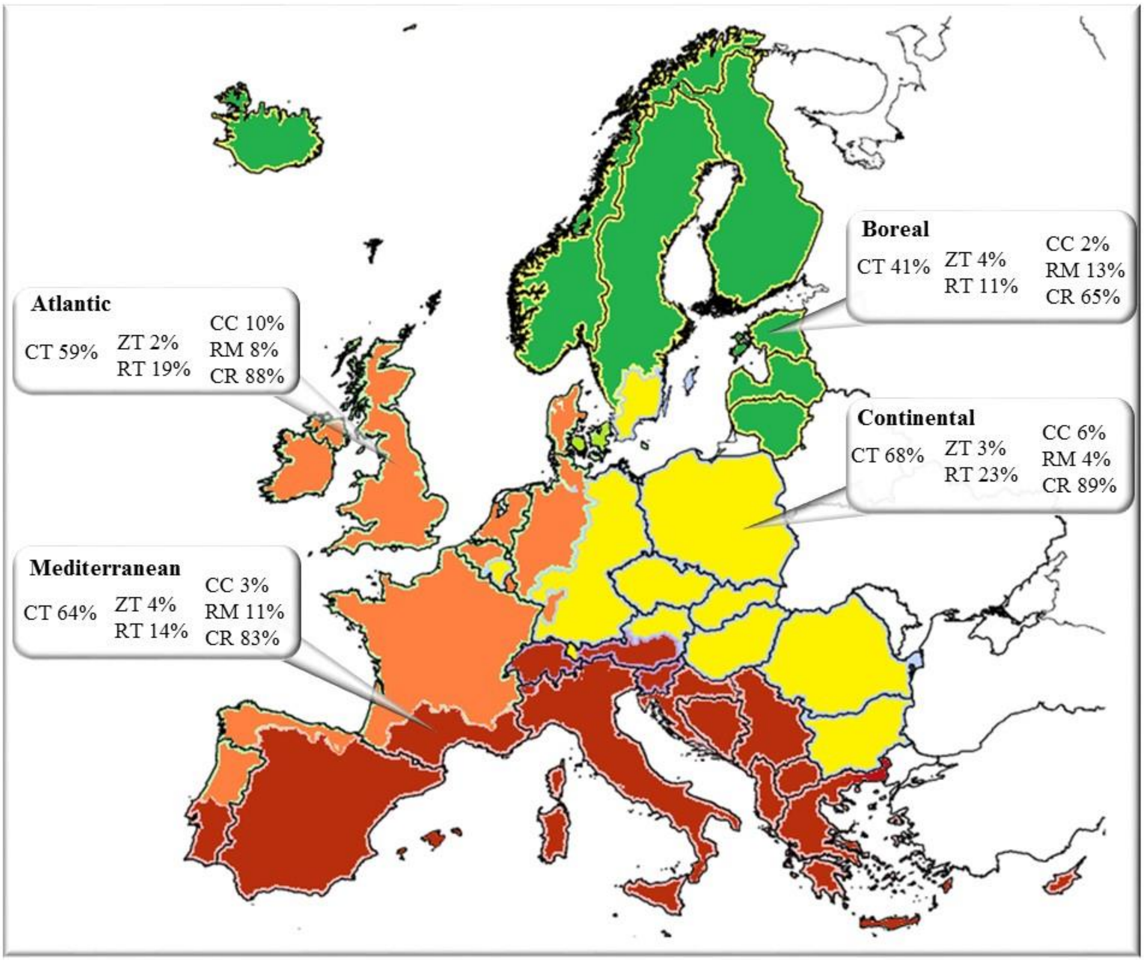

Fig. 5. Average **i**mplementation of the SOC management practices in European Regions.
CT, conventional tillage; ZT, zero tillage; RT, reduced tillage; CC, cover crops; RM, residue management; CR, crop rotations.

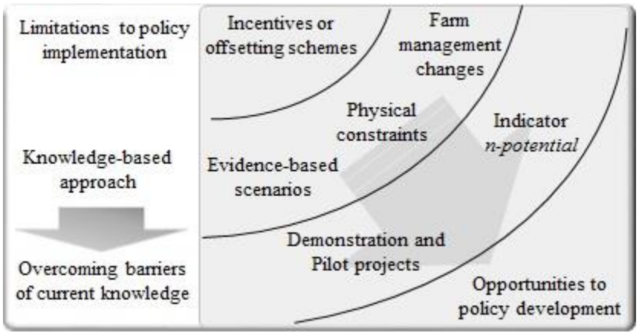

Fig. 6. The knowledge-based approach scheme towards opportunities to policy development.