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Deliverable 2.4 - Report on critical low soil organic matter contents, which jeopardise good functioning of farming systems

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Deliverable 2.4

Report on critical low soil organic matter contents, which jeopardise good functioning of farming systems

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Summary

Soil Organic Matter content (SOM) is a key parameter that needs to be assessed as directly supplies nutrients to crops and plants in farming systems. Moreover, SOM is essential to maintain water and nutrient function in the soil as well as to enhance soil biodiversity (European Commission, 2002, 2006). Consequently, low SOM values might threaten soil productivity or even lead to a collapse of the farming system itself. For this reason, the identification of which levels of SOM are critically low, as well as to which extent and in which areas of Europe these levels might occur is a sustainable challenge in order to evaluate systems' abilities to handle external stress as well as to apply the appropriate strategies to restore these areas.

This Deliverable 2.4 is framed into Work Package (WP) 2 titled "Current and future crop and soil management systems in Europe" and Task 2.3 ("Farming systems at risk"). The objective of Task 2.3 was to elucidate which levels of soil organic matter are critically low, to what extent and the main areas at risk in SOM for the European regions at NUTS2 level. More specifically, this deliverable wants to define European risk profiles as determined by SOM low levels which jeopardise good functioning of farming systems. Thus, the identification of areas in Europe with critically low SOM levels or with a negative carbon balance is a challenge in order to apply the appropriate strategies to restore these areas or prevent further SOM losses.

Soil organic carbon (SOC) plays crucial roles in determining and maintaining important soil functions. Indeed, in the form of organic matter, SOC has the capacity of influencing the fluxes of key plant nutrients and thus the soil productivity. Furthermore, it affects soil structure and related properties (e.g. water retention, bulk density, friability, tillage) by contributing to the formation of stable aggregates. With respect to this latter point, arable land areas in Europe with critically low SOC/SOM levels were identified by computing two indicators: "Soil potential stability indicator (*n*)" and the "SOC balance indicator".

The first one (*n*- Soil potential stability indicator) derived from the ratio between the clay content and the amount of SOC. This ratio enabled us to classify soils in terms of potential capacity to protect C, and to provide beneficial conditions for crop production. In fact, the ability of a soil to preserve organic carbon (OC) from its degradation relies on the degree of interactions that the OC establishes with the fine mineral particles (Dexter et al., 2008). On the other hand, due to relatively low SOC amount, the presence of dispersed clay particles may result in a soil structureless mass affecting soil physical properties such as soil workability, soil water and air circulation, etc. Two different value ranges of n were identified: $n \geq 10$ (clay content is greater than that which could be complexed by the SOC), $n < 10$ (there is a larger availability of SOC per unit of clay). According to our results, most of southern EU-regions soils are characterized by the presence of a substantial content of non-complexed clay ($n \geq 10$) which undermines their physical quality. On the opposite, fewer NUTS2 level regions, mainly located in northern Europe, resulted with a higher amount of SOC per unit of clay ($n < 10$), with positive impacts on soil functions and thus on crop productivity. Nevertheless, n-results derive from a wide range of combinations of clay and OC contents; for this reason, results should be analysed case-by-case. For instance, soils with $n < 10$, though well structured, may encompass soils with a very low percentage of both clay (< 5%) and OC (between 0.8 and 0.5). Conversely, soils resulting with $n \geq 10$ (unstable) have a great potential for improvement by implementing practices encompassing OC amendments. The combination of current SOC management practices with the n-indicator was also theoretically analysed in order to determine classes of risk.

The second indicator (SOC balance indicator) was calculated with RothC using input data from the MITERRA-Europe model. Modelling was used to estimate carbon inputs from crops, crop residues and manure at regional scale (NUTS2 level). The average SOC balance resulted neutral or slightly negative for most NUTS regions, however some regions showed a high negative balance, mostly located in areas where soils have a high carbon stock. In order to identify areas at risk, SOC balance indicator was also combined with carbon stock by defining arbitrary thresholds. Results showed that the NUTS2 region with on average a low SOC risk are

mainly located in Central and parts of Western Europe, whilst Mediterranean regions depicted the highest risk in SOC decline.

1. Introduction

It is widely recognized that 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). Soil C, which occurs in the soil as organic matter (OM), influences fluxes of key plant nutrients and thus soil productivity (Dexter et al., 2008; Whitbread, 1995; Lal, 2006) by being an important carbon reservoir and source for metabolic activity. On the other hand, it heavily influences soil structure and related properties (e.g. water retention, bulk density, friability, tillage) by contributing to the formation of stable aggregates (Lefroy et al., 1995). This in turn results in the C sequestration in stable forms contributing to mitigate some aspects of climate change (Dexter et al., 2008).

It is clear that a decline of soil organic carbon content, and in turn of organic matter, implies a decline of soil quality. Several of its key properties would therefore be altered with both adverse effects on crop productivity and reduction of the soil capacity to protect C from its mineralization. Moreover, the presence of SOC and its associated nutrients, positively contributes to soil resilience, i.e. its ability to recover the initial state after a deterioration event (Hoyle et al., 2011).

These issues are the core of the European Commission's concerns, which calls for the European Parliament to pursue the implementation of actions to restore organic matter in soils in order to overcome the shortfall of OM occurring in many European regions (EC communication, 2011). In such a context, it is a priority to establish critical thresholds of SOC, namely those SOC contents below which, the soil productivity and the soil capacity to stock C decreases, hence threatening farming systems existence. Besides, based on such thresholds, agricultural areas in Europe that are at risk of loss of soil productivity and reduction of soil C stock need to be identified. Nevertheless, critical low levels of SOC are difficult to be identified. Indeed, SOC is a key factor for several and different soil functions and the definition of risk due to low SOC levels can vary according to the specific soil function considered. Loveland and Webb (2003) identified 2% as the universal SOC levels, corresponding to Soil Organic Matter (SOM) = 3.4%, that are critical to soil stability of arable farming systems in temperate regions. Likewise, Greenland et al. (1975) suggested the same SOC critical threshold below which soil structural stability will suffer a significant worsening. On the other hand, Lal (2013) pointed out that 1% of SOC is the critical level for soil quality decline. This level is confirmed also by Kay and Agers (1999) who identified 1% of SOC as critical threshold below which water limited yield potential may not be achieved as well as soil's key functions be performed. Conversely, several authors (Schjønning et al., 2009; Verheijen et al., 2005; van Camp et al., 2004) concluded that no universal lower critical SOC thresholds for securing soil functions can be established across soil types and climatic regions.

Based on the LUCAS soil data (Toth et al., 2013) an analysis was made of the percentage of observations below a certain threshold (Figure 1). For arable soils a threshold of 2% organic carbon (which is about 3.5% OM) would mean that for most EU countries more than 60% of the soils under arable land would classify as too low, with a threshold of 1% this would be considerably lower (about 20% of the area). However, one universal value for a critical minimum SOC level is probably unattainable, since this value would depend on other soil properties, especially the clay content (Goulding et al., 2013).

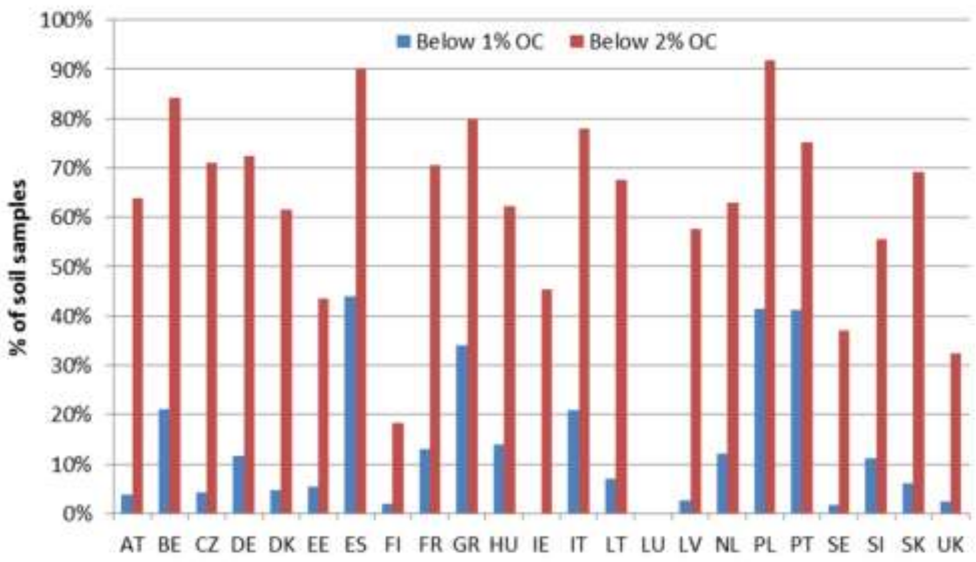

Figure 1. Percentage of arable soil samples LUCAS below SOC threshold of 1 or 2%

Despite this, indicators that, related to the soil chemical, physical and biological properties, enable us to appreciate the capacity of a soil to function, i.e. the soil quality (Karlen et al., 1997), can be identified. Paz-Ferreiro and Fu (2013) stated that though physical and chemical indicators are the most used to assess soil quality, those related to biological and biochemical properties may be more appropriate to reveal management activities impact on soil. Schoenholtz et al. (2000) suggested the use of a range of chemical (e.g. SOC, fertility, pH) and physical (e.g. texture, bulk density, erosion potential) soil properties as indicators of soil quality by distinguishing them in static (i.e. point in time) and dynamic (i.e. process-related) indicators. Other authors, acknowledging the complexity of soil properties and functions, recommended the use of a set of physical, chemical and biological indicators as to monitor soil quality (Larson and Pierce, 1991 from Reeves, 1997). Because of its impact on several soil functions, soil organic matter, is recognized as 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) proposed aggregate stability as an indicator of soil quality. It is indeed acknowledged that, the presence of stable aggregates positively affects agricultural productivity and significantly contributes to preserve environmental quality (Amézketa, 1999).

Building on these premises, in this deliverable, two indicators were analysed with the aim of assessing which levels of SOC/SOM are critically low, to what extent and where this is a problem for arable lands in EU-27. The first indicator is the soil potential stability indicator “*n*”, based on the Dexter ration between clay and SOC, the second indicator is the soil carbon balance, calculated with RothC using input data from the MITERRA-Europe model.

2. Material and Methods

2.1 Soil potential stability indicator - *n*

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, highly contributes to water movements and water retention, soil aeration and soil biological activity, thus influencing key soil functions. Moreover, the ability of a soil to preserve OC from its degradation relies on the degree of soil stability which in turn is inherently connected to the content of soil organic carbon 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 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). With respect to carbon sequestration, Dexter et al. (2008) suggested the use of factor *n* defined as the ratio of the amount of clay to the amount of clay that can be complexed by 1 g of organic carbon, to identify the maximum amount of C that can be complexed with clay only. These authors indeed, referred to that organic carbon which is insensitive to soil management practices because stored within micro aggregates (Tisdall and Oades, 1982 in Dexter et al., 2008). Their reasoning is put as follows:

$$\text{CMax} = \text{clay}/n$$

Within the aforesaid context, Dexter et al. 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 result in an amount of carbon that is non-complexed (NCC) and thus more exposed to decomposition. In contrast, amounts of carbon under the capacity factor determine a value of n > 10 and thus the presence of non-complexed clay, which, as such, will be more easily dispersed in water than the complexed clay (CC) (Amézketa, 1999; Dexter et al., 2008). Thus, an inverse relationship exists between the amount of NCC and that of organic matter (Czyz et al., 2002 in Dexter, 2004). The presence of dispersed clay particles in soil results in a soil structureless mass (Dexter, 2004) affecting therefore 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; Kay and Dexter, 1992) affecting aspects such as the soil workability and the soil water and air circulation.

The organic carbon is distributed among different sized aggregates. 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. They also stressed the fact that the OC in macro-aggregates is in forms that are relatively labile and thus easily subject to potential decomposition. In accordance to that, Carter and colleagues (2003) identified in the water-stable macro aggregates (> 250 μm), the particulate (> 53μm), the light fraction organic matter and in clay and silt the fractions the C is associated with. However, only the C in micro-aggregates can be considered "protected", labelling as labile the other fractions.

Bearing in mind the above, we relate the soil texture, more specifically the clay content, with the amount of organic carbon (OC) in soil to calculate the soil potential stability indicator (i.e. n = clay/SOC). Based on it, we identify regions within the EU-27 where the SOC content compared to the amount of clay could potentially threaten the soil quality and the soil capacity to protect C.

To this end, two different value ranges of *n* are identified:

- *n* values ≥ 10 which comprise soils where the clay is greater than that which could be complexed by the SOC . These soils are characterized by the presence of NCC content;
- *n* values < 10 that imply, compared to the previous class of soils, a larger availability of SOC per unit of clay, thus a greater amount of complexed clay (CC).

In this document we mostly refer to the soil organic carbon because generally taken into account to analyse soil characteristics and properties as well as to identify areas at risk. Nevertheless, our analysis, considerations and results could also be referred to soil organic matter content (SOM) assuming a constant mass ratio of SOM/SOC = 1.724 kg kg^{-1}. This implies that, if 1 g of OC can complex 10 g clay, 5.8 g of OM would need to complex 10 g clay. Thus, relating n to SOM the classes above identified would be n ≥ 20 and n < 20, respectively.

2.2 Soil organic carbon balance indicator

The soil organic carbon balance is the difference between the inputs of carbon to the soil and the carbon outputs. A negative balance, i.e. outputs are larger than the inputs, will reduce the SOC stock and might lead to crop production losses on the long term. To calculate the soil carbon balance at regional (NUTS2 level) we used the MITERRA-Europe model to provide the input data and the RothC model to calculate the soil carbon dynamics. Manure and crop residues are the main carbon inputs that were included. Other inputs such as compost, sludge and sedimentation might be important inputs in certain regions or for certain crops, but in total these inputs are only very small compared to the C input from manure and crop residues. SOC decomposition has been included as the only carbon output, other possible C outputs, such as leaching and erosion, are not accounted for.

MITERRA-Europe, developed by Alterra, is an environmental assessment model, which calculates GHG (CO_2, CH_4 and N_2O) emissions, soil organic carbon stock changes and nitrogen emissions from agriculture on a deterministic and annual basis. MITERRA-Europe is based on the CAPRI and GAINS models, supplemented with a nitrogen leaching model, a soil carbon module and a module for representing mitigation activities (Velthof et al., 2009; Lesschen et al., 2011; de Wit et al., 2014). The model comprises about 35 crops and 10 livestock categories. MITERRA covers the agriculture sector at different spatial scales, e.g. for Europe this consists of EU-27 scale, Member State scale and NUTS2 scale.

The RothC model (Coleman and Jenkinson, 1999) was used to calculate the SOC balance. RothC (version 26.3) is a model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total organic carbon (ton C ha^{-1}), microbial biomass carbon (ton C ha^{-1}) and Δ14C (from which the radiocarbon age of the soil can be calculated) on a years to centuries timescale (Coleman and Jenkinson, 1999). For this study RothC was only used to calculate the current soil organic carbon balance based on the current carbon inputs.

Soil organic carbon is split into four active compartments and a small amount of inert organic matter (IOM) in RothC. The four active compartments are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Each compartment decomposes by a first-order process with its own characteristic rate. The IOM compartment is resistant to decomposition. RothC requires the following input data: 1) monthly rainfall (mm), 2) monthly open pan evaporation (mm), 3) average monthly air temperature (^{o}C), 4) clay content of the soil (as a percentage), 5) an estimate of the decomposability of the incoming plant material – the DPM/RPM ratio, 6) soil cover (is the soil bare or vegetated in a particular month), 7) monthly input of plant residues (ton C ha^{-1}), 8) monthly input of manure (ton C ha^{-1}), and 9) soil depth (cm). Initial carbon content can be provided as an input or calculated according to long term equilibrium (steady state).

2.3 Input data

Percentage of organic carbon content as well as clay content for calculating both soil potential stability and SOC balance indicators was derived from the LUCAS soil survey (Toth et al., 2013) (see Figure 2). LUCAS (Land Use/Cover Area frame statistical Survey) is a harmonised survey across all 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 the 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 out of the main LUCAS grid for the collection of soil samples. A standardised sampling procedure was used to collect around 0.5 kg of topsoil (0-20 cm). The samples were sent to an accredited laboratory where a range of chemical and physical soil properties were analysed. SOC content (g C kg−1) was measured by dry combustion (ISO 10694:1995). In 2012 also samples from Romania and Bulgaria were collected and are currently being analysed. A new monitoring survey is foreseen in 2015. The benefit of LUCAS data is that it is recently observed data and there is a clear link to land use. Only the LUCAS data from arable soils were used (this includes permanent crops, but excludes grassland).

For each individual LUCAS sample points, the ***n*-indicator** was calculated as the ratio between the percentage of clay and the percentage of SOC. Results were then aggregated at NUTS2 region level by simply calculating the normal average of all LUCAS points on arable soils within one NUTS2 region (Figure 2).

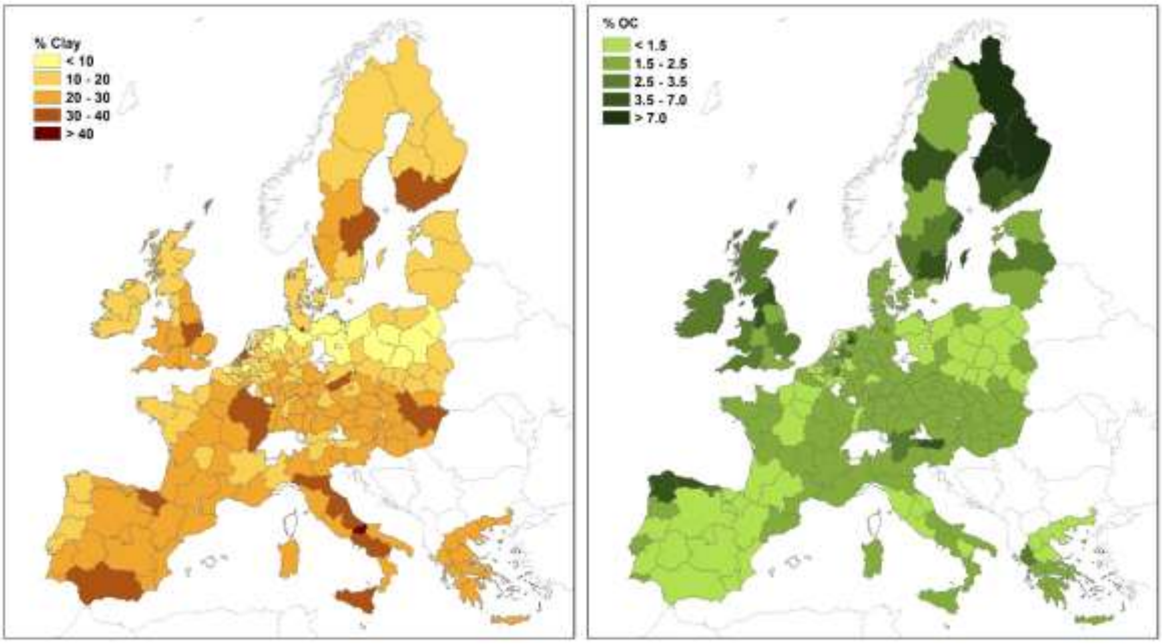

Figure 2. Average of percentage of soil organic carbon content (left) and clay content (right) for arable soils derived from the LUCAS 2009 soil survey

Likewise, the initial organic carbon content and clay content for computing **SOC balance indicator** were derived from LUCAS database, whilst climate data, requested as input by RothC model, were derived from the WorldClim[1] database (Hijmans et al., 2005) at NUTS2 level. Average values of SOC content were calculated for mineral soils (peat soils > 12% C were excluded) per NUTS2 region for arable land (Figure 3).

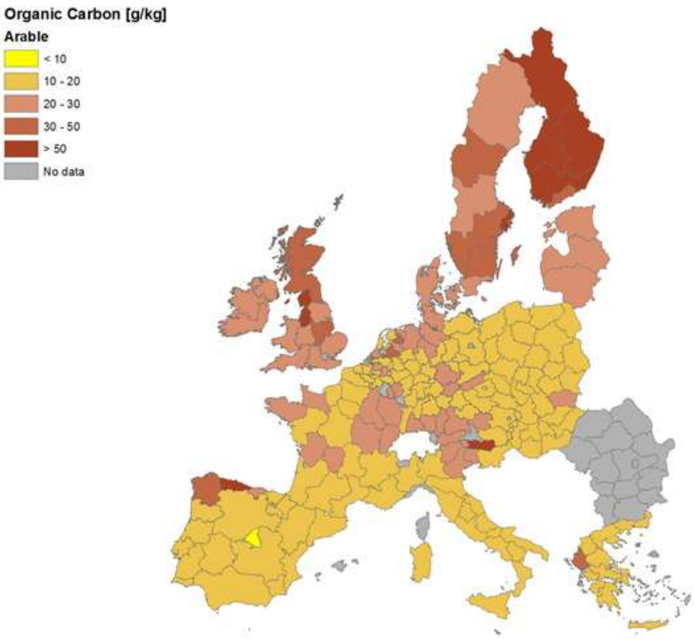

Figure 3. Average soil organic carbon content for arable soils derived from the LUCAS 2009 soil survey

[1] http://www.worldclim.org/

The carbon input from manure was derived from MITERRA-Europe, following the allocation of manure nitrogen to crops and a livestock type specific CN ratio. Carbon input from crop residues was derived from the crop areas and crop yield in MITERRA-Europe and the harvest index, the ratio between crop yield and annual net primary production (Vleeshouwers and Verhagen, 2002). Activity data (crop and livestock data) from 2008 were used for the analysis. For straw crops the C input from crop residues was differentiated into straw, stubbles/chaff and belowground C inputs from roots. Based on Scarlat et al. (2010) the amount of aboveground residues was calculated as function of the crop yield. For the division between straw and other residues (stubbles and chaff) we used a straw: other residue ratio of 55:45, which is based on Panoutsou and Labalette (2006) and a review by Powlson et al. (2011). For the belowground C input from roots and rhizodeposits we used a value of 25% of the total assimilated C based on Taghizadeh-Toosi et al. (2014). Finally, we used a soil depth of 20 cm, which is the sample depth from the LUCAS soil survey, to assess the SOC balance.

3. Results

3.1 Soil potential stability in Europe

Figure 4 depicts the *n*-potential soil stability indicator distribution within the EU-27 at regional scale (NUTS2 level). In order to better appreciate the *n* distribution among the European regions we identify five different levels/categories of *n:* < 5; 5-10; 10-15; 15-20; >20.

The category "> 20" encompasses soils where the content of SOC is able to complex a very limited amount of the present clay because of: (i) the very limited C content; (ii) the particularly high content of clay (up to 40%) or (iii) because of the combination of both conditions. This category also includes soils with an adequate C content (up to 2.5) at which correspond a good level of OM (slightly higher than 4%) which, however, is coupled with a high content of clay (up to 40%) which in some exceptional case can be over 40% (Central Italy). These soils, regardless to the relative amounts of OC and clay, are characterized by the presence of a substantial content of NCC, which undermine their quality. Moreover, if the content of clay is lower than 15% the soils that fall in this category register an insignificant content of OC (up to 0.7%) as well as of the corresponding OM (up to 1.2%).
Nonetheless, soils in this n category have a great potential for improvement. Indeed, increasing the amount of OC/OM they can exponentially increase their quality and their capacity to store and protect OC.

Soils that have still a high content of clay but an increasing content of OC/OM per unit of clay, fall under the categories"15-20" and "10-15". In particular, the latter category seizes soils with a clay content that range from 10 to 30% and the OC amount ranging between 1.5 % and 2.5% with few exceptions where the OC content can be slightly below 1 % (Central Portugal) or the clay is lower than 10% (South of Sweden). However, in these soils the content of NCC tends to decline with beneficial effects for the soils that result with a better quality than the category "> 20". Furthermore, these conditions allow improving the soils' capacity to store OC.

Categories "5-10" and "< 5" presume an amount of OC/OM per unit of clay greater than that which occurs in the previous categories. This, in turn, entails an improvement of the soil quality due to a decline of NCC content, with positive impacts on soil functions and thus on crop productivity. Furthermore, these soils have a very high capacity to store and protect OC, with the proviso that their texture is characterized by a high content of clay particles. At this stage, a consideration needs for these last two categories. The category "5-10" encompasses a wide range of combinations of clay and OC contents, with the clay mostly ranging between 0 and 20% and the carbon that can be present for as many as 3.5 % (an extreme case is in North of England where the OC and the clay content may be up to 7% and up to 40% respectively). On the other hand, this category may include also soils with a very low percentage of both clay (< 5%) and OC (between 0.8 and 0.5), which implies that even though the clay is likely entirely complexed, they may contribute only to a limited extent to the productivity because of their low OM content.

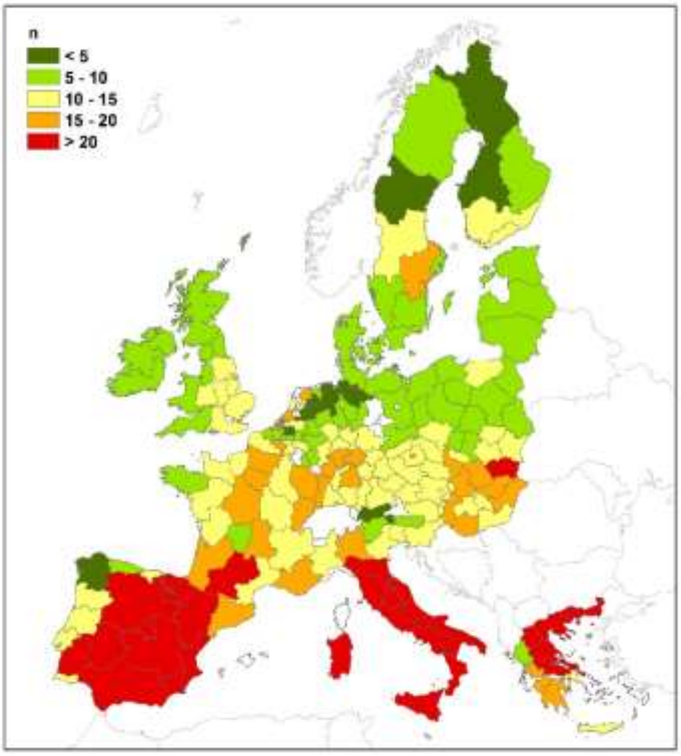

Figure 4. Map of the *n*-categories for arable land at NUTS-2 level

Instead, soils with the highest amount of organic carbon per unit of clay come into the category "< 5". Nevertheless, this category includes both combinations of a very low content of clay (i.e. 0-10%) with a carbon amount that results to be higher than 7% (Finland and Sweden) and soils in which up to maximum of 20% of clay is coupled with OC ranging between 3.5 and 7% (North West of Spain). However, though the portion of OC that may complex the clay is unknown, we can assume that within this category the NCC is absent. Because of that, a further addition of OM does not affect (raising) the amount of C that can be protected. Indeed, where the saturation level is within reach or already achieved (n=10), the more OC will be mostly devoted to the other pools of OM but the complexed one, and thus more exposed to decomposition and thus also to the possibility of being lost. On the other hand, an increased content of OM may positively affect crop productivity.

3.2 SOC balance in Europe

Figure 5 shows the carbon inputs from manure and crop residues on arable land for the EU-27 NUTS2 regions. The carbon input from crop residues is on average about a factor 5 higher compared to the inputs from manure. Only in livestock dense regions, e.g. the Netherlands, Belgium and Brittany, the C input from manure is significant and more than 1000 kg C per ha. C input from crop residues are highest in NW Europe where crop yields are highest as well.

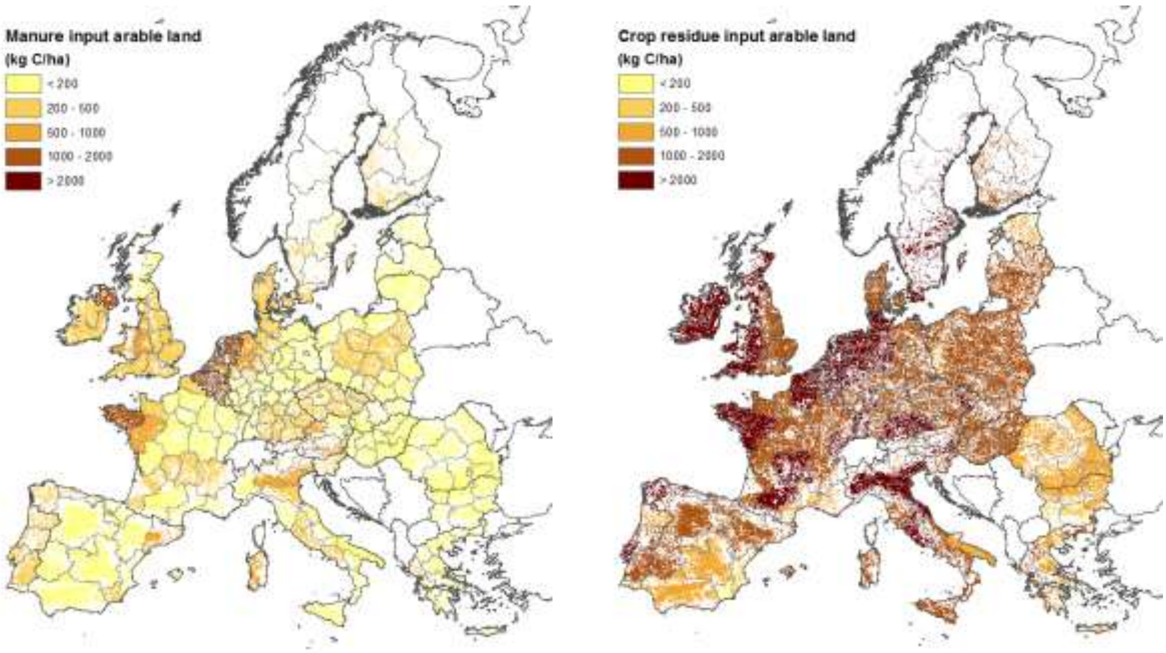

Figure 5. Carbon inputs to the soil (left manure and right crop residues)

For arable land the calculated average of SOC balance is neutral or slightly negative for most NUTS2 regions (Figure 6). Some regions have a high negative balance (< -400 kg C/ha/year), in most cases these are regions where soils have a high C stock (see Figure 3). Although peat soils (> 12% C) were excluded, there may still be soils included with peaty layers, or soils that are very wet. In these cases RothC might overestimate the decomposition of carbon and therefore lead to too negative C balances.

On average the calculated SOC balance on arable lands is negative (-100 kg C/ha/year), and is in line with the values derived by Ciais et al. (2010) in their European Carbon balance paper.

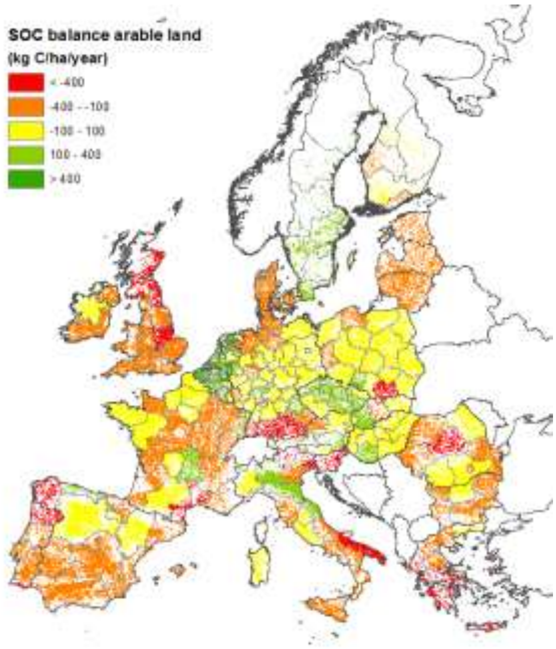

Figure 6. Soil organic carbon balance for arable land

4. Discussion

4.1 Soil potential stability indicator and SOC balance indicator

The soil potential stability indicator (*n*-indicator) provides a measure of the existing equilibrium between clay and SOC, as well as information about potential SOC content that can be complexed with clay particles in the soil. In turn, relevant considerations can be put forward with regard to the soil quality. Indeed, information about the potential presence of non-complexed clay (NCC), which highly affects several soil properties, can be extrapolated by analysing the quantitative relation between the clay content and the SOC content.

At this stage, it should be stressed that without considering SOC portion that really interact with clay (i.e. the carbon organic content effectively involved in clay complexation), the *n*-indicator provides information that needs to be analysed and interpreted case by case and for qualitative assessments only. Indeed, with $n>10$, by one hand the presence of NCC may compromise the soil quality, on the other hand it may enhance the soil potential to store C. On the opposite, if $n<10$, it suggests that most of the clay (and in some cases the total clay content) results complexed with organic carbon. This entails an improvement in terms of soil quality (and productivity) but a decline of the potential to store C.

The *n*-indicator seizes different kind of soils, both in terms of soil quality and storing C capacity. Indeed, there are soils that in spite of their high content of SOC (SOC ≥ 7%) – which denotes a good soil productivity - have a very limited capacity to store carbon (in the complexed form) because of their low clay content (clay ≤ 10%). This is the case of some regions of Finland (Figure 3). Conversely, there are soils in Europe (Italy) with a good capacity to store carbon due to the relevant clay content (clay ≥ 30%) which are nonetheless associated with a very low organic carbon content (SOC ≤ 2%). In between these two extremes, several combinations of clay content and SOC may occur, characterizing soils with different capacity to both protect C from its loss and stabilize SOC.

In any case, however, the soil characteristics (and thus the properties and related capacities) might be heavily influenced by agricultural practices that are included within different farming systems. Indeed, while conventional management, such as the intensive use of tillage practices are associated to losses of SOC and to soil erosion and degradation processes, the SOC management practices may greatly contribute – they can either favour the C accumulation or reducing the C losses - to enhance soil organic carbon stocks, providing greater physical protection of SOC (Hoyle et al., 2011).

The current SOC balance results clearly show that there is a large difference among regions in Europe and that especially for arable land there are many regions with negative SOC balances. There are significant uncertainties involved in the calculations, especially the carbon input from crop residues, in particular the input from roots, and the soil depth over which the SOC dynamics should be calculated are uncertain. Although the absolute value of the SOC balance is uncertain, the relative differences among regions are less uncertain and do indicate which regions are more at risk.

4.2 Potential areas at risk

There is a need of knowledge on critical SOC threshold and strategies for restoring SOC levels of agricultural areas that are at risk. On this regard, as theoretical approach, areas of risks could be identified by plotting in a graph one of the two calculated indicators (*n*-indicator or SOC balance indicator) against a variable, for instance the effects of SOC management practices - in terms of carbon sequestration - or SOC stocks. By this graph, a bi-dimensional surface could be delimited and the probability of risk could be plotted versus the magnitude of consequence. The further the point is plotted from the origin, the lower is the risk (see Figure 7).

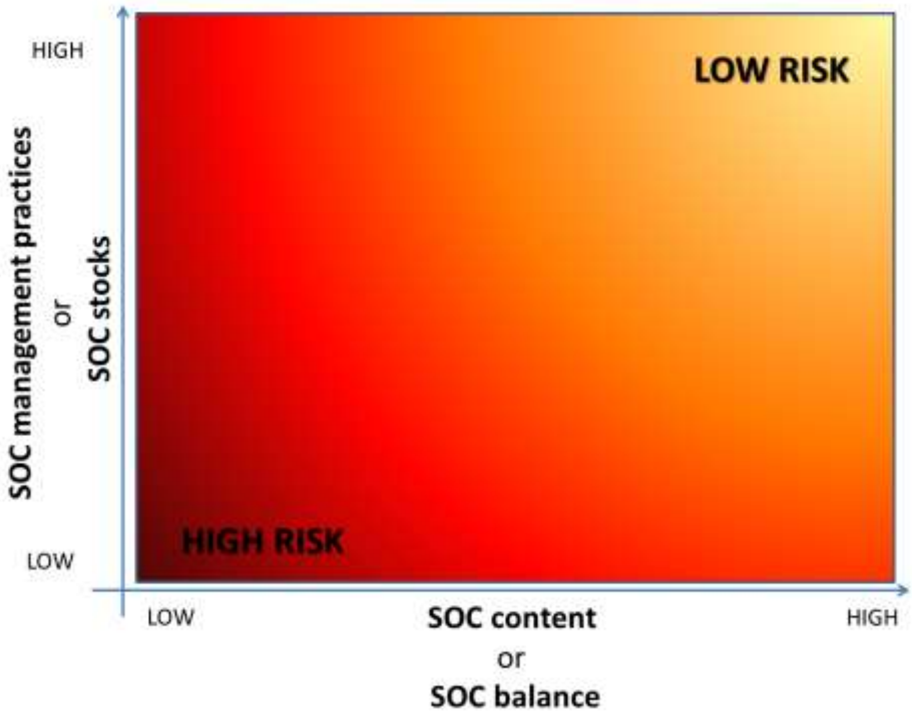

Figure 7. Theoretical approach for identifying areas of SOC risk

4.2.1 Potential areas at risk according to *n*-indicator

The combination of the SOC management implementation with the SOC levels in agricultural soils may give an integrated perspective on the European farming systems currently at risk in terms of soil stability and SOC content. In Deliverable 2.2, key SOC management practices were selected for their applicability among all the European agricultural regions and include reduced tillage, zero tillage, winter cover crops, crop rotation, residue management and cover or intermediate crop. An increase of such practices can avoid further losses of SOC across the different European farming system and help to both maintain organic carbon levels and improve stability in agricultural soils.

The combination of the SOC management practices implementation with the SOC levels in agricultural soils may be proposed as a complementary tool that could be used to inform policy decisions and promote policy foresight on mitigation strategies throughout soil management. Changes to a specific management are a much comprehensible issue than the actual development of mitigation policy. Moreover, defining mitigation strategies at the regional level by small changes in farming practices can be more effective than a long term mitigation strategy for whole country, since the effects of mitigation practices are perceived by farmers and society to be more tangible (Sánchez et al. 2014). Iglesias et al. (2011a; 2011b) assessed the risk to climate change for worldwide agricultural regions by combining the current SOC management implementation and the SOC content and taking into account the projected impacts and the adaptive capacity dimensions.

Based on the aforementioned rationale, we could approach the measure of risk combining the current SOC management, expressed in terms of the percentage of farming practices currently implemented, to the potential soil stability *n*-indicator, which instead encompasses both the SOC content and the soil texture. This combination may give an integrated perspective on the European farming systems by defining areas of risk. Indeed, splitting the SOC management implementation in two classes (i.e. >0.5 and <0.5, where the current percentage of SOC management practices implemented is over 50% of arable land and below 50% of arable land, respectively) and the *n*-indicator in three classes ($n\leq5$; $5<n\leq10$; $n>10$), five areas of risk of the current soils' capacity to sequestrate C may be described as following (see Figure 8):

- No risk ($n\leq5$ and SOC management>0.5): this class includes areas where SOC is able to complex the whole amount of clay (stable soils) and SOC management measures are largely implemented.
- Low risk ($5<n\leq10$ and SOC management>0.5): this class includes areas where SOC is likely able to complex the whole amount of clay (stable soils) concurrently with SOC management measures implementation.
- Medium-low risk ($n\leq10$ and SOC management<0.5): this class includes areas where SOC is able to complex the whole amount of clay (stable soils) but SOC management measures are barely implemented (moving toward worsening of soil condition)
- Medium-high risk ($n>10$ and SOC management>0.5) this class includes areas where SOC is able to complex a very limited amount of the present clay (unstable soils) but SOC management measures are currently implemented (moving toward improvement of soil condition).
- High risk ($n>10$ and SOC management<0.5): this class includes areas where SOC is able to complex a very limited amount of the present clay (unstable soils) and SOC management measures are barely implemented.

Some overlapping areas may be considered suggesting how the risk profiles could be affected by other factors that are not directly considered, such as water and nutrients availability, climate and biodiversity, among others.

As a general statement, if a region has a high SOC management implementation and the *n* indicator is below 10 the region may not face a future significant risk. When the *n* indicator is below 10, but the SOC management implementation is low, the region can face a slight risk that could be increased in the long term, unless the region improves the management to avoid further SOC content reductions. If *n* indicator is above 10, the region, though it is at significant risk (medium with SOC management < 50% or high with SOC management > 50%) has a large potential to enhance SOC content by increasing SOC management implementation.

To be noted that, some of the classes of risk include soils that, in spite of their current risk status, have a significant room for improvement. It is the case of soils falling within the Medium low risk category ($n\leq10$ and SOC management<0.5), which if subjected to conservative practices (i.e. SOC management practices > 50%) would raise the rates of carbon stored, moving in the Low or even in the No risk category. Similarly, the high riskiness to lose C of soil with a poor quality (i.e. n>10 and a high percentage of NCC), could be greatly mitigated by increasing the adoption (of more than 50%) of SOC management practices. Nevertheless, the two situations just described are profoundly different. Indeed, in the first case the improvement shall be determined by practices which do not alter the complexing status established between SOC and clay (indeed n<10) such as the minimum or zero tillage. Whereas, in the latter case the practices shall aim towards the increasing of the soil carbon content, achievable by the cover crops and/or a proper residues management.

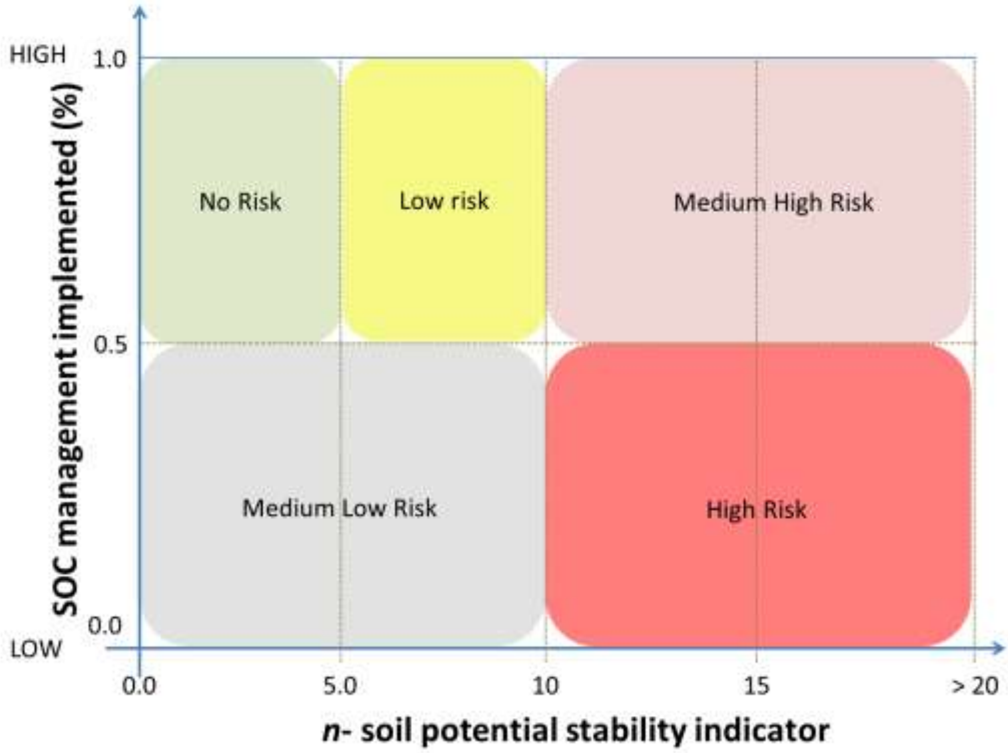

Figure 8. Areas of risk deriving from the combination of SOC management practices and *n*-indicator

Nevertheless, there are particular soil conditions for which the adoption of both type of practices (that increase SOC and do not disturb the soil) is desirable. These are soils characterized by a very low percentage of both clay and SOC (that were already discussed for the category *n* "5-10" in the result section), where the OC added through specific practices will be stored in labile forms (though the low clay), provided that tillage operations that slightly affect the soil structure (i.e. the soil is little disturbed or undisturbed) are adopted.

However, beyond the aforementioned general considerations, the combination of the two indicators and the choice of the practices for improving the current soils' capacity to sequestrate C and to protect it from its degradation should be analysed case by case as already stated above for the *n*-indicator.

4.2.2 Potential areas at risk according to SOC balance indicator

The SOC balance is a useful indicator to assess where net carbon losses are occurring, but it is not directly an indicator for risk on loss of functioning of farming systems, as it only considers the carbon flows and not the carbon stocks. In case the SOC stocks are high a negative

SOC balance does not have to decrease productivity. Therefore we also developed a risk-based approach for crop production losses by combining the carbon stocks with the carbon flows (SOC balance). We defined some arbitrary thresholds for carbon stocks and the carbon balance, which should be further underpinned and maybe be made regional specific. For SOC stocks a threshold of 40 ton C/ha was used, and for the SOC balance a threshold of -100 kg C/ha/year. Combining the two thresholds results in three risk classes:

- High risk: low stocks and negative SOC balance
- Medium risk: low stock or negative SOC balance
- Low risk: no low stock and (near) positive SOC balance

Figure 9 shows the risk maps for arable land. For arable land the NUTS2 regions with on average a low SOC risk, according to the defined thresholds, are mainly located in Central and parts of Western Europe (Netherlands, Germany, Czech Republic, Hungary). Areas with high SOC risk are mainly located in the Mediterranean regions.

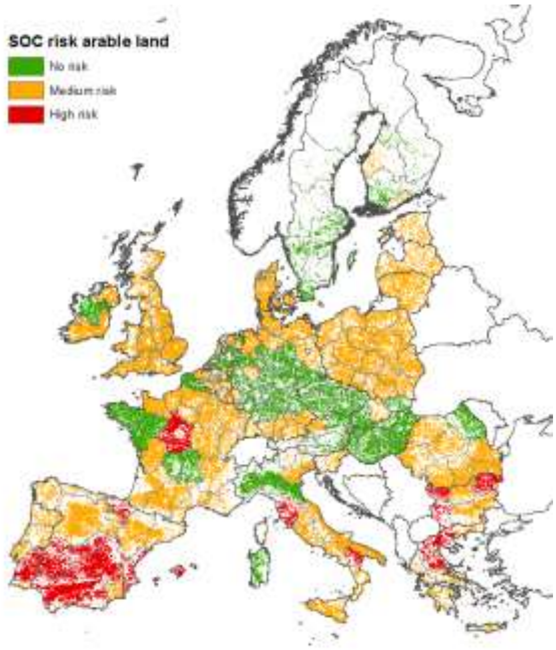

Figure 9. Soil organic carbon risk classes for arable land

The SOC balance calculation will be further refined in the course of the SmartSOIL project. This will comprise the inclusion of some additional carbon inputs (compost and sludge) and carbon outputs (leaching and erosion) and taking account of land management, based on data from the Survey on Agricultural Production Methods (SAPM), which was conducted among all farmers in Europe during the Farm System Survey in 2010. This survey contains data on soil tillage, soil cover, manure application, irrigation and crop rotations. These improvements will provide a better representation of the actual SOC balance in the NUTS2 regions, but the overall picture will not change much, as the main carbon flows are already well accounted for.

The results of this study are useful for policy makers at EU and national level, however, an individual farmer should take account of the specific circumstances at his field. Based on the same calculation rules as used in the RothC and MITERRA-Europe model, a simple tool could be developed, which would allow a farmer to calculate the carbon balance of his fields.

5. Conclusion

Both the indicators calculated in this task (*n*-indicator of potential soil stability and SOC balance indicator) resulted to provide relevant information on SOC content which may jeopardize good functioning of European farming systems. The results from the *n*-indicator of potential soil stability, suggest that there are many European regions which can be at risk since their soils are at or close to the threshold of unstable soil due to an unbalanced relationship between clay particles and SOC content. Particularly, the Mediterranean regions seem to be mostly at risk. This is confirmed also by the soil organic carbon balance indicator, which resulted relevant, especially when combined with the carbon stock, for identifying areas at risk. In fact, the results from the SOC balance identify Mediterranean areas with negative SOC balances and often low SOC stocks.

Moreover, the combination of *n* indicator and the SOC balance with other indicators, allows us both to identify the areas/regions at potential risk of SOC sequestration and to retrieve specific information. The latter shall be pivotal to define actions that need to improve both the soils' capacity to store C and to protect it from its degradation. According to our results, several areas of the EU, despite their "riskiness" have a high potential for increasing SOC through an appropriate planning (choice of the SOC practice, timeliness) of implementation of farming practices. The broad range of information that can be retrieved and the related considerations that can be made suggest that successful mitigation policy needs to be focused on strategies that are region specific and provide flexibility to facilitate SOC management practices adoption and SOC content enhancement. Once areas under risk are identified, risks have to be regionally reduced by setting simple objectives which involve farmers and stakeholders in the process. The current policies that promote agricultural mitigation have also to provide regional information of cost and incentives associated to the management adoption.

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