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Ideas and perspectives: Can we use the soil carbon saturation deficit to quantitatively assess the soil carbon storage potential, or should we explore other strategies?

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Abstract. An increase in soil organic carbon stock can contribute to mitigate climate change. International negotiation mechanisms and initiatives call for countries to consider land use change and soil management to achieve atmospheric CO_2 removal through storage in terrestrial systems (http://4p1000.org/). As a result, policy makers raised a specific operational question to the soil science community: how much and at which annual rate additional carbon can be stored in soils in different locations? It has been suggested that the ability of a soil to store additional organic carbon can be estimated from its carbon saturation deficit ($C_{sat\text{-}def}$), which is defined as the difference between the maximum amount of carbon that can be associated to its fine (<20 µm) fraction and the current amount of carbon associated to its fine fraction. In this opinion paper, we explain why, for conceptual reasons, the soil $C_{sat\text{-}def}$ is not appropriate, at least in its present form, for assessing quantitatively the whole-soil (total) organic carbon storage potential for operational purposes. We then propose alternative approaches based on new opportunities offered by the development of national and international soil monitoring programs (possibly coupled with modelling) that can provide quantitatively relevant estimates of soil total carbon storage potential. This pragmatic approach will require a sustained effort to maintain and develop soil monitoring programs worldwide and research allowing proper use of such a large amount of data.

1 Introduction

An increase in soil organic carbon (SOC) stock can partly compensate anthropogenic greenhouse gas (GHG) emissions (Lal, 2004; Paustian *et al.*, 2016). Therefore, international negotiation mechanisms call for countries to consider soil management (and not only land use changes) when accounting for CO_2 fluxes in terrestrial systems (UNFCCC, 2011; EU, 2013). Soil carbon management is the basis of the 4 per 1000 initiative, a voluntary action plan under the Lima-Paris Action Agenda to ensure food security and mitigate climate change through the increase of soil carbon stocks (http://4p1000.org/). This initiative invites all partners to implement programs with farming methods known to increase soil carbon stocks, *e.g.* agroecology, agroforestry, conservation agriculture (Lal, 2016; Minasny *et al.*, 2017). In line with this initiative, policy makers have raised operational questions to the scientific community: What is the soil C storage potential? Can this storage potential be measured/estimated and mapped at different spatial scales from the field to the globe? What are the most appropriate management techniques and how long does it take to reach this potential?

To address these questions the SOC storage potential first needs to be defined. We propose the following definition: the C storage potential of a soil is the maximum gain in soil C stock (kg m^{-2} or Mg ha^{-1}) attainable at a given timeline (*e.g.* IPCC default time period: 20 years), by implementing changes in land management, i.e. land-use, agricultural or forestry practices changes. This potential is known to vary with pedoclimatic conditions (Post & Kwon, 2000, Batjes, 2011, Stockman *et al.*, 2013; Barré *et al.*, 2017). In the context of the 4 per 1000 initiative, the target is "an annual growth rate of soil carbon stock" by 0.4%. This target therefore clearly relates to whole-soil (or total) SOC stock as_explicitly mentioned in the name of the initiative and in the proposed themes of the related international research program.

The soil mineral fraction is a key feature for SOC stabilization (*e.g.* Kleber *et al.*, 2015). It has been proposed that the soil mineral fraction has a finite capacity to protect C (Hassink, 1997). On the basis of this assumption, the notion of soil C saturation deficit ($C_{sat\text{-}def}$ in g C kg^{-1} soil) has been defined as the difference between the maximum OC content of the mineral fraction and its current C content (Figure 1):

$$C_{sat\text{-}def} = C_{sat} - C_{cur} \qquad (1)$$

where C_{sat} is the maximum amount of OC in the soil fine (typically <20 µm) mineral fraction (g C kg^{-1} soil) and C_{cur} is the current measured amount of OC in this soil fine (typically <20 µm) mineral fraction (g C kg^{-1} soil).

Several authors have suggested that the ability of a soil to store additional OC can depend on its $C_{sat\text{-}def}$. For instance, O'Rourke *et al.* (2015) considered that "Translating what is known about SOC at the particle scale into meaningful policy can be achieved through the concept of SOC saturation" and Misnany *et al.* (2017) citing the work by Hassink (1997) suggested that determining soil C saturation deficit would be needed to identify regions with the highest SOC stock increase potential. The potential link between soil C saturation deficit and soil C storage potential is therefore actively discussed.

The objective of this Opinion Paper is to contribute to this debate by discussing why, in its current form, the concept of C saturation deficit is not sufficient to determine quantitatively the C storage potential of a soil and thereby cannot contribute alone to answer operational questions raised by policy makers in the context of the 4 per 1000 initiative. We also explore other options to estimate the soil C storage potential for operational purposes.

2 The carbon saturation deficit of fine soil particles : concept, calculation methods and limiattions to calculate whole-soil OC storage potential

2.1 Why may fine particles have a limited ability to store soil organic carbon ?

The stabilizing action of soil minerals on OC has been established for more than 2 centuries (Thaer, 1809 in Feller & Chenu, 2012) and has been taken into account in soil organic carbon dynamic models for decades (Hénin & Dupuis, 1945). As the stabilization of organic compounds is partly due to their adsorption onto mineral surfaces, it has been proposed that the mineral matrix have a finite capacity to store OC. This is the concept of the soil fine fraction C saturation (Hassink, 1997; Angers, 1998; Stewart *et al.*, 2007). This concept allows explaining why in spite of increasing C inputs to the soil, the amount of OC associated to fine fractions is not systematically increasing (Stewart *et al.*, 2008; Chung *et al.*, 2008). Since the early studies by Hassink (1996; 1997), several authors have thus attempted to estimate the maximum capacity of fine particles to protect OC, *i.e.* the C saturation value of fine particles.

2.2 How to quantitatively estimate the maximal organic carbon concentration of fine soil particles?

In a seminal paper, Hassink (1997) made a first attempt to quantify the maximum amount of OC that can be associated to fine particles (<20 µm; clay + fine silt particles). He observed that in spite of differing total SOC concentrations, the amounts of OC associated to fine particles were similar in two paired grassland-cropland plots in the Netherlands. Then, Hassink plotted the OC content in the fine (<20 µm) soil fraction against the percentage of fine particles using data from 35 grassland topsoils (0-10 cm), which had been under grass for at least 30 years, from tropical and temperate regions. Hassink obtained the following significant relationship between the OC contained in the fine soil fraction and the percentage of the fine soil fraction (Figure 1):

$$C_{sat} = 4.09\ (\pm\ 1.59) + 0.37\ (\pm\ 0.04) \times FF \qquad (2)$$

where FF is the percentage of soil particles <20 µm (%) and numbers in parentheses refer to standard errors.

This so-called Hassink’s equation has been extensively used and several authors have attempted to refine this equation. In particular, Six *et al.* (2002) provided relationships between fine particles (<20 µm and <50 µm) proportion and fine particles associated OC for different land-uses (cropland, forest and grassland) and different soil clay mineralogical compositions (2:1 vs 1:1 dominated soils). Feng *et al.* (2013) proposed alternative calculation methods to estimate the maximum amount of OC that can be associated to fine particles. Beare *et al*. (2014) related the maximum amount of OC associated to fine fractions to several other soil parameters such as pH, pyrophosphate extractable Al, oxalate extractable Al and Si, dithionite-citrate extractable Fe or specific surface area. They thereby accounted for other constituents and for physical conditions known to control the stabilization of OC by fine sized soil minerals.

2.3 The carbon saturation of fine soil particles is not relevant for the calculation of the whole-soil OC storage potential

We defined the C storage potential of a soil as the maximum gain in soil C stock (kg m^{-2} or Mg ha^{-1}) attainable at a given timeline by implementing changes in land management. This C storage potential refers to total SOC (or whole-soil OC) stock. Quantifying the total C storage potential of a soil using the soil C saturation deficit of the fine fraction is therefore an inadequate use of the concept of Hassink (1997). Indeed, by definition, the soil $C_{sat\text{-}def}$ refers to the OC associated with fine soil particles (<20 µm), which represents only a fraction of total SOC. The amount of soil C distributed in coarse-sized particulate organic matter and associated with sand-sized particles represents a significant and variable proportion of total SOC stock. For instance, Wiesmeier *et al.* (2014) reported that OC associated to the >20 µm fraction is highly variable and represents on average ca. 60% and 40% of total SOC of surface soil layers in Bavarian forests and grasslands, respectively. Several other studies have reported significant (>20%) contributions of >20 µm SOC to total SOC in various systems such as agricultural temperate soils (Balesdent *et al.*, 1998; Besnard *et al.*, 2001) or cultivated tropical soils (Barthes *et al.*, 2008; Gelaw *et al.*, 2015). Moreover, several authors observed that increases in SOC stocks following a land management change were mostly due to an increase in sand-size particulate organic matter (*e.g.* Feng *et al.*, 2014; Cardinael *et al.*, 2015; Chimento *et al.*, 2016). As a result, a significant part of SOC stock increase induced by the implementation of farming methods known to promote soil carbon stocks is expected to occur mostly in the soil >20 µm fraction. This is illustrated in Figure 2, where we show that the $C_{sat\text{-}def}$ calculation allows estimating the amount of OC that can be stored in the <20 µm fraction upon the implementation of a storing practice or a land-use change, which is totally different from the actual whole-soil OC storage potential which is the sum of the $C_{sat\text{-}def}$ and the gain in particulate C in the >20 µm fraction. It follows that the $C_{sat\text{-}def}$ of the fine soil fraction alone is conceptually not appropriate to estimate the whole-soil C storage potential.

Of note, as OC associated to sand-size fractions have on average shorter residence times in soils, the fact that a significant part of SOC stock increase induced by land-management changes is expected to occur mostly in the soil coarse fractions suggests that this SOC may be susceptible to rapid loss if the virtuous farming methods are not sustained. The non-permanence of OC storage in soils is a recognized limitation for the contribution of soils to climate change mitigation (*e.g.* Smith, 2012).

2.4 The carbon saturation of fine soil particles may inform on the long-term C sequestration potential

The OC associated to fine particles has on average a longer residence time compared to bulk soil OC (*e.g.* Balesdent *et al.*, 1987; Balesdent, 1996). Evaluating the C saturation deficit of the fine soil fraction may thus provide information on the potential of increasing the stock of SOC with long residence time. Carbon sequestration is “the process of transferring CO_2 from the atmosphere into the soil of a land unit, through plants, plant residues and other organic solids which are stored or retained in the unit as part of the soil organic matter with a long residence time” (Olson *et al.*, 2014). Therefore, the C saturation deficit can help evaluating the long-term soil C sequestration potential as proposed by Wiesmeier *et al.* (2014), Beare *et al.*

(2014), Castellano *et al.* (2015) or McNally *et al.* (2017). However, the quantitative link between the $C_{sat\text{-}def}$ of a soil and its potential to store OC persistent at a pluri-decadal timescale has not been clearly established yet and deserves further research.

3 How to progress towards the quantification of the carbon storage potential of a soil?

Recent studies using the $C_{sat\text{-}def}$ proposed appealing results to policy makers such as regional (Wiesmeier *et al.*, 2014; 2015) or national estimates (Angers *et al.*, 2011; McNally *et al.*, 2017) of the soil C sequestration potential. Our point is that, if the soil $C_{sat\text{-}def}$ may be used to study the soil C *sequestration* potential, this concept is irrelevant alone to estimate the soil C *storage* potential which refers to total SOC and not only to SOC associated to fine particles (Figure 2). Alternative approaches to the $C_{sat\text{-}def}$ should therefore be used and developed to assess the soil C storage potential.

We see two avenues to progress towards an improved quantification of the C storage potential of a soil for operational purposes such as the 4 per 1000 initiative: (1) establishing references with estimates of the highest SOC stock that can be reached by a given soil, and (2) estimating possible storage kinetics (*i.e.* annual growth rate of SOC stocks) between the current SOC stock of a given soil and its targeted highest SOC stock value for various land-use and management scenarios. Both avenues can be achieved by complementary data (empirical observations of SOC stocks and storage) and model (mechanistic simulations of SOC stocks and storage) driven approaches.

3.1 A data-driven approach

We suggest that the new opportunities offered by the development of national and international soil monitoring programs (*e.g.* RMQS for France, Lucas-Soil for Europe, Global Soil Map or ISRIC for the world) can allow a data-driven approach for determining the highest SOC stock values (considered at steady state corresponding to SOC stock at t_{eq} in Figure 2) as well as SOC storage rates (corresponding to the green line in Figure 2) that can be reached for the different pedoclimatic conditions under a given land-use or land management practices.

The highest SOC stock values under a specific land-use would be equivalent to the attainable potential of C stocks defined by Lal (2016). Total SOC content of forest or permanent grassland could also be considered as aspirational maximum C storage potential in some cases where changes in land use can be considered. The appropriate methodology to determine the highest reachable SOC stocks needs to be discussed. For instance, the highest reachable SOC stock for a given pedoclimatic condition under a given land-use could correspond to the mean of the top 10% of the measured SOC stocks for these conditions. Depending on the operational question, this approach may be conducted at different scales from regional to global. For example, SOC stocks under natural vegetation have been termed as “reference SOC stocks” and have been determined for 7 IPCC soil classes and 10 IPCC climatic zones from available world databases (IPCC, 2006; Batjes, 2011). Maximal rather

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than mean C stocks could be calculated, and further refined by land-use, and also for at least all WRB soil types and more detailed climatic zones.

The IPCC has also defined default SOC storage rates (Tier 1) based on current knowledge (*i.e.* based on field measurements) of the changes in SOC stocks upon changes in land-use, management, or organic input on a time period of 20 years on the 0-30 cm depth (IPCC 2006). Those SOC stock change factors have further been derived for specific IPCC climatic zones, but accurate regional or national (Tier 2) SOC stock change factors that are soil and climate specific are still missing.

Such data-driven or statistical approaches have already been explored to assess or refine estimates of highest SOC stock values or default IPCC SOC storage rates. For instance, Sparling *et al.* (2003) have estimated desirable values of soil organic carbon in New Zealand, which were proposed to be above the lower quartile of SOC stocks in New Zealand pasture soils, for each major soil type. Reference values of SOC stocks under natural vegetation have recently been used to assess soil C storage potential in Nigeria (Apka *et al.*, 2016). Stolbovoy & Montanarella (2008) estimated the potential of SOC gain of European soils by subtracting the observed SOC stocks per soil typological unit, with the maximum observed SOC stocks in the same typological unit and the same climate, using the European Soil Portal databases. Similarly, Lilly & Baggaley (2013) subtracted the calculated median SOC and the observed maximum SOC contents to compute the C storage potential of various Scottish soil series. The use of chronosequences with changes in land management can allow refining default IPCC SOC change factors for differing pedoclimatic conditions. For instance, Kurganova *et al.* (2014) have calculated the annual SOC storage rates in different pedoclimatic contexts following the abandonment of arable lands and the subsequent natural vegetation establishment induced by the collapse of collective farming in Russia.

A data driven approach to estimate highest SOC stock values or SOC storage rates can easily be implemented in several pedoclimatic regions. However, estimating empirically highest SOC stock values has several limitations. First, the observed SOC stock values for given pedoclimatic conditions (or part of the top 10% values) might be well below the maximum, if for example all pastures were degraded in the considered pedoclimatic condition or if steady-state conditions for SOC stocks were not attained for most soils. Second, this approach allows estimating a soil storage potential value for known practices. If new storing practices are designed or implemented in the considered region, the highest reachable SOC stock value could obviously not be calculated. Another limitation is that the impact of land-use change is generally better documented than the effects of management practices. Therefore, while estimating highest reachable SOC stocks or SOC storage rates may be straightforward in a context of land-use change, it would be more difficult to implement in a context of land management modification. Indeed, most soil databases, such as Lucas-Soil or ISRIC, do not systematically provide comprehensive information on management practices. However, with the active development of soil monitoring networks, regional to local estimates of highest reachable SOC stocks and SOC storage rates may progressively become available worldwide for management practices.

Such a data-driven approach has therefore already proven appropriate to estimate quantitatively soil C storage potential and refine IPCC default factors in some occasions. We suggest that this data-driven approach could also be an avenue for calculating SOC storage potential of soils that should be explored further.

3.2 A model driven approach

Complementary to the data-driven approach, SOC dynamic models can also be efficient tools to estimate SOC storage potential. A modelling approach (Tier 3) may solve the lack of data on SOC stock changes, provided that these models are reliable and accurate. Such an approach has been, to some extent, proposed by Lugato *et al.* (2014a, b). They have used the CENTURY model at the European scale and compared the model outputs to the data provided by the LUCAS survey (*ca.* 20 000 soil samples across Europe). In a second step (Lugato *et al.*, 2014b), they have used the model to produce a spatially explicit estimation of soil C storage potential in European arable soils by 2050, according to different management scenarios (*e.g.* implementing cover crops, ley rotations), highlighting changes in the annual growth rate of SOC stocks with time. They verified that the model reproduced quite well the effect of the considered practices on SOC stocks by comparing with measured changes in SOC in long-term experiments in Europe.

Lugato *et al.* (2014b) have clearly provided an interesting estimate of SOC storage potential in European arable lands (management-specific reachable stocks and annual growth rate of stocks). Nevertheless, there is room for improvement on the data, modelling and predictions parts of their approach. First, the LUCAS survey only considers topsoil horizons and the bulk density is not measured in this monitoring program. Second, SOC dynamic models can still be significantly improved, in particular their initialization is still very problematic, and they do not accurately simulate the effect on SOC stocks of management practices such as no tillage with permanent cover crop or agroforestry (*e.g.* Luo *et al.*, 2016). Third, the model predictions need to be validated using data from resampled monitoring networks. This step may be conducted in the coming years as several monitoring networks including LUCAS have started a second sampling campaign.

Overall, the two proposed approaches, *i.e.* data driven, and model driven are complementary by the type of information required. Their comparison on specific situations would allow to better define their limits and potential for estimating the SOC storage potential.

4 Conclusion

The soil $C_{sat\text{-}def}$ concept refers to a theoretical potential to store C in a persistent form (fine fraction). In its current form, this concept is not appropriate alone to quantitatively assess the whole-soil total C storage potential from an operational perspective. To respond to the questions that are raised by the implementation of the 4 per 1000 initiative, coupling data mining and modeling approaches seems more appropriate in a short-term and operational perspective. However, this pragmatic approach is not straightforward to implement. It will need a sustained effort to maintain and develop soil monitoring programs worldwide and research efforts for an adequate use of such a large amount of data. Moreover, this approach would allow little progress in understanding the mechanisms explaining soil C storage potential (Dignac *et al*. 2017). Research on these aspects should therefore be carried out in parallel. In this respect, the questions of OC stabilization by the soil mineral fine fractions and the soil $C_{sat\text{-}def}$ concept remain relevant and may provide fruitful tracks to improve soil C dynamic model formalism in a longer-term perspective.

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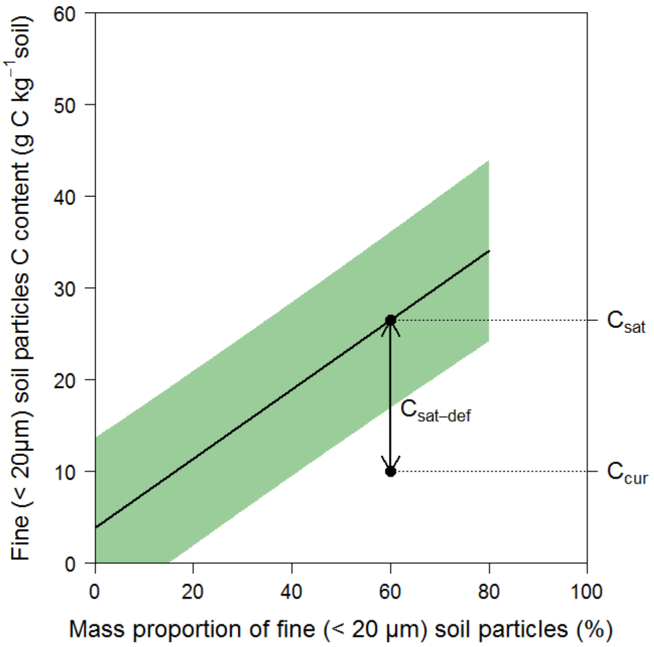

Figure 1: Maximal amount of OC contained in the soil fine (<20 µm) fraction plotted against mass percentage of the fine fraction (from Hassink 1997). The calculation of the $C_{sat\text{-}def}$ is illustrated for a soil containing 20 g C kg^{-1} soil in its fine (<20 µm) fraction and whose fine fraction represents 60% of its mass. The green zone around the fitted relationship corresponds to the 95% prediction confidence interval.

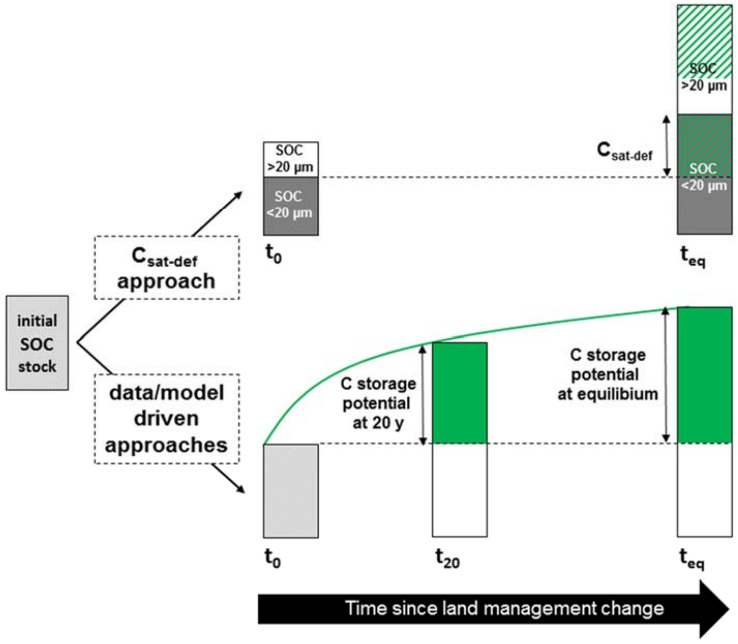

Figure 2: Illustration of the differences between the C saturation deficit and the data/model driven approaches based calculations of the SOC storage potential at given timelines (20 years = t_{20} and equilibrium = t_{eq}) when implementing farming methods known to increase SOC stocks. The $C_{sat\text{-}def}$ takes only into account the maximum amount of SOC associated to fine particles (<20 µm) at equilibrium. Upon the $C_{sat\text{-}def}$ approach, the two hatched boxes in green represent the storage potential in the <20 µm fraction and in the >20 µm fraction. The sum of these storage potentials correspond to the whole SOC storage potential. The data/model driven approaches refer to total (whole-soil) increase at given timelines. The data/model driven approaches can yield discrete (green boxes) or continuous (green line) temporal estimates of the SOC storage potential.