Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations

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ABSTRACT

Recent initiatives, such as the United Nations declaring 2015 as the International Year of Soils and the French « 4 per 1000 » initiative call attention on soils and on the importance of maintaining and increasing soil organic matter stocks for soil fertility and food security, and for climate change adaptation and mitigation. We stress that soil organic carbon storage (i.e. an increase of soil organic carbon stocks) should be clearly differentiated from soil organic carbon sequestration, as the latter assumes a net removal of atmospheric CO_2. Implementing management options that allow increasing soil organic carbon stocks at the local scale raises several questions, which are discussed in this article: how can we increase SOC stocks, at which rate and for how long; where do we prioritize SOC storage; how do we estimate the potential gain in C and which agricultural practices should we implement? We show that knowledge and tools are available to answer many of these questions, while further research remains necessary for others. A range of agricultural practices would require a re-assessment of their potential to store C and a better understanding of the underlying processes, such as no tillage and conservation agriculture, irrigation, practices increasing below ground inputs, organic amendments, and N fertilization. The vision emerging from the literature, showing the prominent role of soil microorganisms in the stabilization of soil organic matter, draw the attention to more exploratory potential levers, through changes in microbial physiology or soil biodiversity induced by agricultural practices, that require in-depth research.

1. Introduction

The 4 per 1000 initiative aims at increasing the organic matter content of soils, with a special focus on agricultural land, in order to contribute to food security, adaptation to climate change, and mitigation of climate change (http://4p1000.org). The first two aims of the initiative are based on common knowledge regarding the central role of soil organic matter (SOM) in soil fertility and soil water retention (Lal, 2008). Thus SOM indirectly contributes to agro-ecosystem productivity, and hence to food security. Soil organic matter also provides agro-ecosystems with the ability to adapt to a changing climate with less frequent and regular precipitation and more extreme rainfall, with related erosion problems (Chenu et al., 2000; Pan et al., 2009). The third aim of the initiative, regarding mitigation, is based on quantitative data on soil organic carbon (SOC) pools (Jobbagy and Jackson, 2000) and

fluxes (Le Quéré et al., 2015) showing that small changes in world SOC stocks could aggravate or mitigate the global greenhouse gas (GHG) effect, as early suggested by Balesdent and Arrouays (1999) and developed for example in recent articles (Chambers et al., 2016; Lal, 2016; Minasny et al., 2018, 2017; Paustian et al., 2016; Soussana et al., 2017).

Accounting for soil carbon as part of the GHG assessment may be subject of misunderstanding (Minasny et al., 2018). Two terms are often used interchangeably: carbon sequestration and carbon storage, which can sometimes lead to confusion. Here, according to Olson et al. (2014), we define **Carbon sequestration** as "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 (humus). Retention time of sequestered carbon in the soil (terrestrial pool) can range from short-term (not immediately released back to atmosphere) to long-term (millennia)

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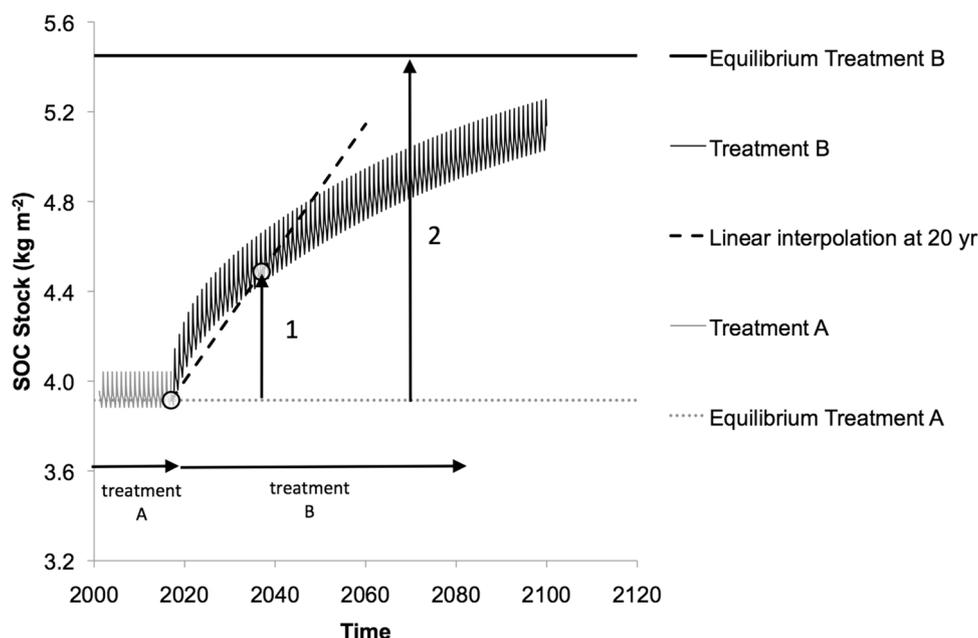 E-mail address: claire.chenu@inra.fr (C. Chenu).

Fig. 1. Schematic increase in SOC stocks following changes in land-use or management practices (increased OC inputs or decreased OC outputs). 1. Carbon storage in 20 years. 2. Maximum C storage. Mean monthly variations of SOC stocks are figured.

storage.". Sequestration can therefore be quantified for a given duration. Twenty years is often chosen (IPCC, 2006). **Carbon storage** is broader as it is defined as the increase in SOC stocks over time in the soils of a given land unit, not necessarily associated with a net removal of CO_2 from the atmosphere. For example adding the available manure resources on a given agricultural field rather than spreading it homogenously over the landscape may locally increase SOC stocks (where manure has been added), but not increase the associated CO_2 removal from the atmosphere at the landscape scale. While storing organic carbon for long times is preferable in terms of GHG mitigation, labile fractions of SOC (e.g. with residence times of months to years) are essential in terms of soil fertility (their mineralization provides nutrients to plants), of soil physical condition (aggregate stability largely depends on labile C (e.g., Angers and Mehuys, 1989; Cosentino et al., 2006), and of soil biodiversity (labile organic matter being the trophic resource of organisms). Hence it is desirable to increase stocks of both labile and stable forms of organic matter. In any case, the time horizon at which SOC storage or SOC sequestration are being considered should be specified. Here, we consider both organic carbon storage and sequestration and will use the term soil carbon storage when no assumption is made on a net atmospheric CO_2 removal.

Increasing organic matter in soils via management practices not only encompasses soil carbon related questions, but also agronomic and environmental dimensions, as well as sociological, economical and ethical ones. These will not be considered here, while we do not disregard their importance, (e.g., Aubert et al. (2017). Moreover, mitigating GHG emissions by increasing SOC stocks should not be regarded as a way to compensate for CO_2 emissions due to the combustion of fossil fuel nor for N_2O or CH_4 emissions related to agricultural activities and hence allow to continue business as usual, but rather as an additional lever in the portfolio of options that countries can consider to reduce their agricultural GHG emissions (Wollenberg et al., 2016).

Implementing management options that allow increasing soil organic carbon stocks at the local scale raises several questions: how can we increase SOC stocks, at which rate and for how long? Where do we prioritize SOC storage? How do we estimate the potential gain in carbon and which agricultural practices should we implement? In this overview, we will consider the knowledge available to answer these questions and several related knowledge gaps, and propose potential innovations.

2. SOC stocks result from a balance between inputs and outputs

If the OC inputs to a soil become larger than the OC outputs by mineralization or erosion, then its SOC stock will increase. SOC stock evolution can be described as follows:

$$dC/dt = I(t) - k(t).C \quad (1)$$

where I is OC inputs and k is the rate of C loss (i.e., the probability to be lost in the interval dt, by mineralization, erosion or leaching). Assuming that OC inputs and C loss rates are constant over time, SOC stock displays a steady-state value, C^*

$$C^* = I/k \quad (2)$$

Let's assume that either input or loss rate is altered due to a change in land use or land management. The SOC stock will evolve out of steady state for a certain period, to eventually reach the new equilibrium value. This is illustrated in Fig. 1. When considering a soil, except well-documented plots for which records of SOC stocks over time are available, it is not easy to determine a priori if the OC stock of this soil is at equilibrium with the OC inputs, or somewhere between two equilibria. It explains why, even if annual OC inputs are constant in a given period, SOC stocks can increase or decrease during that period. This phenomenon may explain for example the changes of SOC stocks observed in French forest soils. SOC stocks in mineral soils (0–40 cm) were monitored between 1993 and 2012 in 102 plots across France and increased on average by $0.035 \, \mathrm{kgC\,m^{-2}\,y^{-1}}$ (Jonard et al., 2017): SOC stocks were probably not yet at equilibrium at the start of the monitoring. Furthermore the C accumulation rate was found to decline with stand age (Jonard et al., 2017), what could be interpreted as getting closer to an equilibrium between the soil C stock and C input. This result among others stresses the need to have good constraints on the soil past land-uses when studying its OC stock evolution. However, in the context of a continuously changing climate SOC values at equilibrium may also continuously change, although these aspects will not be considered here.

If we consider that the loss rate is constant over time, an increase in OC inputs will result in SOC stock accrual. Such an increase can be obtained either by increasing C inputs from the vegetation (increase in net primary production or increase in residue return) or by increasing

exogenous organic matter addition (manure, organic wastes, organic amendments…).

The reduction of C outputs (i.e., a decrease in the decay rate k) can be achieved by reducing SOC mineralization by soil micro-organisms or SOC erosion. The role of microorganisms as drivers of soil C cycling, storage and sequestration in soil is not conceptually new, but is increasingly acknowledged as crucial (Dungait et al., 2012; Lehmann and Kleber, 2015; Schimel and Schaeffer, 2012). Microorganisms contribute both to the biodegradation and mineralisation of soil organic substrates, and to the genesis of new organic metabolites. Their action could be viewed as decreasing C storage through the mineralisation of SOM, but increasing the residence time of C as their metabolites exhibit a high affinity for the protecting mineral phases (Cotrufo et al., 2013; Kallenbach et al., 2015; Miltner et al., 2012). The breakdown and biosynthesis rates of the various biochemical components of OM are determined by the microbial community dynamics and by their functional traits. These rates are limited by physical accessibility of substrate to microbes or to their enzymes and by the micro-habitat conditions (oxygen, pH, water content, nutrient resources) (e.g. Juarez et al., 2013b; Pinheiro et al., 2015; Ruamps et al., 2011). As such, any agricultural practice altering the soil physical structure or affecting the microbe resources and the environmental conditions can modify the mineralisation rate of SOC. Regarding erosion, it is established that the downslope transport of SOC in the landscape might redistribute it to sites where it persists longer that it would have in its original location (Berhe et al., 2012; Chaopricha and Marin-Spiotta, 2014; Quinton et al., 2010). The relative effects of the loss of SOC from eroded areas, the loss of C during transportation and its accumulation in depositional areas on the global carbon budget are still under debate (Sanderman and Berhe, 2017; Wang et al., 2017; Yue et al., 2016). While erosion may create a C sink (Berhe et al., 2007), it remains a major soil degradation process, not compatible with sustainable food security and environmental quality (Sanderman and Berhe, 2017).

3. By how much, at which rate and for how long can SOC stocks be increased?

The **carbon storage potential** of a given soil unit may be defined as the maximum gain in soil OC stock attainable under a given climate and a given timeline (e.g. time required to attain a new equilibrium or a given time period, such as 20 y for IPCC) (Fig. 1). Similarly, the carbon **sequestration** potential of a given soil would be the maximum gain in SOC allowing a net removal of CO_2 from the atmosphere under a given climate and for a specified timeline. From current knowledge of SOM dynamics, we can infer the magnitude and kinetics of SOC change as related to yearly carbon inputs to the soil and pedoclimatic conditions. This knowledge is synthesized in several models of SOC dynamics (see the review of models by Campbell and Paustian, 2015). In Table 1 we calculated for a few representative situations the increase in plant material input or the decrease in decay rates that are required to increase SOC by 4 per 1000 per year during 20 years, i.e., increase soil C by +8% after 20 years, using the model RothC 26.3 (Coleman and Jenkinson, 2014). Typically, the magnitude of the relative changes in plant C inputs or decay rates to reach the target stands in the range of 15–25% (Table 1). It is noticeable that the maximum C gain is much higher than the gain in 20 years: from 1.6 times higher in light-textured tropical soil where OC turnover is rapid, to 3.0 times higher in cool, clayey soils where OM turnover is slowest. Similarly, differences between environments regarding the required OM input increment typically depends on (i) the differences in mineralization kinetics, and (ii) the initial C content, since the calculation is based on a *relative* increase in SOC. Around these general features, other inputs than plant material, such as composted amendments, are expected to have a higher yield in SOC (see Section 5); in case of progressive increase in inputs, e.g., through the positive feedback of SOC on net primary production, SOC increase will be slower.

Soil organic matter dynamics models have been developed in the 1970's and 1980's based on long-term experiments in either temperate or tropical agricultural environments. Their parameters have been calibrated so as to fit observed C changes over decades under controlled C inputs or management practices. The major difficulties encountered in the use of these model predictions at the local scale concern: (i) the initial state of soil carbon, which can be under steady or non-steady state depending on past conditions (see above discussion in Section 2); (ii) the difficulty in initializing accurately the size of the SOC pools (Luo et al., 2016), in particular those with long turnover times such as for

Table 1

Indicative model calculations of required changes in either plant material C input to the soil or mean mineralization rates, to reach a relative increment of SOC by +8% in twenty years (+4‰ per year). Prediction using the RothC 26.3 default model parameters of SOC dynamics applied to A horizons.

		case 1 temper. crops, sandy	case 2 temper. crops, clayey	case 3 tropical crops, sandy	case 4 tropical crops, clayey	case 5 temper. forest, sandy	case 6 tropical forest, clayey
Pedo-climatic conditions							
MAT (°C)		12	12	24	24	12	24
Clay (%)		5	40	5	40	5	40
Proportion of resistant material in carbon input		0.41	0.41	0.41	0.41	0.80	0.80
Inert Organic C/kg m^{-2}		0.4	0.8	0.4	0.8	0.4	0.8
Initial practice A							
SOC (equilibrium)/kg m^{-2}	I	3	5	2	3	4	4
Yearly carbon input/kg m^{-2} yr^{-1}	II	0.268	0.305	0.424	0.411	0.315	0.531
Average decay rate of SOC inputs (IOM excluded)/yr^{-1}		0.103	0.073	0.265	0.187	0.088	0.166
Practice B reaching the 4 per 1000							
SOC increase after 20 years / kg m^{-2}	III = I*0.004*20	0.24	0.40	0.16	0.24	0.32	0.32
(i) by increasing carbon inputs only:							
Additional C input/ kg m^{-2} yr^{-1}	IV	0.064	0.088	0.070	0.080	0.060	0.089
Relative increase in C input	V = IV/II	24%	29%	17%	19%	19%	17%
Equilibrium SOC practice B/ kg m^{-2}		3.62	6.22	2.26	3.43	4.69	4.54
(ii) by decreasing SOC decomposition rates only :							
Relative decrease in SOC decomposition rates		−21%	−25%	−16%	−17%	−17%	−15%
Equilibrium SOC practice B / kg m^{-2}		3.70	6.43	2.29	3.47	4.75	4.58

example the "passive" pool in the Century model having turnover times of several centuries (Parton et al., 1988) and the "inert" pool, of the RothC model with residence times of several thousands of years (Jenkinson and Rayner, 1977); (iii) the estimate of the actual C inputs to the soil; (iv) a generally poor accounting of soil types besides their clay content; (v) the impact of practices on decay rates of SOC (the management practices currently simulated in SOC models being limited and SOC models do not simulate the effects of innovative cropping systems such as associated crops or agroforestry); and (v) the lack of consideration of deep soil layers. As a result, models parameterization may be still rough concerning important factors driving SOC dynamics. Furthermore, model's linearity (i.e., amounts of SOC formed on the long-term assumed to be proportional to inputs) has been questioned.

Hassink (1997) suggested that soils have a finite capacity to protect organic matter from mineralization, i.e., a finite capacity to store carbon for decades or more, which was termed the carbon saturation capacity. In this concept, which was expanded by Six et al. (2002) and then by Beare et al. (2014), long residence times of organic matter are essentially due to fine sized minerals ($< 20 \, \mu m$), clay minerals and sesquioxides, that provide protection by organo-mineral interactions (physico-chemical protection) or reduced accessibility of organic compounds to decomposers or oxygen to decomposers (physical protection). The abundance of the $< 20 \, \mu m$ size fraction would determine the amount of C that can be stored for decades to centuries, in association with this fraction.

If we assume a linear relationship between C inputs and SOC stocks at steady state (as assumed by almost all soil C dynamic models, Fig. 2a), the only limitation for SOC stock increase is the amount of OC inputs that can be provided. Several authors challenged the concept that an extra C input would always produce a similar SOC stock increase (Stewart et al., 2007). Their alternative referred to two concepts. The first concept assumes a saturation behaviour towards C inputs, C inputs becoming less and less efficient as the soil is approaching its saturation capacity (Fig. 2b). Here the saturation concept was expanded to the total soil organic carbon, contrary to the original proposal of Hassink (1997). This alternative view allows explaining the results of the few studies showing little or no increase of SOC stocks following increased OC inputs. However, there is little or no difference between the linear and saturation relationships for most of field data (Stewart et al., 2007). The second concept is the so-called "priming effect", which has been evidenced in deep soil layers: when SOC mineralization is limited by the energy supply to microorganisms, increased C inputs of fresh material may accelerate old SOC mineralization (Fontaine et al., 2007). Whatever the considered formalism, establishing which factors are playing on dSOC/dI remains largely an open question. Establishing quantitatively the SOC saturation limit for fine particles associated organic matter and for bulk soil organic matter, if it exists, is also still a debated scientific issue.

4. Where to store carbon? Are some soils or soil horizons better targets than others?

Increasing SOC stocks is not necessarily simple or even possible at all locations. Obviously, it can be more difficult to increase C inputs at some places due to limited access to necessary resources such as fertilizer or water. Using a proportion of actual SOC (4 per 1000) to name the so-called initiative and not an actual SOC amount, implicitly expresses the need to adapt the effort to the climate-dependency of C sequestration costs, which are, for instance, much higher in water-limited and hot areas than in cool moist climates. Soils that have the higher carbon storage potential (i.e., that have SOC stocks well below an estimated SOC stock under favourable practices) could be prioritized. They also exhibit the faster storage rate (Fig. 1). As illustrated in Table 1, for a given increase in C inputs different soils can present different SOC stock increases in relation with soil properties, i.e. the efficiency of the storage may vary with the decay rate of organic matter (k in Eq. (1)). In the examples of Table 1, a given additional yearly carbon input, leads to higher additional C stocks in temperate situations compared to tropical ones and in clayey soils compared to sandy ones.

For a given soil, different horizons can be targeted. Subsoil horizons have lower SOC concentration (Jobbagy and Jackson, 2000), and thus their SOC storage potential, i.e. the difference between present and potential stocks, would be higher than topsoil. Furthermore, the contribution of belowground inputs (roots) to SOC are much higher than aboveground residues (e.g. Balesdent et al., 2017; Rasse et al., 2005; Rumpel and Kogel-Knabner, 2011). An option to increase the efficiency of C inputs to the soil can therefore be to place C inputs preferentially towards deep soil layers where the storage potential is large and their mineralization rates may be lower. Indeed, certain soil types exhibit deep organic rich layers, i.e. chernozems, vertisols and more generally black soils (Jobbagy and Jackson, 2000). These are characterized by medium to fine textures and developed under grassland vegetation, i.e. characterized by perennial deep rooting systems. The high potential of deep horizons for SOC storage was quantified by a meta-analysis of studies tracking the incorporation of plant residues into the soil profile on the basis of the natural ^{13}C labelling technique (Balesdent et al., 2017). This work showed that the global mean residence time of SOC is approximately four times higher in the subsoil (30–100 cm depth) than in the topsoil (0–30 cm) (Fig. 3). The analysis of world soil radiocarbon profiles also provides evidence for both the long-term stabilization of C in deep horizons of such soils, as well as the deep incorporation of active C by bioturbation and rooting (Mathieu et al., 2015). However, the balance between increased OC inputs to subsoil and destabilization of pre-existing SOC at depth due to priming effects remains uncertain. While the occurrence of a priming effect induced by roots and their rhizodeposits has been widely demonstrated (e.g. reviews by Cheng et al., 2014; Kuzyakov, 2002), very few estimates of the priming are available *in situ*, in conditions corresponding to the subsoil (e.g.,
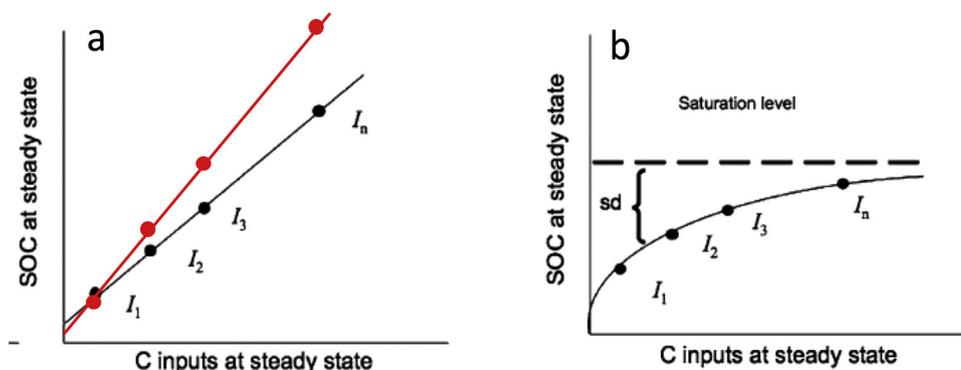

Fig. 2. (a) Relationship between C inputs and SOC stocks at steady state for two different soils assuming a linear relationship between C inputs and SOC stocks; (b) Relationship between C inputs and SOC stocks at steady state assuming a saturation behaviour. (Figure adapted from Stewart et al. (2007)).
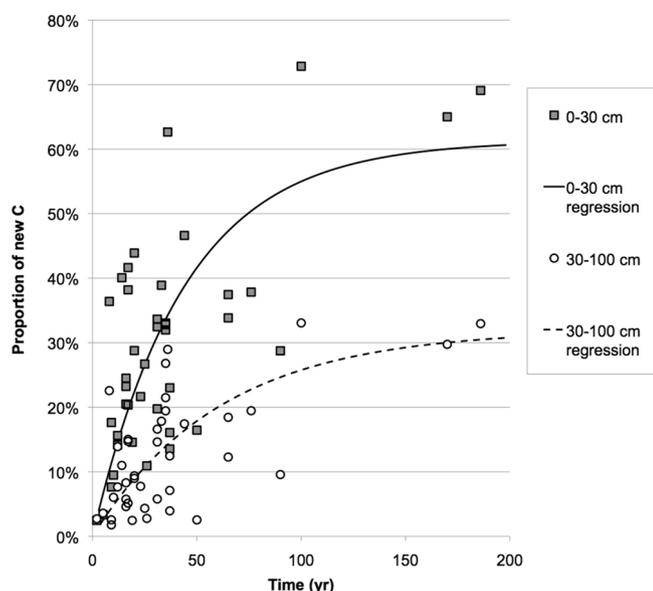
Fig. 3. A meta-analysis of natural abundance of ^{13}C in cropped soils shows that the residence time of SOC is approximately four times higher in the subsoil (30–100 cm depth) than in the topsoil (0–30 cm). (Balesdent et al., 2017).

Shahzad et al., 2015). Another process that warrants thorough estimation is the burial of topsoil organic matter by anecic earthworms and its consequences in terms of SOC storage and persistence (e.g., Arrouays and Pelissier, 1994; Don et al., 2008).

Another way to increase OC inputs to the subsoil is deep ploughing. Not very common, this practice can be performed occasionally to break the hard pan of Podzols in cropped soils or as a preparation measure of soil before afforestation (Alcantara et al., 2017). The SOC rich topsoil is buried at 60–120 cm depth while the SOC poor subsoil is brought to the surface. It was found to affect SOC storage in two ways : the buried topsoil material decomposed more slowly than the reference topsoil material and new SOC accumulated in the initially C poor new topsoil (Alcantara et al., 2017). As a result, after 36–48 year, the whole soil profile SOC stock was larger in agricultural deep ploughed soils than in reference situations (Alcantara et al., 2016). While very informative in terms of process understanding, this practice might not be applicable nor desirable everywhere.

Potential positive feedbacks should also be considered when identifying the best fields or areas where to implement SOC storing practices. In soils with an initially low OC content, the build-up in SOC would ameliorate soil fertility which would in turn increase plant production and then C inputs to the soil (e.g. Sanderman et al., 2017). OC-poor soils are also more prone to erosion and increasing their SOC content would contribute also to reduce soil erosion by improving their aggregate stability. The increase in SOC stocks in C-poor soils can therefore trigger a positive feedback loop. Indeed, a voluntary action designed to increase SOC stocks of C-poor soils has the potential to initiate a virtuous cycle and such soils should be considered in priority given the importance of the expected benefits.

5. Practically, how to estimate the SOC storage potential?

The carbon storage potential of a soil may be defined as the maximum gain in soil OC stock attainable under a given climate, soil type and timeline (e.g. time required to attain a new stock after IPCC time period: 20 y, or a new equilibrium) (Fig. 1). In the previous sections, we have given some qualitative insights on how SOC stocks could be increased but no quantitative indications on storage potential. As presented in Fig. 1, there is a transient period between the two steady-

states. To quantify SOC accrual rates, one should be able to determine the difference between steady-state 1 and steady-state 2, and the trajectory between the two. This remains a major research question.

To estimate SOC changes, the IPCC developed a tiered approach depending on the spatial scale of the project or study and the data available. Tier 1 corresponds to very large scale approaches, with default SOC stocks values for eco-regions and average SOC stock changes values (soil carbon change factors) for changes in land-use, management or organic input applied to a given surface area over a time period of 20 years for the 0–30 cm depth (IPCC, 2006). The Tier 2 approach is similar but uses data specific to a state or region. For example, a Tier 2 approach has been used to estimate the potential of agricultural practices to mitigate GHG emissions and to store C in soils of Canada (VandenBygaart et al., 2008) and of mainland France (Pellerin et al., 2013). Tier 2 SOC stock change factors are still missing for many regions, soil type, and management practices, calling for meta-analyses (Söderström et al., 2014). However, in some agricultural regions, agronomists have for long established reference SOC stocks values (Hénin and Dupuis, 1945) that allow estimating the reachable SOC content of a given soil according to the most common practices (Bayer et al., 2006; Saffih-Hdadi and Mary, 2008). The Tier 3 approach, which is either based on a comprehensive acquisition of field data or on the use of models, has seldom been applied at large scales, although is the basis of the United States estimate of its soil related agricultural GHG emissions (Milne et al., 2007; Ogle et al., 2010). Indeed, SOC dynamics models are *a priori* good candidates to estimate the potential gain of organic carbon following land-use or agricultural practices changes (to determine the new steady-state value as well as the temporal trajectory to reach it). However, they require to be fully validated and properly represent land use management effects relevant to the study area.

Another possible methodology is based on the use of available SOC stocks data at the territory to the regional scale, i.e. what may be called a data-driven approach. Stolbovoy and Montanarella (2008) calculated the carbon storage potential for cultivated soils in EU by subtracting the average present SOC stock, for each soil typological unit, from the maximum SOC content observed for that soil typological unit, both numbers being obtained from the 1:1,000,000 European soil spatial data set. Lilly and Baggaley (2013) applied this method to Scotland, i.e. at a finer resolution. The same approach could be developed at the scale of small regions, provided a soil map is available as well as sufficient data on SOC stocks.

Estimates of the storage potential of SOC with very long residence time is more difficult to provide as there exists to date no method to estimate the size of the pluri-decadal/ pluri- centennial persistent SOC. As a result, the only way to quantitatively estimate the potential of soils to store additional SOC with residence times of decades to centuries with changes in management is to use models to estimate the change in the size of pools with high residence times (e.g. the Passive pool in Century model with a turnover time of 400–2000 y, Parton et al., 1987). Designing a method that allows determining the concentration in pluri-decadally persistent SOC would be very helpful to progress in the estimate of SOC storage potential, but the various attempts towards this goal using hydrolysis or oxidation methods have been questioned (Chenu et al., 2015; Greenfield et al., 2013; Lutfalla et al., 2014). Indeed, it would allow providing direct measures to assess the storage potential of various management techniques. In addition, several authors have proposed estimates of SOC storage potentials based on the carbon saturation deficit approach (Angers et al., 2011; Wiesmeier et al., 2014; McNally et al., 2017). However, these estimates have to date neither been compared to modelling ones nor to actual data. In practice, the methods available to estimate the SOC storage potential of a soil are the tiered ones proposed in the IPCC methodology, and future research should aim at comparing them with the carbon saturation approach.
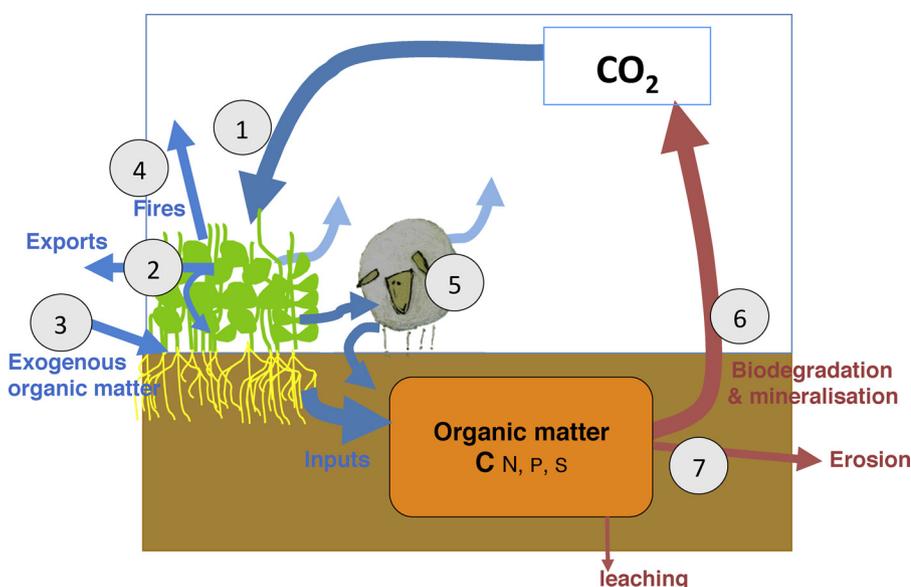
Fig. 4. Levers associated with agricultural practices that may influence SOC stocks: (1) increasing primary production (e.g. crop rotations, agroforestry, cover crops), (2) increasing biomass return to soil (crop residue return), (3) importing organic wastes to soil (manures, composts..), (4) avoiding fires, (5) grassland management (fertilization, grazing), (6) decreasing biodegradation and mineralisation rates (no tillage, water management), (7) decreasing erosion rates.

6. Which practices can be implemented to increase SOC stocks? Towards innovative soil carbon management practices

Management practices can influence SOC stocks by either increasing C inputs to soil or decreasing SOC losses (Fig. 4). These practices have been extensively reviewed at global (e.g., Conant et al., 2016; Paustian et al., 2016; Smith et al., 2008; Stockmann et al., 2013), or national or regional scales (e.g., Pellerin et al., 2017; VandenBygaart et al., 2008). An examination of the literature suggests that management practices are not always documented for the different regions where they are used (e.g. there are more published studies on the effect of agroforestry on SOC in tropical than in temperate areas) which calls for more systematic meta-analyses for the different pedo-climatic contexts. Reasons for the observed variability of the effects of a given practice are not always identified (e.g. effect of tillage, see below). Here we focus on knowledge gaps, and hence research needs, for innovative SOC management practices, in the light of recent studies in soil ecology and biogeochemistry.

6.1. Category 1: Assessments, balances or re-evaluation required

6.1.1. No-tillage and conservation agriculture

Tillage is generally considered to increase SOC mineralization due to the mechanical and rain-induced disruption of soil aggregates and the consequent release of CO_2. Therefore no-tillage, i.e. direct seeding implementation has been considered as a suitable practice to increase/

maintain SOC stocks compared to so-called conventional tillage, i.e. mouldboard ploughing or inversion tillage. The results of recent global meta-analyses and reviews confirm that SOC stocks increase in the upper soil layers (0–15 or 0–20 cm) with no-tillage implementation, but shows that it has on average a low to non-significant effect on SOC stocks over 30 cm depth or deeper (Angers and Eriksen-Hamel, 2008; Haddaway et al., 2017; Luo et al., 2010; Meurer et al., 2018; Powlson et al., 2014, [Powlson et al., 2016]2016; Virto et al., 2012; West and Post, 2002) as shown in Table 2. Additional SOC storage is even less pronounced when other techniques are considered, such as chisel, harrow or disk (Meurer et al., 2018; West and Post, 2002). Hence when reducing soil tillage, there may be an additional SOC storage in superficial soil layers, but no or little SOC sequestration for the land unit considered if the whole soil profile is considered. This seems to be particularly the case in humid and temperate conditions (e.g., Dimassi et al., 2014; VandenBygaart et al., 2010) as opposed to drier climates such as the semi-arid Canadian Prairies (VandenBygaart et al., 2010) or the Mediterranean regions (Blanco-Moure et al., 2013), where significant beneficial effects of no-till relative to mouldboard ploughing are observed. However, the origin of this variability and the underlying processes have not yet been explained (Luo et al., 2010; Meurer et al., 2018; Virto et al., 2012) nor thoroughly studied. Helgason et al. (2014) showed that under the cool and moist climatic conditions of Eastern Canada, the decomposition of ^{13}C barley residues was the same whether the residues were incorporated or not, whereas under the semi-arid conditions of the Canadian Prairies, decomposition was greater when

Table 2
Effect of no-tillage (NT) compared to full inversion tillage or mouldboard ploughing, i.e. conventional tillage (FIT), on SOC stocks reported by meta-analyses. In the dataset from West and Post (2002) pairs of plots may also differ in the rotation, 22 cm is the average depth sampled. The dataset from Meurer et al. (2018) is a sub-set of that of Haddaway et al. (2017).

References	Climate zone	Number of sites	Number of pairs of plots	Depth considered (cm)	Duration of trials (years)	SOC stock NT-FIT (kg C m^{-2})	SOC stock NT-FIT (kg C m^{-2} y^{-1})
West and Post (2002)	any		93	0–22	≥5	0.62 ± 0.16	0.048
Angers and Eriksen-Hamel (2008)	any	23	47	0–100	≥5	0.49	0.032
Luo et al. (2010)	any	29	69	0–60	any	−0.02	
Virto et al. (2012)	any	37	92	0–30	≥5	0.34	0.022
Haddaway et al. (2017)	boreo-temperate	29		0–30	≥10	0.46 ± 0.19	
		14		0–150		0.15 ± 0.34	
Meurer et al. (2018)	boreo-temperate		46	0–30	≥10	0.42 ± 0.18	0.023
			11	0–60		0.15 ± 0.22	< 0.01

residues were incorporated than left at the surface. Decomposition would be limited at the soil surface due to drier conditions. Dimassi et al. (2014) also show that the response of SOC to no tillage is dependent on climate, and in particular precipitation, with a greater response in drier conditions. Changes in micro-environmental conditions induced by ploughing seem to be the main mechanisms controlling the effects of tillage on SOC dynamics (Dimassi et al., 2014; Oorts et al., 2007). Overall, these results also cast doubts on the direct mechanical effect of tillage on SOC mineralization and raise concerns about the relations between physical protection and tillage, in agreement with other studies suggesting that physical protection of organic would only take place at very fine spatial scales (< 100 μm) (e.g., Juarez et al., 2013a). Part of SOC stock differences induced by conversion to no tillage can also be explained by C inputs changes induced by no tillage implementation (Virto et al., 2012).

Conservation agriculture encompasses a range of cropping systems that propose alternative management practices aiming at maintaining or improving the sustainability of agricultural production, which rely on three pillars: reduced tillage, permanent soil cover, with the use of cover crops, and diversified rotations. In its simplest form, conservation agriculture often refers to no-till systems which we covered in the previous paragraph. In its more complex forms it comprises no-tillage with diversified rotations and cover crops which are conducted between successive crops as well as in association with the cash crop. A recent meta-analysis showed that, in a tropical context, such conservation agriculture cropping systems had the potential to store additional carbon while with a large variability and with cases where no increase in SOC stocks was measured (Powlson et al., 2016). Recent field studies (Autret et al., 2016) and meta-analyses (Poeplau and Don, 2015) have clearly shown the potential of cover crops to increase SOC stocks relative to their absence (Autret et al., 2016; Poeplau and Don, 2015). Hence the potential of no-tillage to store SOC is limited while it is much larger when cover crops are associated with no-tillage, i.e. in conservation agriculture. In a study where C inputs and SOC stocks have either been measured or modelled, increases in OC inputs due to alternative management were sufficient to explain the observed SOC stocks changes (Autret et al., 2016). A similar observation was made in agroforestry systems (Cardinael et al., 2015a, [Cardinael et al., 2018] 2018). In addition, in a meta-analysis of the effects of no tillage on SOC stocks increased OC inputs were the only factor explaining additional SOC storage under not till (Virto et al., 2012). All together, these observations suggest that increasing inputs is probably the best option to increase SOC stocks compared than decreasing outputs by mineralisation through no tillage. This assumption however requires further studies.

In addition to providing additional C inputs to the soil, the use of cover crops also involves some diversification of the quality of the C inputs. The influence of C input quality on SOC storage is still a matter of debate (Schmidt et al., 2011). Field studies suggest that the use of legumes either as cover crops (e.g., Boddey et al., 2010) or as intercrop (e.g. Martins et al., 2012) is particularly efficient in increasing SOC in no tillage systems. This would be consistent with the idea that higher-quality residues are more efficiently utilized by the soil microflora, resulting in greater production of microbial by-products and SOC formation (Cotrufo et al., 2013).

6.1.2. Irrigation

Several practices affect different components of the overall carbon balance. Fertilization (Ladha et al., 2011), liming (Paradelo et al., 2015) and irrigation (Trost et al., 2013; Zhou et al., 2016) increase primary production and thus increase inputs to soil, modify plant rooting (fertilization and irrigation), and accelerate C and N mineralization. Their net effect on SOC stocks is hence highly variable, and likely depends on local conditions. For example, from the temperature and moisture dependence of SOM decay rates in current models such as RothC, summer irrigation versus summer drought may increase yearly mineralization

by as much as 50% in cool to warm regions. The meta-analysis performed by Trost et al. (2013) showed that the effects of irrigation on SOC stocks depended on the climate and initial soil organic carbon content. Irrigation had strong positive effects of SOC stocks in desert soils, positive ones in semi-arid areas, and no consistent trend was observed in humid areas. While irrigation may have similar effects on SOC decomposition in all situations, its effects on primary production are likely to be much higher in arid and semi-arid areas compared to humid regions with dry summers. Deep root irrigation is a practice which effect on SOC stocks warrants evaluation as it may increase soil moisture in the vicinity of roots in the subsoil but not in the organic matter rich topsoil, hence allowing to increase plant growth and OC inputs to soil, but have limited effects on SOC mineralization. In the context of forecasted climate changes, the effects of irrigation on SOC stocks and dynamics particularly clearly require more assessments and research.

6.1.3. Increasing below-ground inputs

Below ground OC inputs (roots and associated inputs) contribute more to soil carbon as compared to above ground inputs (Balesdent and Balabane, 1992; Kätterer et al., 2011; Menichetti et al., 2015; Rasse et al., 2005). This is ascribed to its different chemical nature and because the C contained in fine roots, root hairs, associated mycorrhizae and root exudates would enter the soil directly in sites (small pores, microaggregates), where it would be stabilized by adsorption or physical protection (Rasse et al., 2005). This would suggest that management practices that increase below ground C inputs would be particularly efficient in enhancing SOC stocks. Increasing C belowground inputs to soil can be achieved through cropping deep rooting crop varieties (Kell, 2012), deep-rooting perennials (Carter and Gregorich, 2010), and agroforestry (Cardinael et al., 2018; Peichl et al., 2006). Plant breeding should therefore assess the C storage potential of crop genotypes that have a high levels of root biomass or rhizodeposition, and assess the cost and benefits of photosynthate allocation to roots vs harvested organs (Kell, 2012). As previously mentioned (see Section 4), the trade-offs between increased below ground inputs and priming effect need to be assessed.

6.1.4. Organic amendments

While a considerable amount of literature has been devoted to studying the effects of organic fertilizers and amendments on soil organic carbon contents and stocks, synthesis and assessments are still limited by a general poor characterization of the organic inputs, especially in the case of compost and manure, generally limited to their C content, C/N ratio and pH (e.g. Maillard and Angers, 2014). Methods have been developed to characterize the decomposability of these organic materials, based on a biochemical characterization of the organic amendments and short term incubations (e.g. Lashermes et al., 2009) that can be used to parametrise SOC dynamics models (Peltre et al., 2012), but these methods are not widespread yet. A re-estimate of the contribution of organic fertilizers and amendments to long-term soil carbon, would help optimizing the use and the processing of organic wastes.

The influence of residue quality on long-term SOC is still a matter of debate. Many convergent studies have now revealed that the most labile and easy-degradable compounds contribute more to SOM on the long-term than so-called "recalcitrant" materials (e.g., lignin-rich), especially in clayey soils (Cotrufo et al., 2013). Three explanations have been proposed: long-lasting SOM are essentially derived from microbial material (Kallenbach et al., 2015; Miltner et al., 2012); easily degradable substrates are processed with a high microbial carbon use efficiency (Wieder et al., 2014); soluble compounds migrate in soil between mineral surfaces, where they can be protected. Since the quality of organic amendments is often estimated from short-term incubations (Lashermes et al., 2009), the extrapolation to long-term could be counter-intuitive. Such products should be described at least by two

parameters in the frame of C models.

Organic residues and wastes can be applied to soil, either as fresh organic matter, or after composting, methanisation or even pyrolysis. An assessment of these pathways of organic residues processing would require to compare their effects on soil organic carbon and nitrogen on the basis of the same initial amount of "fresh" organic matter, which is seldom performed. For example, Cardinael et al. (2015b), using a long term bare fallow experiment, showed that the effect of fresh vs composted straw on SOC stocks after was the same after 52 years, showing here that there was no benefit of composting in terms of CO_2 removal from the atmosphere. Similarly, Thomsen et al. (2013) have shown that the retention of C over decades to centuries appears to be similar whether the initial turnover of plant biomasses occurs in the soil, in the digestive tract of ruminants, in an anaerobic reactor, or in a combination of the latter two. Sector scale budgets of C, but also of the associated N and P are needed.

6.1.5. Managing soil nitrogen

The role of nitrogen input on SOC storage and sequestration is still debated. Nitrogen availability has two opposite effects on SOC stocks. On the one hand, N can increase primary production and thus increase the amount of above and below ground litter added to soil, which can result in increased SOC (e.g. Campbell et al., 2000). In this case, the availability of nitrogen can be a limiting factor to additional SOC storage, as discussed by van Groenigen et al. (2017). On the other hand, increased N availability may also accelerate the rate of biodegradation of both litter and indigenous soil organic matter (Melillo et al., 1982; Recous et al., 1995) and thereby lead to enhanced loss of SOC. The balance between these processes seems to depend on the ecosystem considered. In a meta-analysis, nitrogen fertilization was found to reduce the rate at which SOC is declining in agricultural soils worldwide (Ladha et al., 2011), i.e. it promoted SOC storage. Lu et al. (2011) observed a 3.48% relative increase of SOC stocks with N fertilization in agricultural soils in a meta-analysis with 340 paired observations. However, grasslands receiving high nitrogen fertilization may have lower OC content than less fertilized ones (Soussana et al., 2004). Lu et al. (2011) concluded from their meta-analysis that N stimulation of SOC storage primarily occurred in plant pools and less in soil pools. The small magnitude of the effect of N addition on SOC stocks was explained by the higher stimulation of above ground biomass production than that of belowground biomass while, as described previously, above ground biomass contributes less to soil carbon compared to below ground biomass. Furthermore, the dataset gathered by Lu et al. (2011) showed that N addition stimulated soil organic matter mineralization. They suggested that earth system models need to treat soil OC inputs from aboveground and belowground sources differentially for soil C storage in response to N deposition and fertilization.

Regarding stabilization of organic matter, obviously, old SOM is N-rich, and soil proteinaceous material belong to pools of SOM with decadal or centennial turnover times (Bol et al., 2009). The role of proteinaceous compounds on SOM sorption and stabilization on the long term has been hypothesised (Kleber et al., 2007), but the quantitative impact of N input on the long term C stabilization still requires quantitative assessments. Kirkby et al. (2014) demonstrated that the "stable" organic C pool, defined in their study as the SOC fine fraction (< 0.4 mm) was increased with N additions, due to two processes: more fine-sized SOC was formed from the added fresh organic matter, i.e. there was more litter decomposition, but also less old organic matter was lost, i.e. less priming effect occurred (less microbial nutrient mining) (Kirkby et al., 2014). Indeed, microorganisms were shown in other studies to meet their nutrient requirements by mining N from stable SOM by inducing a priming effect (Chen et al., 2014; Derrien et al., 2014).

Assessing the role of nitrogen on SOC storage, and the same comment applies to phosphorus, requires research differentiating its effect on primary production and its allocation between above and below

ground biomass, litter decomposition, priming effect and long term SOC stabilization.

6.2. Category 2. More speculative, but exciting research findings, to be tested

6.2.1. Plant secondary metabolites

Northup et al. (1998) illustrated the production of polyphenol-rich litters as an example of fitness, enhancing ecosystem productivity through several mechanisms, including the inhibition of soil bacterial mineralization of C and N, maximizing N recovery by mycorrhizae and soil organic matter. The effect of plant secondary metabolites on biotic regulation of SOM degradation remains to be investigated.

6.2.2. Mineral amendments

Fine cristallized-minerals are undoubtedly considered as the first factor of C stabilization in soils (Mathieu et al., 2015). Extremely high SOC stabilization is found in andosols (Torn et al., 1997) and is explained by the presence of very-fine aluminosilicates called allophanes, which are derived from volcanic glasses. Adding fine minerals to soils is not a common management practice. Although some soils have been ameliorated for a long time by addition of clay-rich minerals (e.g., marls) the effects of this management practice on CO_2 balance remains questionable due to the large amounts needed and the related energy consumption to transport them. Basile-Doelsch et al. (2015) developed a new paradigm of co-stabilization of OM with the poorly-crystallized minerals that result from the alteration of primary minerals. In the light of this work, alumino-silicates such as those present in basalt rocks, which are sometimes used as amendments of base-poor soils (Gillman et al., 2002), or clay refuses from bauxite processing (Churchman et al., 2014) could be tested as OM stabilizers.

6.2.3. Manipulating microbial physiology

Several organic cropping systems, characterized by a diversified rotation including legume cover crops, exhibited similar or higher SOC stocks than their conventional counterparts, while fresh OC inputs to soil were not higher and tillage was more frequent (Autret et al., 2016; Gregorich et al., 2001; Syswerda et al., 2011) (a process not represented in Fig. 4). Kallenbach et al. (2015) recently showed that in an organic cropping system, soil microorganisms had a higher carbon use efficiency and higher growth rates than under the reference conventional system. As suggested by the authors, this should result in more microbial necromass being formed per unit of C input. Microbial necromass represents a significant fraction of soil organic matter and a major constituent of SOM stabilized in the long term (Cotrufo et al., 2013; Grandy and Neff, 2008), which would explain the increased or preserved SOC stocks cited above. The carbon use efficiency depends on the type of microorganisms (i.e. fungi and actinomycetes vs bacteria, oligotrophs vs copiotrophs), and on the quality of organic inputs (compound providing more available energy and with lower C:N ratio are assimilated with a higher carbon use efficiency). The effects of cropping practices such as cover crops, reduced fertilization, or organic fertilization on the carbon use efficiency of microorganisms remain to be studied as well as the consequences of such changes in terms of SOC stocks.

6.2.4. Managing soil biodiversity

A range of studies have shown that increasing the diversity of soil organisms and plants can result in greater SOC stocks and more stabilized organic carbon. Plant diversity increases SOC stocks and the magnitude of SOC storage is related to the abundance of fine roots (Lange et al., 2015; Steinbeiss et al., 2008). Regarding the effects of earthworms on SOC stocks, very contrasted results have been observed (Blouin et al., 2013) and a meta-analysis showed that, in the short term, they increase SOC mineralization (Lubbers et al., 2013). In fact, earthworms would have two opposite effects on SOC stocks, at different

time scales. They simultaneously increase the mineralization of both fresh and old soil organic matter (by fragmentation, by their own respiration and their stimulation of soil microorganisms), and incorporate fresh residues into aggregates, i.e., their casts (e.g. Bossuyt et al., 2005) and bury carbon at depth (e.g., Schon et al., 2015) which would increase their stabilization. The simultaneous occurrence of these processes that impact SOC at different time scales has been demonstrated in incubation experiments (Lubbers et al., 2017; Zhang et al., 2013).

A similar debate has taken place concerning mycorrhizae (Verbruggen et al., 2013), which were found to increase the mineralization of litter (Cheng et al., 2012) in the short term, while increasing soil aggregation and thus presumably the stabilization of organic matter in the long term (Verbruggen et al., 2016), with opposite effects on SOC stocks depending on the time scale of observation and the relative importance of the two processes (Verbruggen et al., 2013). These results, along with the demonstration that soil organic matter with decadal residence time is mostly microbial (microbial necromass and metabolites, (Liang and Balser, 2008; Miltner et al., 2012), suggest that while increasing the abundance and diversity of decomposers will increase decomposition rates of organic matter, it may result in increased SOC stocks, and/or in a higher proportion of the SOC having long residence times. A recent study by Sanderman et al. (2017) shows that increased productivity due to different rotations in a long term experiment was associated with increased SOC stocks after 40 years, but decreased turnover time of SOC, which supports the idea that increased microbial activity promotes carbon storage.

These findings call for further research on the effects of agricultural practices that have positive effects on the abundance and diversity of soil organisms in order to analyse the consequences on SOC stabilization. SOC dynamics in intensive cropping systems could be revisited: such systems may have higher C inputs to the soil than natural ecosystems, thanks to their very high productivity and the return of crop remains to the soil, but lower soil C content. The much higher decay rates of SOM in cropped systems (e.g. Arrouays et al., 1995) are not fully explained by tillage nor N inputs. These intensive cropping systems are also characterized by decreased soil biodiversity, especially mycorrhizal and invertebrates, due to the effects of the concurrent plant diversity reduction (monocultures or simple rotations) and pesticides use. However, when comparing different cropping systems or land uses it is difficult to disentangle the effects of fresh OC inputs to soil from that of modified trophic network and decomposers communities or modified environmental conditions.

7. Perspective

The vision emerging from recent studies on soil organic matter dynamics and on the processes explaining its persistence show that there is still a need to appraise or reappraise and understand the effects of cropping systems and practices on SOC storage and sequestration, and that there is potential for innovation. Long term experiments, which are indispensable, cannot however cover the huge diversity of management options available to farmers. A participatory approach is then needed, which faces the difficulty to measure reliably SOC stock changes at the field scale over only a few years, a time scale relevant to the farmer (Perez et al., 2007). To this regard, since the residence time of SOM under the tropics is *ca.* four times shorter than under temperate climates, and the effects of management thus measurable much faster, medium-term experiments in tropical countries could provide results of general interest even concerning colder climates, and should be clearly encouraged (Milne et al., 2016). Besides, as mentioned in the introduction, the selection of management practices to increase SOC stocks cannot be made solely on criteria based on the potential SOC storage or sequestration. An increase in NPP can be obtained through irrigation or higher addition of mineral fertilizers, which may compromise the sustainability of resources (water use) and have adverse environmental impacts (altered water quality due to nitrate leaching, a

negative GHG balance, the increase in soil OC being offset by increased N_2O and CH_4 emissions (*e.g.* Schulze et al., 2010). SOC sequestration in agricultural soils must thus be envisioned in a much broader perspective than considering only the global carbon cycle. Furthermore, the feasibility of SOC storing management practices may be limited, such as for instance, increasing crop residues return to the soil can be socially and economically very difficult (e.g., Naudin et al., 2011). While a process-oriented approach shows the need to reappraise or test a wide range of practices for their ability to sequester carbon in soils and for the permanence and vulnerability of the storage, a much broader approach of these practices, including environmental, agricultural, social and economic evaluations, is also needed to ensure a sustainable management of agricultural soils.

The 4 per 1000 initiative promotes carbon storage in soils. Its Scientific and Technical Committee made it clear that the aim is to increase SOC stocks compared to business as usual, with no numerical target value (www.4p1000.org). The initiative remains very ambitious, with its threefold objective of contributing to food security, to climate change adaptation and to mitigation of climate change and with its commitment to the UN Sustainable Development Goals. It has the merit of challenging the scientific community, and in particular the soil organic matter scientific community, asking to clarify concepts and vocabulary and make them known broadly, asking for quantitative estimates of the current state of soil organic resources and of SOC storage potential in a wide variety of pedoclimatic contexts, requiring to position SOC storage questions in a much broader perspective, and revealing gaps in knowledge that need to be explored. The 4 per 1000 initiative is thereby very stimulating for research.

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