



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

Claire Chenu, Denis A. Angers, Pierre Barré, Delphine Derrien, Dominique Arrouays, Jérôme Balesdent

► To cite this version:

Claire Chenu, Denis A. Angers, Pierre Barré, Delphine Derrien, Dominique Arrouays, et al.. Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. Soil and Tillage Research, 2019, 188, 10.1016/j.still.2018.04.011 . hal-01789417

HAL Id: hal-01789417

<https://hal.science/hal-01789417>

Submitted on 21 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Increasing organic stocks in agricultural soils: knowledge gaps and potential innovations.

Authors:

Claire Chenu¹, Denis A. Angers², Pierre Barré³, Delphine Derrien⁴, Dominique Arrouays⁵,
Jérôme Balesdent⁶

¹ Ecosys, INRA-AgroParisTech, Université Paris-Saclay AgroParisTech, 78850 Thiverval-
Grignon, France

² Quebec Research and Development Centre. Agriculture and Agri-Food Canada, 2560 Boul.
Hochelaga, Québec, Québec, G1V 2J3, Canada

³ Laboratoire de Géologie de l'ENS, PSL Research University, UMR8538 du CNRS, 24 rue
Lhomond, 75231 Paris cedex 05, France

⁴ Biogéochimie des Ecosystèmes Forestiers, INRA, 54280 Champenoux, France

⁵ Infosols, INRA, Unité InfoSol, 45075, Orléans cedex 02, France

⁶ CEREGE, Aix-Marseille Université, CNRS, IRD, Coll France, INRA, F-13545 Aix-en-
Provence, France

* Corresponding author: Claire Chenu, email: claire.chenu@inra.fr, phone: +33 1 30 81 53 77

Key words

Carbon storage, carbon sequestration, carbon storage potential, agricultural practices, 4 per
1000 initiative

24 **Abstract**

25 Recent initiatives, such as the United Nations declaring 2015 as the International Year of
26 Soils and the French « 4 per 1000 » initiative call attention on soils and on the importance of
27 maintaining and increasing soil organic matter stocks for soil fertility and food security, and
28 for climate change adaptation and mitigation. We stress that soil organic carbon storage (i.e.
29 an increase of soil organic carbon stocks) should be clearly differentiated from soil organic
30 carbon sequestration, as the latter assumes a net removal of atmospheric CO₂. Implementing
31 management options that allow increasing soil organic carbon stocks at the local scale raises
32 several questions, which are discussed in this article: how can we increase SOC stocks, at
33 which rate and for how long; where do we prioritize SOC storage; how do we estimate the
34 potential gain in C and which agricultural practices should we implement? We show that
35 knowledge and tools are available to answer many of these questions, while further research
36 remains necessary for others. A range of agricultural practices would require a re-assessment
37 of their potential to store C and a better understanding of the underlying processes, such as no
38 tillage and conservation agriculture, irrigation, practices increasing below ground inputs,
39 organic amendments, and N fertilization. The vision emerging from the literature, showing
40 the prominent role of soil microorganisms in the stabilization of soil organic matter, draw the
41 attention to more exploratory potential levers, through changes in microbial physiology or soil
42 biodiversity induced by agricultural practices, that require in-depth research.

43 **1- Introduction**

44 The 4 per 1000 initiative aims at increasing the organic matter content of soils, with a special
45 focus on agricultural land, in order to contribute to food security, adaptation to climate
46 change, and mitigation of climate change (<http://4p1000.org>). The first two aims of the

47 initiative are based on common knowledge regarding the central role of soil organic matter
48 (SOM) in soil fertility and soil water retention (Lal, 2008). Thus SOM indirectly contributes
49 to agro-ecosystem productivity, and hence to food security. Soil organic matter also provides
50 agro-ecosystems with the ability to adapt to a changing climate with less frequent and regular
51 precipitation and more extreme rainfall, with related erosion problems (Chenu et al., 2000;
52 Pan et al., 2009). The third aim of the initiative, regarding mitigation, is based on quantitative
53 data on soil organic carbon (SOC) pools (Jobbagy and Jackson, 2000) and fluxes (Le Quéré et
54 al., 2015) showing that small changes in world SOC stocks could aggravate or mitigate the
55 global greenhouse gas (GHG) effect, as early suggested by Balesdent and Arrouays (1999)
56 and developed for example in recent articles (Chambers et al., 2016; Lal, 2016; Minasny et
57 al., 2018; Minasny et al., 2017; Paustian et al., 2016; Soussana et al., 2017).

58 Accounting for soil carbon as part of the GHG assessment may be subject of
59 misunderstanding (Minasny et al., 2018). Two terms are often used interchangeably: carbon
60 sequestration and carbon storage, which can sometimes lead to confusion. Here, according to
61 Olson et al. (2014), we define **Carbon sequestration** as “the process of transferring CO₂ from
62 the atmosphere into the soil of a land unit, through plants, plant residues and other organic
63 solids which are stored or retained in the unit as part of the soil organic matter (humus).
64 Retention time of sequestered carbon in the soil (terrestrial pool) can range from short-term
65 (not immediately released back to atmosphere) to long-term (millennia) storage.”.
66 Sequestration can therefore be quantified for a given duration. Twenty years is often chosen
67 (IPCC, 2006). **Carbon storage** is broader as it is defined as the increase in SOC stocks over
68 time in the soils of a given land unit, not necessarily associated with a net removal of CO₂
69 from the atmosphere. For example adding the available manure resources on a given
70 agricultural field rather than spreading it homogenously over the landscape may locally
71 increase SOC stocks (where manure has been added), but not increase the associated CO₂

72 removal from the atmosphere at the landscape scale. While storing organic carbon for long
73 times is preferable in terms of GHG mitigation, labile fractions of SOC (e.g. with residence
74 times of months to years) are essential in terms of soil fertility (their mineralization provides
75 nutrients to plants), of soil physical condition (aggregate stability largely depends on labile C,
76 (e.g., Angers and Mehuys, 1989; Cosentino et al., 2006), and of soil biodiversity (labile
77 organic matter being the trophic resource of organisms). Hence it is desirable to increase
78 stocks of both labile and stable forms of organic matter. In any case, the time horizon at
79 which SOC storage or SOC sequestration are being considered should be specified. Here, we
80 consider both organic carbon storage and sequestration and will use the term soil carbon
81 storage when no assumption is made on a net atmospheric CO₂ removal.

82

83 Increasing organic matter in soils via management practices not only encompasses soil carbon
84 related questions, but also agronomic and environmental dimensions, as well as sociological,
85 economical and ethical ones. These will not be considered here, while we do not disregard
86 their importance, e.g., Aubert et al. (2017). Moreover, mitigating GHG emissions by
87 increasing SOC stocks should not be regarded as a way to compensate for CO₂ emissions due
88 to the combustion of fossil fuel nor for N₂O or CH₄ emissions related to agricultural activities
89 and hence allow to continue business as usual, but rather as an additional lever in the portfolio
90 of options that countries can consider to reduce their agricultural GHG emissions (Wollenberg
91 et al., 2016).

92 Implementing management options that allow increasing soil organic carbon stocks at the
93 local scale raises several questions: how can we increase SOC stocks, at which rate and for
94 how long? Where do we prioritize SOC storage? How do we estimate the potential gain in
95 carbon and which agricultural practices should we implement? In this overview, we will

96 consider the knowledge available to answer these questions and several related knowledge
97 gaps, and propose potential innovations.

98

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

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

$$102 \quad dC/dt = I(t) - k(t).C \quad (1)$$

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

$$106 \quad C^* = I/k \quad (2)$$

107 Let's assume that either input or loss rate is altered due to a change in land use or land
108 management. The SOC stock will evolve out of steady state for a certain period, to eventually
109 reach the new equilibrium value. This is illustrated in Figure 1. When considering a soil,
110 except well-documented plots for which records of SOC stocks over time are available, it is
111 not easy to determine *a priori* if the OC stock of this soil is at equilibrium with the OC inputs,
112 or somewhere between two equilibria. It explains why, even if annual OC inputs are constant
113 in a given period, SOC stocks can increase or decrease during that period. This phenomenon
114 may explain for example the changes of SOC stocks observed in French forest soils. SOC
115 stocks in mineral soils (0-40 cm) were monitored between 1993 and 2012 in 102 plots across
116 France and increased on average by $0.035 \text{ kgC m}^{-2} \text{ y}^{-1}$ (Jonard et al., 2017): SOC stocks were
117 probably not yet at equilibrium at the start of the monitoring. Furthermore the C accumulation
118 rate was found to decline with stand age (Jonard et al., 2017), what could be interpreted as
119 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.

Figure 1: 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 presented.

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 than 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) (Figure 1). Similarly, the carbon **sequestration** potential of a given soil would be the maximum gain in SOC allowing a net removal of CO₂ 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 to 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 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 ($<20\text{ }\mu\text{m}$), 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 $<20\text{ }\mu\text{m}$ 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, Figure 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 (Figure 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.

Figure 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 for the bulk soil organic matter. (sd= saturation deficit. Figure adapted from Stewart et al., 2007).

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 eqn. 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) (Figure 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., 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.

Figure 3. A meta-analysis of natural ^{13}C labelling technique 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).

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) (Figure 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 Figure 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.

315

316 To estimate SOC changes, the IPCC developed a tiered approach depending on the spatial
317 scale of the project or study and the data available. Tier 1 corresponds to very large scale
318 approaches, with default SOC stocks values for eco-regions and average SOC stock changes
319 values (soil carbon change factors) for changes in land-use, management or organic input
320 applied to a given surface area over a time period of 20 years for the 0-30 cm depth (IPCC,
321 2006). The Tier 2 approach is similar but uses data specific to a state or region. For example,
322 a Tier 2 approach has been used to estimate the potential of agricultural practices to mitigate
323 GHG emissions and to store C in soils of Canada (VandenBygaart et al., 2008) and of
324 mainland France (Pellerin et al., 2013). Tier 2 SOC stock change factors are still missing for
325 many regions, soil type, and management practices, calling for meta-analyses (Söderström et
326 al., 2014). However, in some agricultural regions, agronomists have for long established
327 reference SOC stocks values (Hénin and Dupuis, 1945) that allow estimating the reachable
328 SOC content of a given soil according to the most common practices (Bayer et al., 2006;
329 Saffih-Hdadi and Mary, 2008). The Tier 3 approach, which is either based on a
330 comprehensive acquisition of field data or on the use of models, has seldom been applied at
331 large scales, although is the basis of the United States estimate of its soil related agricultural
332 GHG emissions (Milne et al., 2007; Ogle et al., 2010). Indeed, SOC dynamics models are *a*
333 *priori* good candidates to estimate the potential gain of organic carbon following land-use or
334 agricultural practices changes (to determine the new steady-state value as well as the temporal
335 trajectory to reach it). However, they require to be fully validated and properly represent land
336 use management effects relevant to the study area.

337 Another possible methodology is based on the use of available SOC stocks data at the
338 territory to the regional scale, i.e. what may be called a data-driven approach. Stolbovoy and
339 Montanarella (2008) calculated the carbon storage potential for cultivated soils in EU by

340 subtracting the average present SOC stock, for each soil typological unit, from the maximum
341 SOC content observed for that soil typological unit, both numbers being obtained from the
342 1:1,000,000 European soil spatial data set (JRC, 2003). Lilly and Baggaley (2013) applied
343 this method to Scotland, i.e. at a finer resolution. The same approach could be developed at
344 the scale of small regions, provided a soil map is available as well as sufficient data on SOC
345 stocks.

346 Estimates of the storage potential of SOC with very long residence time is more difficult to
347 provide as there exists to date no method to estimate the size of the pluri-decadal/ pluri-
348 centennial persistent SOC. As a result, the only way to quantitatively estimate the potential of
349 soils to store additional SOC with residence times of decades to centuries with changes in
350 management is to use models to estimate the change in the size of pools with high residence
351 times (e.g. the Passive pool in Century model with a turnover time of 400-2000 y, (Parton et
352 al., 1987). Designing a method that allows determining the concentration in pluri-decadally
353 persistent SOC would be very helpful to progress in the estimate of SOC storage potential,
354 but the various attempts towards this goal using hydrolysis or oxidation methods have been
355 questioned (Chenu et al., 2015; Greenfield et al., 2013; Lutfalla et al., 2014). Indeed, it would
356 allow providing direct measures to assess the storage potential of various management
357 techniques. In addition, several authors have proposed estimates of SOC storage potentials
358 based on the carbon saturation deficit approach (Angers et al., 2011; Wiesmeier et al., 2014,
359 McNally et al., 2017). However, these estimates have to date neither been compared to
360 modelling ones nor to actual data. In practice, the methods available to estimate the SOC
361 storage potential of a soil are the tiered ones proposed in the IPCC methodology, and future
362 research should aim at comparing them with the carbon saturation approach.

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 (Figure 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.

Figure 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 e.g. 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 (e.g. cover crops, no tillage, hedges).

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

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 CO₂. 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; 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 ¹³C 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 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 ($< 100 \mu\text{m}$) (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). 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).

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.

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, microoaggregates), 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.

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 CO₂ 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.

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.

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

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.

Mineral amendments

Fine crystallized-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 CO₂ 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 (Gilman et al., 2002), or clay refuses from bauxite processing (Churchman et al., 2014) could be tested as OM stabilizers.

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 Figure 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.

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 N₂O and CH₄ emissions (*e.g.* Schultz et al., 2009). 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.

References

- Alcantara, V., Don, A., Vesterdal, L., Well, R., Nieder, R., 2017. Stability of buried carbon in deep-ploughed forest and cropland soils - implications for carbon stocks. *Scientific Reports* 7, 1-12.
- Alcantara, V., Don, A., Well, R., Nieder, R., 2016. Deep ploughing increases agricultural soil organic matter stocks. *Global Change Biology* 22, 2939-2956.
- Angers, D.A., Arrouays, D., Saby, N., Walter, C., 2011. Estimating and mapping the carbon saturation deficit of French agricultural topsoils. *Soil Use and Management* 448-452, 448-452.
- Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. *Soil Science Society of America Journal* 72, 1370-1374.
- Angers, D.A., Mehuys, G.R., 1989. Effects of cropping on carbohydrate content and water stable aggregation of a clay soil. *Canadian Journal of Soil Science* 69, 373-380.
- Arrouays, D., Balesdent, J., Mariotti, A., Girardin, C., 1995. Modelling organic carbon turnover in cleared temperate forest soils converted to maize cropping by using ¹³C natural abundance measurements. *Plant and Soil* 173, 191-196.
- Arrouays, D., Pelissier, P., 1994. Changes in carbon storage in temperate humic loamy soils after forest clearing and continuous corn cropping in France. *Plant and Soil* 160, 215-223.

717 Aubert, P.M., Treyer, S., Sablé, A.L., Apollin, F., Matthieu, B., Levard, L., Burger, P.,
 718 Berton, S., 2017. Implementing the "4 per 1000" initiative: contribution for a reference /
 719 normative framework, In: IDRI Policy Brief (Ed.), Paris, p. 4p.
 720 Autret, B.n.d., Mary, B., Chenu, C., Balabane, M., Girardin, C., Bertrand, M., Grandeau, G.,
 721 Beaudoin, N., 2016. Alternative arable cropping systems: A key to increase soil organic
 722 carbon storage? Results from a 16 year field experiment. *Agriculture, Ecosystems and*
 723 *Environment* 232, 150-164.
 724 Balesdent, J., Arrouays, D., 1999. An estimate of the net annual carbon storage in French
 725 soils induced by land use change from 1900 to 1999. [French]. *Comptes Rendus de*
 726 *L'Academie D'Agriculture de France* 85, 265-277.
 727 Balesdent, J., Balabane, M., 1992. Maize-root derived C to soil organic carbon estimated by
 728 natural ¹³C abundances. *Soil Biology and Biochemistry* 24, 97-101.
 729 Balesdent, J., Basile-Doelsch, I., Chadoeuf, J.I., Cornu, S., Fekiacova, Z., Fontaine, S.b.,
 730 Guenet, B., Hatté, C., 2017. Renouvellement du carbone profond des sols cultivés : une
 731 estimation par compilation de données isotopiques. *Biotechnol. Agron. Soc. Environ.* , 1-12.
 732 Basile-Doelsch, I., Balesdent, J.r.m., Rose, J.r.m., 2015. Are interactions between organic
 733 compounds and nanoscale weathering minerals the key drivers of carbon storage in soils?
 734 *Environmental Science and Technology* 49, 3997-3998.
 735 Bayer, C., Lovato, T., Dieckow, J., Zanatta, J.A., Mielniczuk, J., 2006. A method for
 736 estimating coefficients of soil organic matter dynamics based on long-term experiments. *Soil*
 737 *and Tillage Research* 91, 217-226.
 738 Beare, M.H., Mcneill, S.J., Curtin, D., Parfitt, R.L., Jones, H.S., Dodd, M.B., Sharp, J., 2014.
 739 Estimating the organic carbon stabilisation capacity and saturation deficit of soils : a New
 740 Zealand case study. *Biogeochemistry* 120, 71-87.
 741 Berhe, A.A., Harden, J.W., Torn, M.S., Kleber, M., Burton, S.D., Harte, J., 2012. Persistence
 742 of soil organic matter in eroding versus depositional landform positions. *Journal of*
 743 *Geophysical Research: Biogeosciences* 117, n/a-n/a.
 744 Berhe, A.A., Harte, J., Harden, J.W., Torn, M.S., 2007. The significance of erosion-induced
 745 terrestrial carbon sink. *BioScience* 57, 337-346.
 746 Blanco-Moure, N., Gracia, R., Bielsa, A.C., López, M.V., 2013. Long-term no-tillage effects
 747 on particulate and mineral-associated soil organic matter under rainfed Mediterranean
 748 conditions. *Soil Use and Management* 29, 250-259.
 749 Blouin, M., Hodson, M.E., Delgado, E.A., Baker, G., Brussaard, L., Butt, K.R., Dai, J.,
 750 Dendooven, L., Peres, G., Tondoh, J.E., Cluzeau, D., Brun, J.J., 2013. A review of earthworm
 751 impact on soil function and ecosystem services. *European Journal of Soil Science* 64, 161-
 752 182.
 753 Boddey, R.M., Jantalia, C.P., Conceição, P.C., Zanatta, J.A., Bayer, C., Mielniczuk, J.,
 754 Dieckow, J., Dos Santos, H.P., Denardin, J.E., Aita, C., Giacomini, S.J., Alves, B.J.R.,
 755 Urquiaga, S., 2010. Carbon accumulation at depth in Ferralsols under zero-till subtropical
 756 agriculture. *Global Change Biology* 16, 784-795.
 757 Bol, R., Poirier, N., Balesdent, J., Gleixner, G., 2009. Molecular turnover time of soil organic
 758 matter in particle - size fractions of an arable soil. *Rapid Communications in Mass*
 759 *Spectrometry* 23, 2551-2558.
 760 Bossuyt, H., Six, J., Hendrix, P.F., 2005. Protection of soil carbon by microaggregates within
 761 earthworm casts. *Soil Biology and Biochemistry* 37, 251.
 762 Campbell, C.A., Zentner, R.P., Miang, B.C., Roloff, G., Gregorich, E.G., Blomert, B., 2000.
 763 Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan: Effect
 764 of crop rotations and fertilizers. *Canadian Journal of Soil Science* 80, 179-192.
 765 Campbell, E.E., Paustian, K., 2015. Current developments in soil organic matter modeling
 766 and the expansion of model applications: a review. *Environmental Research Letters* 10, 1-36.

Cardinael, R., Chevallier, T., Barthès, B., Saby, N., Parent, T.o., Dupraz, C., Bernoux, M., Chenu, C., 2015a. Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon - a case study in a Mediterranean context. *Geoderma* 259–260 288–299.

Cardinael, R., Eglin, T., Guenet, B., Neill, C., Houot, S., Chenu, C., 2015b. Is priming effect a significant process for long-term SOC dynamics? Analysis of a 52-years old experiment. *Biogeochemistry* 123, 203-219.

Cardinael, R., Guenet, B., Chevallier, T., Dupraz, C., Cozzi, T., Chenu, C., 2018. High organic inputs explain shallow and deep SOC storage in a long-term agroforestry system, combining experimental and modeling approaches. *Biogeosciences* 15, 297-317.

Carter, M.R., Gregorich, E.G., 2010. Carbon and nitrogen storage by deep-rooted tall fescue (*Lolium arundinaceum*) in the surface and subsurface soil of a fine sandy loam in eastern Canada. *Agriculture, Ecosystems & Environment* 136, 125-132.

Chambers, A., Lal, R., Paustian, K., 2016. Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per Thousand Initiative. *Journal of Soil and Water Conservation* 71, 68A-74A.

Chaopricha, N.T., Marin-Spiotta, E., 2014. Soil burial contributes to deep soil organic carbon storage. *Soil Biology & Biochemistry* 69, 251-264.

Chen, R., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Lin, X., Blagodatskaya, E., Kuzyakov, Y., 2014. Soil C and N availability determine the priming effect: Microbial N mining and stoichiometric decomposition theories. *Global Change Biology* 20, 2356-2367.

Cheng, L., Booker, F.L., Tu, C., Burkey, K.O., Zhou, L., Shew, H.D., Rufty, T.W., Hu, S., 2012. Arbuscular mycorrhizal fungi increase organic carbon decomposition under elevated CO₂. *Science* 337, 1084-1086.

Cheng, W., Parton, W.J., Gonzalez-Meler, M.A., Phillips, R., Asao, S., McNickle, G.G., Brzostek, E., Jastrow, J.D., 2014. Synthesis and modeling perspectives of rhizosphere priming. *New Phytologist* 201, 31-44.

Chenu, C., Le Bissonnais, Y., Arrouays, D., 2000. Organic matter influence on clay wettability and soil aggregate stability. *Soil Science Society of America Journal* 64, 1479-1486.

Chenu, C., Rumpel, C., Lehmann, J., 2015. Methods for Studying Soil Organic Matter: Nature, Dynamics, Spatial Accessibility, and Interactions with Minerals, In: Paul, E.A. (Ed.), *Soil Microbiology, Ecology and Biochemistry*. Elsevier, pp. 381-417.

Churchman, G.J., Noble, A., Bailey, G., Chittleborough, D., Harper, R., 2014. Clay addition and redistribution to enhance carbon sequestration in soils, In: Hartemink, A.E., McSweeney, K. (Eds.), *Soil Carbon. Progress in Soil Science* 327 Springer International Publishing Switzerland, pp. 327-335.

Coleman, K., Jenkinson, D.S., 2014. RothC - A model for the turnover of carbon in soil. Model description and users guide. Rothamsted Research. Harpenden Herts. AL5 2JQ.

Conant, R.T., Cerri, C., Osborne, B., Paustian, K., 2016. Grassland management impacts on soil carbon stocks: a new synthesis. *Ecological applications* 9, 73-76.

Cosentino, D., Le Bissonnais, Y., Chenu, C., 2006. Aggregate stability and microbial community dynamics under drying-wetting cycles in a silt loam soil. *Soil Biology & Biochemistry* 38, 2053-2062.

Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Deneff, K., Paul, E., 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Global Change Biology* 19, 988-995.

Derrien, D., Plain, C., Courty, P.E., Gelhaye, L., Moerdijk-Poortvliet, T.C.W., Thomas, F., Versini, A., Zeller, B., Koutika, L.S., Boschker, H.T.S., Epron, D., 2014. Does the addition of

labile substrate destabilise old soil organic matter? *Soil Biology and Biochemistry* 76, 149-160.

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., Cohan, J.-P., 2014. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. *Agriculture, Ecosystems & Environment* 188, 134-146.

Don, A., Steinberg, B., Schoening, I., Pritsch, K., Joschko, M., Gleixner, G., Schulze, E.D., 2008. Organic carbon sequestration in earthworm burrows. *Soil Biology & Biochemistry* 40, 1803-1812.

Dungait, J.A.J., Hopkins, D.W., Gregory, A.S., Whitmore, A.P., 2012. Soil organic matter turnover is governed by accessibility not recalcitrance. *Global Change Biology* 18, 1781-1796.

Fontaine, S., Barot, S., Barré, P., Bdioui, N., Rumpel, C., Mary, B., 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* 7167, 277-U210.

Grandy, A.S., Neff, J.C., 2008. Molecular C dynamics downstream: The biochemical decomposition sequence and its impact on soil organic matter structure and function. *Science of the Total Environment* 404, 297-307.

Greenfield, L.G., Gregorich, E.G., van Kessel, C., Baldock, J.A., Beare, M.H., Billings, S.A., Clinton, P.W., Condon, L.M., Hill, S., Hopkins, D.W., Janzen, H.H., 2013. Acid hydrolysis to define a biologically-resistant pool is compromised by carbon loss and transformation. *Soil Biology and Biochemistry* 64, 122-126.

Gregorich, E.G., Drury, C.F., Baldock, J.A., 2001. Changes in soil carbon under long-term maize in monoculture and legume-based rotation. *Can. J. Soil Sci.* 81, 21-31.

Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Isberg, P.-E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. *Environmental Evidence* 6, 2-48.

Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant and Soil* 191, 77-87.

Helgason, B.L., Gregorich, E.G., Janzen, H.H., Ellert, B.H., Lorenz, N., Dick, R.P., 2014. Long-term microbial retention of residue C is site-specific and depends on residue placement. *Soil Biology and Biochemistry* 68, 231-240.

Hénin, S., Dupuis, M., 1945. Essai de bilan de la matière organique du sol. *Annales Agronomiques* 15, 17-29.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories Prepared by the National Greenhouse Gas Inventories Programme, In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Japan.

Jenkinson, D.S., Rayner, J.H., 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science* 123, 298-305.

Jobbagy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* 10, 423-436.

Jonard, M., Nicolas, M., Coomes, D.A., Caignet, I., Saenger, A.s., Ponette, Q., 2017. Forest soils in France are sequestering substantial amounts of carbon. *Science of the Total Environment* 574, 616-628.

Juarez, S., Nunan, N., Duday, A.-C., Pouteau, V., Schmidt, S., Hapca, S., Falconer, R., Otten, W., Chenu, C., 2013a. Effects of different soil structures on the decomposition of native and added organic carbon. *European Journal of Soil Biology* 58, 81-90.

Juarez, S., Nunan, N., Duday, A.C., Pouteau, V., Schmidt, S., Hapca, S., Falconer, R., Otten, W., Chenu, C., 2013b. Effects of different soil structures on the decomposition of native and added organic carbon. *European Journal of Soil Biology* 58, 81-90.

Kallenbach, C.M., Grandy, A.S., Frey, S.D., Diefendorf, A.F., 2015. Microbial physiology and necromass regulate agricultural soil carbon accumulation. *Soil Biology and Biochemistry* 91, 279-290.

Kätterer, T., Bolinder, M.A., Andrén, O., Kirchmann, H., Menichetti, L., 2011. Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. *Agriculture, Ecosystems and Environment* 141, 184-192.

Kell, D.B., 2012. Large-scale sequestration of atmospheric carbon via plant roots in natural and agricultural ecosystems: why and how. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367, 1589-1597.

Kirkby, C.A., Richardson, A.E., Wade, L.J., Passioura, J.B., Batten, G.D., Blanchard, C., Kirkegaard, J.A., 2014. Nutrient availability limits carbon sequestration in arable soils. *Soil Biology and Biochemistry* 68, 402-409.

Kleber, M., Sollins, P., Sutton, R., 2007. A conceptual model of organo-mineral interactions in soils: Self-assembly of organic molecular fragments into zonal structures on mineral surfaces. *Biogeochemistry* 85, 9-24.

Kuzyakov, Y., 2002. Review: Factors affecting rhizosphere priming effects. *Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde* 165, 382-396.

Ladha, J.K., Reddy, C.K., Padre, A.T., van Kessel, C., 2011. Role of nitrogen fertilization in sustaining organic matter in cultivated soils. *Journal of Environmental Quality* 40, 1756-1766.

Lal, R., 2008. Carbon sequestration. *Philos Trans R Soc Lond B Biol Sci* 363, 815-830.

Lal, R., 2016. Beyond COP21: Potential and challenges of the "4 per Thousand" initiative. *Journal of Soil and Water Conservation* 71, 20A-25A.

Lange, M., Eisenhauer, N., Sierra, C.a., Bessler, H., Engels, C., Griffiths, R.I., Mellado-Vázquez, P.G., Malik, A.a., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B.C., Trumbore, S.E., Gleixner, G., 2015. Plant diversity increases soil microbial activity and soil carbon storage. *Nature communications* 6, 6707.

Lashermes, G., Nicolardot, B., Parnaudeau, V., Thuries, L., Chaussod, R., Guillotin, M.L., Lineres, M., Mary, B., Metzger, L., Morvan, T., Tricaud, A., Vilette, C., Houot, S., 2009. Indicator of potential residual carbon in soils after exogenous organic matter application. *European Journal of Soil Science* 60, 297-310.

Le Quéré, C., Moriarty, R., Andrew, R.M., Peters, G.P., Ciais, P., Friedlingstein, P., Jones, S.D., Sitch, S., Tans, P., Arneeth, A., Boden, T.A., Bopp, L., Bozec, Y., Canadell, J.G., Chevallier, F., Cosca, C.E., Harris, I., Hoppema, M., Houghton, R.A., House, J.I., Jain, A.K., Johannessen, T., Kato, E., Keeling, R.F., Kitidis, V., Klein Goldewijk, K., Koven, C., Landa, C.S., Landschützer, P., Lenton, A., Lima, I.D., Marland, G., Mathis, J.T., Metzl, N., Nojiri, Y., Olsen, A., Ono, T., Peters, W., Pfeil, B., Poulter, B., Raupach, M.R., Regnier, P., Rödenbeck, C., Saito, S., Salisbury, J.E., Schuster, U., Schwinger, J., Séférian, R., Segsneider, J., Steinhoff, T., Stocker, B.D., Sutton, A.J., Takahashi, T., Tilbrook, B., Van Der Werf, G.R., Viovy, N., Wang, Y.-P.P., Wanninkhof, R., Wiltshire, A., Zeng, N., Le Quéré, C., Moriarty, R., Andrew, R.M., Peters, G.P., Ciais, P., Friedlingstein, P., Jones, S.D., Sitch, S., Tans, P., Arneeth, A., Boden, T.A., Bopp, L., Bozec, Y., Canadell, J.G., Chini, L.P., Chevallier, F., Cosca, C.E., Harris, I., Hoppema, M., Houghton, R.A., House, J.I., Jain, A.K., Johannessen, T., Kato, E., Keeling, R.F., Kitidis, V., Klein Goldewijk, K., Koven, C., Landa, C.S., Landschützer, P., Lenton, A., Lima, I.D., Marland, G., Mathis, J.T., Metzl, N., Nojiri, Y., Olsen, A., Ono, T., Peng, S., Peters, W., Pfeil, B., Poulter, B., Raupach, M.R., Regnier, P., Rödenbeck, C., Saito, S., Salisbury, J.E., Schuster, U., Schwinger, J., Séférian, R., Segsneider, J., Steinhoff, T., Stocker, B.D., Sutton, A.J., Takahashi, T., Tilbrook, B., Van Der Werf, G.R., Viovy, N., Wang, Y.-P.P., Wanninkhof, R., Wiltshire, A., Zeng, N., 2015. Global carbon budget 2014. *Earth System Science Data* 7, 47-85.

Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. *Nature* 528, 60-68.

Liang, C., Balser, T.C., 2008. Preferential sequestration of microbial carbon in subsoils of a glacial-landscape toposequence, Dane County, WI, USA. *Geoderma* 148, 113-119.

Lilly, A., Baggaley, N.J., 2013. The potential for Scottish cultivated topsoils to lose or gain soil organic carbon. *Soil Use and Management* 29, 39-47.

Lu, M., Zhou, X., Luo, Y., Yang, Y., Fang, C., Chen, J., Li, B., 2011. Minor stimulation of soil carbon storage by nitrogen addition: a meta-analysis. *Agriculture, Ecosystems & Environment* 140, 234-244.

Lubbers, I.M., Puleman, M.M., Van Groenigen, J.W., 2017. Can earthworms simultaneously enhance decomposition and stabilization of plant residue carbon? *Soil Biology and Biochemistry* 105, 12-24.

Lubbers, I.M., van Groenigen, K.J., Fonte, S.J., Six, J., Brussaard, L., van Groenigen, J.W., 2013. Greenhouse-gas emissions from soils increased by earthworms. *Nature Climate Change* 3, 187-194.

Luo, Y., Ahlström, A., Allison, S.D., Batjes, N.H., Brovkin, V., Carvalhais, N., Chappell, A., Ciais, P., Davidson, E.A., Finzi, A., Georgiou, K., Guenet, B., Hararuk, O., Harden, J.W., He, Y., Hopkins, F., Jiang, L., Koven, C., Jackson, R.B., Jones, C.D., Lara, M.J., Liang, J., McGuire, A.D., Parton, W., Peng, C., Randerson, J.T., Salazar, A., Sierra, C.A., Smith, M.J., Tian, H., Todd-Brown, K.E.O., Torn, M., van Groenigen, K.J., Wang, Y.P., West, T.O., Wei, Y., Wieder, W.R., Xia, J., Xu, X., Zhou, T., 2016. Toward more realistic projections of soil carbon dynamics by Earth system models. *Global Biogeochemical Cycles* 30, 40-56.

Luo, Z.K., Wang, E.L., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. *Agriculture Ecosystems & Environment* 139, 224-231.

Lutfalla, S., Chenu, C., Barré, P., 2014. Are chemical oxidation methods relevant to isolate a soil pool of centennial carbon? *Biogeochemistry* 118, 135-139.

Maillard, E., Angers, D.A., 2014. Animal manure application and soil organic carbon stocks: a meta-analysis. *Global Change Biology* 20, 666-679.

Martins, M.R., Angers, D.A., Corá, J.E., 2012. Co-accumulation of microbial residues and particulate organic matter in the surface layer of a no-till Oxisol under different crops. *Soil Biology & Biochemistry* 50, 208-213.

Melillo, J.M., Aber, J.D., Muratore, J.F., 1982 Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. *Ecology* 63, 621-626

Menichetti, L., Ekblad, A., Kätterer, T., 2015. Contribution of roots and amendments to soil carbon accumulation within the soil profile in a long-term field experiment in Sweden. *Agriculture, Ecosystems and Environment* 200, 79-87.

Meurer, K.H.E., Haddaway, N.R., Bolinder, M.A., Kätterer, T., 2018. Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach. *Earth-Science Reviews* 177, 613-622.

Milne, E., Adamat, R.A., Batjes, N.H., Bernoux, M., Bhattacharyya, T., Cerri, C.C., Cerri, C.E.P., Coleman, K., Easter, M., Falloon, P., Feller, C., Gicheru, P., Kamoni, P., Killian, K., Pal, D.K., Paustian, K., Powlson, D.S., Rawajfih, Z., Sessay, M., Williams, S., Wokabi, S., 2007. National and sub-national assessments of soil organic carbon stocks and changes: The GEFSOC modelling system. *Agriculture, Ecosystems & Environment* 122, 3-12.

Milne, E., Aynekulu, E., Bationo, A., Batjes, N.H., Boone, R., Conant, R., Davies, J., Hanan, N., Hoag, D., Herrick, J.E., Knausenberger, W., 2016. Grazing lands in Sub-Saharan Africa and their potential role in climate change mitigation: What we do and don't know. *Environmental Development* 19, 70-74.

963 Miltner, A., Bombach, P., Schmidt-Brücken, B., Kästner, M., 2012. SOM genesis: Microbial
 964 biomass as a significant source. *Biogeochemistry* 111, 41-55.
 965 Minasny, B., Arrouays, D., McBratney, A.B., Angers, D.A., Chambers, A., Chaplot, V.,
 966 Chen, Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C., Hong, S.Y., Mandal,
 967 B., Malone, B.P., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S.,
 968 Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I.,
 969 Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B.,
 970 Winowiecki, L., 2018. Rejoinder to Comments on Minasny et al., 2017 Soil carbon 4 per
 971 mille *Geoderma* 292, 59–86. *Geoderma* 309, 124-129.
 972 Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A.,
 973 Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong,
 974 S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S.,
 975 Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I.,
 976 Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B.,
 977 Winowiecki, L., 2017. Soil carbon 4 per mille. *Geoderma* 292, 59-86.
 978 Naudin, K., Scopel, E., Andriamandroso, A.L.H., Rakotosolofo, M., Andriamarosoa
 979 Ratsimbazafy, N.R.S., Rakotozandriny, J.N., Salgado, P., Giller, K.E., 2011. Trade-Offs
 980 between Biomass Use and Soil Cover. The Case of Rice-Based Cropping Systems in the Lake
 981 Alaotra Region of Madagascar. *Experimental Agriculture* 48, 194-209.
 982 Northup, R.R., Dahlgren, R.A., McColl, J.G., 1998. Polyphenols as regulators of plant-litter-
 983 soil interactions in northern California's pygmy forest: a positive feedback? *Biogeochemistry*
 984 42, 189-220.
 985 Ogle, S.M., Jay Breidt, F., Easter, M., Williams, S., Killian, K., Paustian, K., 2010. Scale and
 986 uncertainty in modeled soil organic carbon stock changes for US croplands using a process-
 987 based model. *Global Change Biology* 16, 810-822.
 988 Olson, K.R., Al-Kaisi, M.M., Lal, R., Lowery, B., 2014. Experimental consideration,
 989 treatments, and methods in determining soil organic carbon sequestration rates. *Soil Science*
 990 *Society of America Journal* 78, 348.
 991 Oorts, K., Garnier, P., Findeling, A., Mary, B., Richard, G., Nicolardot, B., 2007. Modeling
 992 soil carbon and nitrogen dynamics in no-till and conventional tillage using Pastis model. *Soi*
 993 *Science Society of Amerlca Journal* 71, 336-346.
 994 Pan, G.X., Smith, P., Pan, W.N., 2009. The role of soil organic matter in maintaining the
 995 productivity and yield stability of cereals in China. *Agriculture Ecosystems & Environment*
 996 129, 344-348.
 997 Paradelo, R., Virto, I., Chenu, C., 2015. Net effect of liming on soil organic carbon stocks: A
 998 review. *Agriculture, Ecosystems & Environment* 202, 98-107.
 999 Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling
 1000 soil organic matter levels in Great Plains Grasslands. *Soil Science Society of America Journal*
 1001 51, 1173-1179.
 1002 Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P and S in grassland
 1003 soils: a model. *Biogeochemistry* 5, 109-131.
 1004 Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-
 1005 smart soils. *Nature* 532, 49-57.
 1006 Peichl, M., Thevathasan, N.V., Gordon, A.M., Huss, J., Abohassan, R.A., 2006. Carbon
 1007 sequestration potentials in temperate tree-based intercropping systems, southern Ontario,
 1008 Canada. *Agroforestry Systems* 66, 243-257.
 1009 Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, G., Butault, J.P., Chenu, C.,
 1010 Colnenne-David, C., De Cara, S., Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-
 1011 Launay, F., Hassouna, M., Hénault, C., Jeuffroy, M.H., Klumpp, K., Metay, A., Moran, D.,
 1012 Recous, S., Samson, E., Savini, I., Pardon, L., 2013. How can French agriculture contribute to

reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures. Synopsis of the study report, INRA (France), p. 80p.

Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, M., Butault, J.-P., Chenu, C., Colnenne-David, C., De Cara, S., Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Hénault, C., Jeuffroy, M.-H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., Savini, I., Pardon, L., Chemineau, P., 2017. Identifying cost-competitive greenhouse gas mitigation potential of French agriculture. *Environmental Science & Policy* 77, 130-139.

Peltre, C.m., Christensen, B.T., Dragon, S., Icard, C., Kätterer, T., Houot, S., 2012. RothC simulation of carbon accumulation in soil after repeated application of widely different organic amendments. *Soil Biology & Biochemistry* 52, 49-60.

Perez, C., Roncoli, C., Neely, C., Steiner, J.L., 2007. Can carbon sequestration markets benefit low-income producers in semi-arid Africa? Potentials and challenges. *Agricultural Systems* 94, 2-12.

Pinheiro, M., Garnier, P., Beguet, J., Martin Laurent, F., Vieublé-Gonod, L., 2015. The millimetre-scale distribution of 2,4-D and its degraders drives the fate of 2,4-D at the soil core scale. *Soil Biology & Biochemistry* 88, 90-100.

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis. *Agriculture Ecosystems & Environment* 200, 33-41.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.a., Sanchez, P.a., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* 4, 678-683.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? *Agriculture, Ecosystems and Environment* 220, 164–174.

Quinton, J.N., Govers, G., Oost, K.v., Bardgett, R.D., 2010. The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience* 3, 311-314.

Rasse, D.P., Rumpel, C., Dignac, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant and Soil* 269, 341–356.

Recous, S., Robin, D., Darwis, D., Mary, B., 1995. Soil inorganic N availability: Effect on maize residue decomposition. *Soil Biology and Biochemistry* 27, 1529-1538.

Ruamps, L.S., Nunan, N., Chenu, C., 2011. Microbial biogeography at the soil pore scale. *Soil Biology & Biochemistry* 43, 280-286.

Rumpel, C., Kogel-Knabner, I., 2011. Deep soil organic matter-a key but poorly understood component of terrestrial C cycle. *Plant and Soil* 338, 143-158.

Saffih-Hdadi, K., Mary, B., 2008. Modeling consequences of straw residues export on soil organic carbon. *Soil Biology & Biochemistry* 40, 594-607.

Sanderman, J., Berhe, A.A., 2017. The soil carbon erosion paradox. *Nature Climate Change* 7, 317-319.

Sanderman, J., Creamer, C., Baisden, W.T., Farrell, M., Fallon, S., 2017. Greater soil carbon stocks and faster turnover rates with increasing agricultural productivity. *Soil* 3, 1-16.

Schimel, J.P., Schaeffer, S.M., 2012. Microbial control over carbon cycling in soil. *Frontiers in Microbiology* 348, 1-11.

Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kogel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478, 49-56.

Schon, N.L., Mackay, A.D., Gray, R.A., Dodd, M.B., Van Koten, C., 2015. Quantifying dung carbon incorporation by earthworms in pasture soils. *European Journal of Soil Science* 66, 348–358.

1063 Shahzad, T., Chenu, C., Genet, P., Barot, S., Perveen, N., Mougin, C., Fontaine, S., 2015.
 1064 Contribution of exudates, arbuscular mycorrhizal fungi and litter depositions to the
 1065 rhizosphere priming effect induced by grassland species. *Soil Biology & Biochemistry* 80,
 1066 146-155.
 1067 Six, J., Connant, R.T., Paul, E.A., Paustian, J., 2002. Stabilisation mechanisms of soil organic
 1068 matter : implications for C-saturation of soils. *Plant and Soil* 241, 155-176.
 1069 Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S.,
 1070 O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G.,
 1071 Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008.
 1072 Greenhouse gas mitigation in agriculture. *Phil. Trans. R. Soc. B* 363, 789-813.
 1073 Söderström, B., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Bracht
 1074 Jørgensen, H., 2014. What are the effects of agricultural management on soil organic carbon
 1075 (SOC) stocks? *Environmental Evidence* 3, 2.
 1076 Soussana, J.-F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards,
 1077 M., Wollenberg, E., Chotte, J.-L., Torquebiau, E., Ciais, P., Smith, P., Lal, R., 2017.
 1078 Matching policy and science: Rationale for the '4 per 1000 - soils for food security and
 1079 climate' initiative. *Soil and Tillage Research*.
 1080 Soussana, J.F., Loiseau, P., Vuichard, N., Ceschia, E., Balesdent, J., Chevallier, T., Arrouays,
 1081 D., 2004. Carbon cycling and sequestration opportunities in temperate grasslands. *Soil Use*
 1082 *and Management* 20, 219-230.
 1083 Steinbeiss, S., Bessler, H., Engels, C., Temperton, V.M., Buchmann, N., Roscher, C.,
 1084 Kreutziger, Y., Baade, J., Habekost, M., Gleixner, G., 2008. Plant diversity positively affects
 1085 short-term soil carbon storage in experimental grasslands. *Global Change Biology* 14, 2937-
 1086 2949.
 1087 Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., Six, J., 2007. Soil carbon saturation:
 1088 concept, evidence and evaluation. *Biogeochemistry* 86, 19-31.
 1089 Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M.,
 1090 Minasny, B., McBratney, A.B., de Courcelles, V.D., Singh, K., Wheeler, I., Abbott, L.,
 1091 Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R.,
 1092 Lehmann, J., O'Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The
 1093 knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture*
 1094 *Ecosystems & Environment* 164, 80-99.
 1095 Stolbovoy, V., Montanarella, L., 2008. Application of soil organic carbon status indicators for
 1096 policy-decision making in the EU, In: Toth, G., Montanarella, L., Rusco, E. (Eds.), *Threats to*
 1097 *soil quality in Europe*, pp. 87–99.
 1098 Syswerda, S.P., Corbin, A.T., Mokma, D.L., Kravchenko, A.N., Robertson, G.P., 2011.
 1099 Agricultural management and soil carbon storage in surface vs. deep layers. *Soil Science*
 1100 *Society of America Journal* 75, 92.
 1101 Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., Baumecker, M., 2013.
 1102 Irrigation, soil organic carbon and N₂O emissions. A review. *Agronomy for Sustainable*
 1103 *Development* 33, 733-749.
 1104 van Groenigen, J.W., van Kessel, C., Hungate, B.A., Oenema, O., Powlson, D.S., van
 1105 Groenigen, K.J., 2017. Sequestering Soil Organic Carbon: A Nitrogen Dilemma.
 1106 *Environmental Science & Technology* 51, 4738–4739.
 1107 VandenBygaart, a.J., Bremer, E., McConkey, B.G., Janzen, H.H., Angers, D.a., Carter, M.R.,
 1108 Drury, C.F., Lafond, G.P., McKenzie, R.H., 2010. Soil organic carbon stocks on long-term
 1109 agroecosystem experiments in Canada. *Canadian Journal of Soil Science* 90, 543-550.
 1110 VandenBygaart, A.J., McConkey, B.G., Angers, D.A., W. Smith, H.d.G., M. Benthams, T.
 1111 Martin, 2008. Soil carbon change factors for the Canadian agriculture national greenhouse gas
 1112 inventory. *Canadian Journal of Soil Science* 88, 671–680.

Verbruggen, E., Jansa, J., Hammer, E.C., Rillig, M.C., de Vries, F., 2016. Do arbuscular mycorrhizal fungi stabilize litter-derived carbon in soil? *Journal of Ecology* 104, 261-269.

Verbruggen, E., Veresoglou, S.D., Anderson, I.C., Caruso, T., Hammer, E.C., Kohler, J., Rillig, M.C., 2013. Arbuscular mycorrhizal fungi--short-term liability but long-term benefits for soil carbon storage? *New Phytol* 197, 366-368.

Virto, I., Barré, P., Burlot, A., Chenu, C., 2012. Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. *Biogeochemistry* 108, 17-26

Wang, Z.G., Hoffmann, T., Six, J., Kaplan, J.O., Govers, G., Doetterl, S., Van Oost, K., 2017. Human-induced erosion has offset one-third of carbon emissions from land cover change. *Nature Climate Change* 7, 345-349.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Science Society of America Journal* 66, 1930-1946.

Wieder, W.R., Grandy, A.S., Kallenbach, C.M., Bonan, G.B., 2014. Integrating microbial physiology and physio-chemical principles in soils with the MIMICS model. *Biogeosciences* 11, 3899-3917.

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D.P., Dickie, A., Neufeldt, H., Sander, B.r.O., Wassmann, R., Sommer, R., Amonette, J.E., Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R.M., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.F.o., Baedeker, T., Sadler, M., Vermeulen, S., Campbell, B.M., 2016. Reducing emissions from agriculture to meet the 2°C target. *Global Change Biology* 22, 3859-3864.

Yue, Y., Ni, J., Ciais, P., Piao, S., Wang, T., Huang, M., Borthwick, A.G., Li, T., Wang, Y., Chappell, A., Van Oost, K., 2016. Lateral transport of soil carbon and land-atmosphere CO₂ flux induced by water erosion in China. *Proc Natl Acad Sci U S A* 113, 6617-6622.

Zhang, W., Hendrix, P.F., Dame, L.E., Burke, R.A., Wu, J., Neher, D.A., Li, J., Shao, Y., Fu, S., 2013. Earthworms facilitate carbon sequestration through unequal amplification of carbon stabilization compared with mineralization. *Nature Communication* 4:2576.

Zhou, X., Zhou, L., Nie, Y., Fu, Y., Du, Z., Shao, J., Zheng, Z., Wang, X., 2016. Similar responses of soil carbon storage to drought and irrigation in terrestrial ecosystems but with contrasting mechanisms: A meta-analysis. *Agriculture, Ecosystems and Environment* 228, 70-81.

Tables captions

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 1000 per year). Prediction using the RothC 26.3 default model parameters of SOC dynamics applied to A horizons.

Table 2. Effect of no tillage compared to full inversion tillage or mouldboard ploughing, i.e. conventional tillage) 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.

Figures captions

Figure 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.

Figure 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).

Figure 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).

Figure 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.

1179

1180

1181 Table 1. Indicative model calculations of required changes in either plant material C input to the soil or mean mineralization rates, to reach a
 1182 relative increment of SOC by +8% in twenty years (+4‰ per year). Prediction using the RothC 26.3 default model parameters of SOC
 1183 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*2 0	0.24	0.40	0.16	0.24	0.32	0.32
<i>(i) by increasing carbon inputs only:</i>							
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
<i>(ii) by decreasing SOC decomposition rates only :</i>							
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

1184

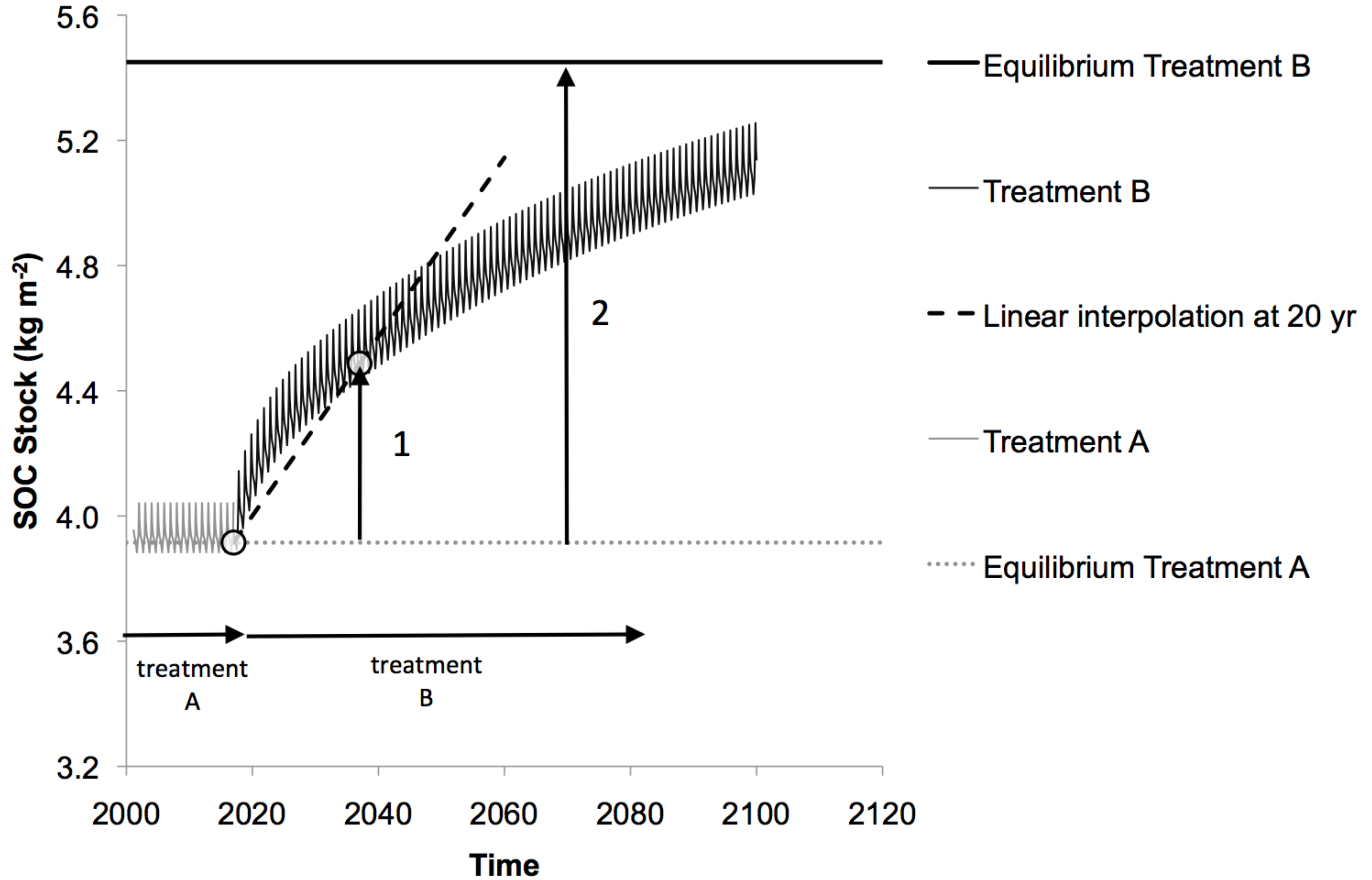
1185

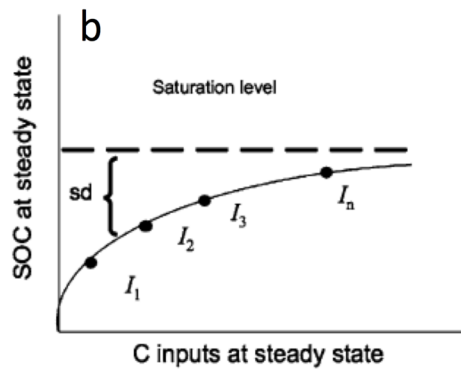
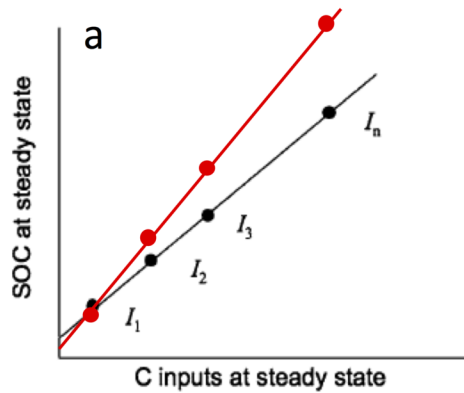
1186

1187 Table 2 Effect of no-tillage (NT) compared to full inversion tillage or mouldboard ploughing, i.e. conventional tillage (FIT), on SOC stocks
 1188 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
 1189 sampled. The dataset from Meurer et al. 2018 is a sub-set of that of Haddaway et al. 2017.
 1190

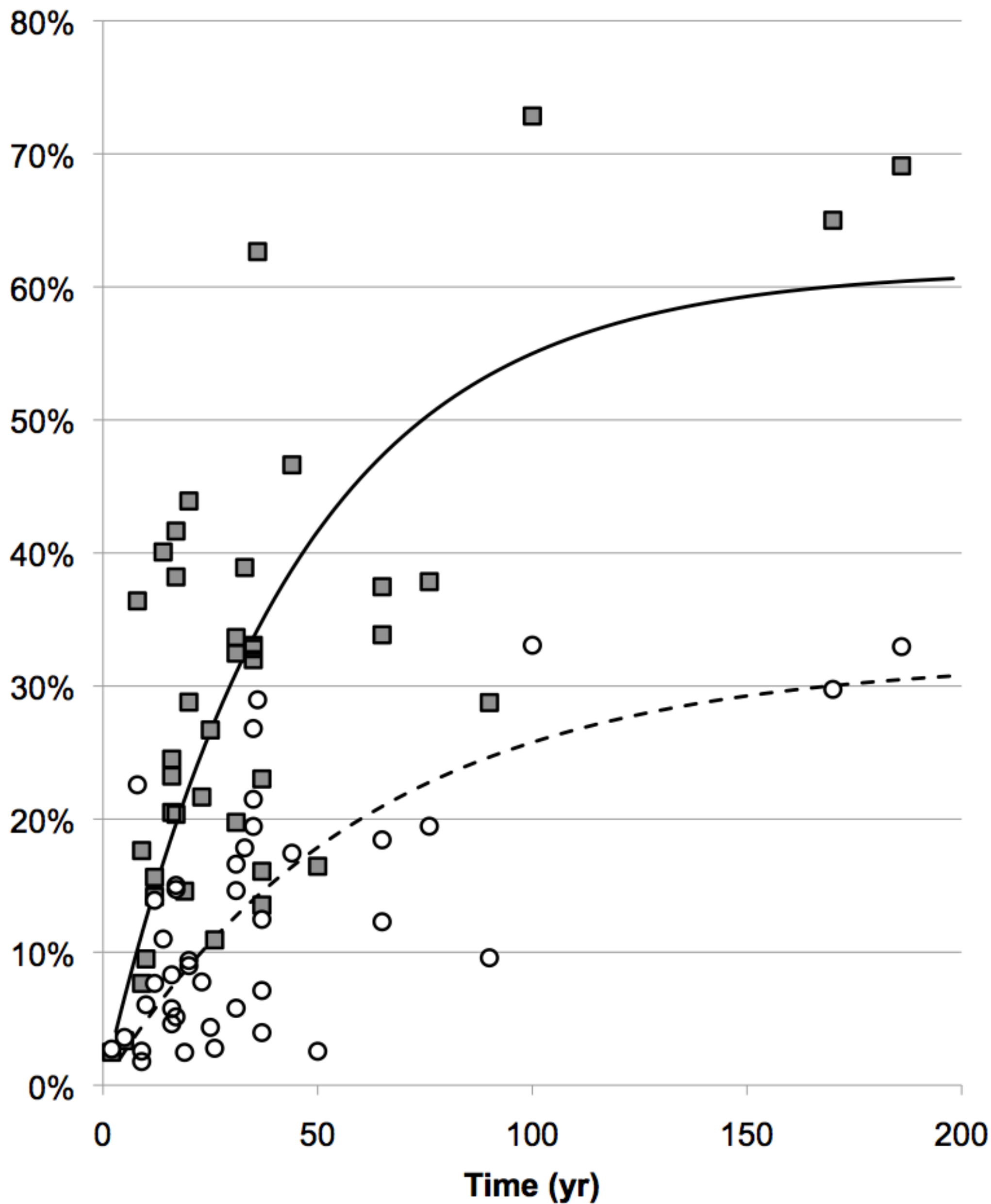
Reference	Climate zone	number of sites	number of pairs of plots	depth considered (cm)	Duration of trials (years)	SOC stock NT-FIT (kg C m ⁻²)	SOC stock NT-FIT (kg C m ⁻² y ⁻¹)
West and Post, 2002	any		93	0-22	≥5	0.62 ± 0.16	0.048
Angers & Eriksen-Hamel, 2008	any	23	47	0-100	≥5	0.49	0.032
Luo et al. 2010	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-	29		0-30	≥10	0.46 ± 0.19	
	temperate	14		0-150		0.15 ± 0.34	
Meurer et al. 2018	boreo-		46	0-30	≥10	0.42 ± 0.18	0.023
	temperate		11	0-60		0.15 ± 0.22	<0.01

1191





Proportion of new C



- 1 Table 1. Indicative model calculations of required changes in either plant material C input to the soil or mean mineralization rates, to reach a
 2 relative increment of SOC by +8% in twenty years (+4‰ per year). Prediction using the RothC 26.3 default model parameters of SOC
 3 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 mil

	III = I*0.004*2 0						
SOC increase after 20 years / kg m ⁻²		0.24	0.40	0.16	0.24	0.32	0.32
<i>(i) by increasing carbon inputs only:</i>							
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
<i>(ii) by decreasing SOC decomposition rates only :</i>							
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

4

5

6 Table 2. Effect of no tillage (full inversion tillage or mouldboard ploughing) on SOC stocks reported by meta-analyses. In the dataset from West
7 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-
8 set of that of Haddaway et al. 2017.

9

Reference	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 & 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-	29		0-30	≥10	0.46 ± 0.19	
	temperate	14		0-150		0.15 ± 0.34	
Meurer et al. 2018	boreo-		46	0-30	≥10	0.42 ± 0.18	0.023
	temperate		11	0-60		0.15 ± 0.22	<0.01

10