



HAL
open science

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

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

3

4 **Authors:**

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

6 Jérôme Balesdent⁶

7

8

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

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

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

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

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

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

19

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

21 **Key words**

22 Carbon storage, carbon sequestration, carbon storage potential, agricultural practices, 4 per

23 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 homogeneously 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

120 others stresses the need to have good constraints on the soil past land-uses when studying its
121 OC stock evolution. However, in the context of a continuously changing climate SOC values
122 at equilibrium may also continuously change, although these aspects will not be considered
123 here.

124

125

126 *Figure 1: Increase in SOC stocks following changes in land-use or management practices*
127 *(increased OC inputs or decreased OC outputs. 1. Carbon storage in 20 years. 2. Maximum C*
128 *storage. Mean monthly variations of SOC stocks are presented.*

129

130 If we consider that the loss rate is constant over time, an increase in OC inputs will result in
131 SOC stock accrual. Such an increase can be obtained either by increasing C inputs from the
132 vegetation (increase in net primary production or increase in residue return) or by increasing
133 exogenous organic matter addition (manure, organic wastes, organic amendments...).

134 The reduction of C outputs (i.e., a decrease in the decay rate k) can be achieved by reducing
135 SOC mineralization by soil micro-organisms or SOC erosion. The role of microorganisms as
136 drivers of soil C cycling, storage and sequestration in soil is not conceptually new, but is
137 increasingly acknowledged as crucial (Dungait et al., 2012; Lehmann and Kleber, 2015;
138 Schimel and Schaeffer, 2012). Microorganisms contribute both to the biodegradation and
139 mineralisation of soil organic substrates, and to the genesis of new organic metabolites. Their
140 action could be viewed as decreasing C storage through the mineralisation of SOM, but
141 increasing the residence time of C as their metabolites exhibit a high affinity for the
142 protecting mineral phases (Cotrufo et al., 2013; Kallenbach et al., 2015; Miltner et al., 2012).
143 The breakdown and biosynthesis rates of the various biochemical components of OM are
144 determined by the microbial community dynamics and by their functional traits. These rates

145 are limited by physical accessibility of substrate to microbes or to their enzymes and by the
146 micro-habitat conditions (oxygen, pH, water content, nutrient resources) (e.g. Juarez et al.,
147 2013b; Pinheiro et al., 2015; Ruamps et al., 2011). As such, any agricultural practice altering
148 the soil physical structure or affecting the microbe resources and the environmental conditions
149 can modify the mineralisation rate of SOC. Regarding erosion, it is established that the
150 downslope transport of SOC in the landscape might redistribute it to sites where it persists
151 longer than it would have in its original location (Berhe et al., 2012; Chaopricha and Marin-
152 Spiotta, 2014; Quinton et al., 2010). The relative effects of the loss of SOC from eroded areas,
153 the loss of C during transportation and its accumulation in depositional areas on the global
154 carbon budget are still under debate (Sanderman and Berhe, 2017; Wang et al., 2017; Yue et
155 al., 2016). While erosion may create a C sink (Berhe et al., 2007), it remains a major soil
156 degradation process, not compatible with sustainable food security and environmental quality
157 (Sanderman and Berhe, 2017).

158 **3. By how much, at which rate and for how long can SOC stocks** 159 **be increased?**

160

161 The **carbon storage potential** of a given soil unit may be defined as the maximum gain in
162 soil OC stock attainable under a given climate and a given timeline (e.g. time required to
163 attain a new equilibrium or a given time period, such as 20 y for IPCC) (Figure 1). Similarly,
164 the carbon **sequestration** potential of a given soil would be the maximum gain in SOC
165 allowing a net removal of CO₂ from the atmosphere under a given climate and for a specified
166 timeline. From current knowledge of SOM dynamics, we can infer the magnitude and kinetics
167 of SOC change as related to yearly carbon inputs to the soil and pedoclimatic conditions. This
168 knowledge is synthesized in several models of SOC dynamics (see the review of models by

169 (Campbell and Paustian, 2015). In Table 1 we calculated for a few representative situations
170 the increase in plant material input or the decrease in decay rates that are required to increase
171 SOC by 4 per 1000 per year during 20 years, i.e., increase soil C by +8% after 20 years, using
172 the model RothC 26.3 (Coleman and Jenkinson, 2014). Typically, the magnitude of the
173 relative changes in plant C inputs or decay rates to reach the target stands in the range of 15 to
174 25% (Table 1). It is noticeable that the maximum C gain is much higher than the gain in 20
175 years: from 1.6 times higher in light-textured tropical soil where OC turnover is rapid, to 3.0
176 times higher in cool, clayey soils where OM turnover is slowest. Similarly, differences
177 between environments regarding the required OM input increment typically depends on (i) the
178 differences in mineralization kinetics, and (ii) the initial C content, since the calculation is
179 based on a *relative* increase in SOC. Around these general features, other inputs than plant
180 material, such as composted amendments, are expected to have a higher yield in SOC (see
181 section 5); in case of progressive increase in inputs, e.g., through the positive feedback of
182 SOC on net primary production, SOC increase will be slower.

183

184 Soil organic matter dynamics models have been developed in the 1970's and 1980's based on
185 long-term experiments in either temperate or tropical agricultural environments. Their
186 parameters have been calibrated so as to fit observed C changes over decades under controlled
187 C inputs or management practices. The major difficulties encountered in the use of these
188 model predictions at the local scale concern: (i) the initial state of soil carbon, which can be
189 under steady or non-steady state depending on past conditions (see above discussion in
190 section 2); (ii) the difficulty in initializing accurately the size of the SOC pools (Luo et al.,
191 2016), in particular those with long turnover times such as for example the "passive" pool in
192 the Century model having turnover times of several centuries (Parton et al., 1988) and the
193 "inert" pool, of the RothC model with residence times of several thousands of years

194 (Jenkinson and Rayner, 1977); (iii) the estimate of the actual C inputs to the soil; (iv) a
195 generally poor accounting of soil types besides their clay content; (v) the impact of practices
196 on decay rates of SOC (the management practices currently simulated in SOC models being
197 limited and SOC models do not simulate the effects of innovative cropping systems such as
198 associated crops or agroforestry); and (v) the lack of consideration of deep soil layers. As a
199 result, models parameterization may be still rough concerning important factors driving SOC
200 dynamics. Furthermore, model's linearity (i.e., amounts of SOC formed on the long-term
201 assumed to be proportional to inputs) has been questioned.

202

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

212

213 If we assume a linear relationship between C inputs and SOC stocks at steady state (as
214 assumed by almost all soil C dynamic models, Figure 2a), the only limitation for SOC stock
215 increase is the amount of OC inputs that can be provided. Several authors challenged the
216 concept that an extra C input would always produce a similar SOC stock increase (Stewart et
217 al., 2007). Their alternative referred to two concepts. The first concept assumes a saturation
218 behaviour towards C inputs, C inputs becoming less and less efficient as the soil is

219 approaching its saturation capacity (Figure 2b). Here the saturation concept was expanded to
220 the total soil organic carbon, contrary to the original proposal of Hassink (1997). This
221 alternative view allows explaining the results of the few studies showing little or no increase
222 of SOC stocks following increased OC inputs. However, there is little or no difference
223 between the linear and saturation relationships for most of field data (Stewart et al., 2007).
224 The second concept is the so-called “priming effect”, which has been evidenced in deep soil
225 layers: when SOC mineralization is limited by the energy supply to microorganisms,
226 increased C inputs of fresh material may accelerate old SOC mineralization (Fontaine et al.,
227 2007). Whatever the considered formalism, establishing which factors are playing on
228 $dSOC/dI$ remains largely an open question. Establishing quantitatively the SOC saturation
229 limit for fine particles associated organic matter and for bulk soil organic matter, if it exists, is
230 also still a debated scientific issue.

231

232 *Figure 2: (a) Relationship between C inputs and SOC stocks at steady state for two different*
233 *soils assuming a linear relationship between C inputs and SOC stocks; (b) Relationship*
234 *between C inputs and SOC stocks at steady state assuming a saturation behaviour for the bulk*
235 *soil organic matter. (sd= saturation deficit. Figure adapted from Stewart et al., 2007).*

236

237 **4. Where to store carbon? Are some soils or soil horizons better** 238 **targets than others?**

239

240 Increasing SOC stocks is not necessarily simple or even possible at all locations. Obviously, it
241 can be more difficult to increase C inputs at some places due to limited access to necessary
242 resources such as fertilizer or water. Using a proportion of actual SOC (4 per 1000) to name

243 the so-called initiative and not an actual SOC amount, implicitly expresses the need to adapt
244 the effort to the climate-dependency of C sequestration costs, which are, for instance, much
245 higher in water-limited and hot areas than in cool moist climates. Soils that have the higher
246 carbon storage potential (i.e., that have SOC stocks well below an estimated SOC stock under
247 favourable practices) could be prioritized. They also exhibit the faster storage rate (Fig. 1). As
248 illustrated in Table 1, for a given increase in C inputs different soils can present different SOC
249 stock increases in relation with soil properties, i.e. the efficiency of the storage may vary with
250 the decay rate of organic matter (k in eqn. 1). In the examples of Table 1, a given additional
251 yearly carbon input, leads to higher additional C stocks in temperate situations compared to
252 tropical ones and in clayey soils compared to sandy ones.

253

254 For a given soil, different horizons can be targeted. Subsoil horizons have lower SOC
255 concentration (Jobbagy and Jackson, 2000), and thus their SOC storage potential, i.e. the
256 difference between present and potential stocks, would be higher than topsoil. Furthermore,
257 the contribution of belowground inputs (roots) to SOC are much higher than aboveground
258 residues (*e.g.* Balesdent et al., 2017; Rasse et al., 2005; Rumpel and Kogel-Knabner, 2011).
259 An option to increase the efficiency of C inputs to the soil can therefore be to place C inputs
260 preferentially towards deep soil layers where the storage potential is large and their
261 mineralization rates may be lower. Indeed, certain soil types exhibit deep organic rich layers,
262 i.e. chernozems, vertisols and more generally black soils (Jobbagy and Jackson, 2000). These
263 are characterized by medium to fine textures and developed under grassland vegetation, i.e.
264 characterized by perennial deep rooting systems. The high potential of deep horizons for SOC
265 storage was quantified by a meta-analysis of studies tracking the incorporation of plant
266 residues into the soil profile on the basis of the natural ^{13}C labelling technique (Balesdent et
267 al., 2017). This work showed that the global mean residence time of SOC is approximately

268 four times higher in the subsoil (30-100 cm depth) than in the topsoil (0-30 cm) (Figure 3).
269 The analysis of world soil radiocarbon profiles also provides evidence for both the long-term
270 stabilization of C in deep horizons of such soils, as well as the deep incorporation of active C
271 by bioturbation and rooting (Mathieu et al., 2015). However, the balance between increased
272 OC inputs to subsoil and destabilization of pre-existing SOC at depth due to priming effects
273 remains uncertain. While the occurrence of a priming effect induced by roots and their
274 rhizodeposits has been widely demonstrated (e.g. reviews by Cheng et al., 2014; Kuzyakov,
275 2002), very few estimates of the priming are available *in situ*, in conditions corresponding to
276 the subsoil (e.g., Shahzad et al., 2015). Another process that warrants thorough estimation is
277 the burial of topsoil organic matter by anecic earthworms and its consequences in terms of
278 SOC storage and persistence (e.g., Arrouays and Pelissier, 1994; Don et al., 2008).

279

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

290

291 *Figure 3. A meta-analysis of natural ¹³C labelling technique in cropped soils shows that the*
292 *residence time of SOC is approximately four times higher in the subsoil (30-100 cm depth)*
293 *than in the topsoil (0-30 cm). Balesdent et al. (2017).*

294

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

304

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

306

307 The carbon storage potential of a soil may be defined as the maximum gain in soil OC stock
308 attainable under a given climate, soil type and timeline (e.g. time required to attain a new
309 stock after IPCC time period: 20 y, or a new equilibrium) (Figure 1). In the previous sections,
310 we have given some qualitative insights on how SOC stocks could be increased but no
311 quantitative indications on storage potential. As presented in Figure 1, there is a transient
312 period between the two steady-states. To quantify SOC accrual rates, one should be able to
313 determine the difference between steady-state 1 and steady-state 2, and the trajectory between
314 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.

363

364 **6. Which practices can be implemented to increase SOC stocks?**

365 **Towards innovative soil carbon management practices.**

366

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

378

379

380 *Figure 4. Levers associated with agricultural practices that may influence SOC stocks: (1)*
381 *increasing primary production (e.g. crop rotations, agroforestry, cover crops), (2) increasing*
382 *biomass return to soil e.g. crop residue return), (3) importing organic wastes to soil*
383 *(manures, composts..), (4) avoiding fires, (5) grassland management (fertilization, grazing),*
384 *(6) decreasing biodegradation and mineralisation rates (no tillage, water management), (7)*
385 *decreasing erosion rates (e.g. cover crops, no tillage, hedges).*

386

387

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

389

390 *No-tillage and conservation agriculture*

391 Tillage is generally considered to increase SOC mineralization due to the mechanical and
392 rain-induced disruption of soil aggregates and the consequent release of CO₂. Therefore no-
393 tillage, i.e. direct seeding implementation has been considered as a suitable practice to
394 increase/maintain SOC stocks compared to so-called conventional tillage, i.e. mouldboard
395 ploughing or inversion tillage. The results of recent global meta-analyses and reviews confirm
396 that SOC stocks increase in the upper soil layers (0-15 or 0-20 cm) with no-tillage
397 implementation, but shows that it has on average a low to non-significant effect on SOC
398 stocks over 30 cm depth or deeper (Angers and Eriksen-Hamel, 2008; Haddaway et al., 2017;
399 Luo et al., 2010; Meurer et al., 2018; Powlson et al., 2014; Powlson et al., 2016; Virto et al.,
400 2012; West and Post, 2002) as shown in Table 2. Additional SOC storage is even less
401 pronounced when other techniques are considered, such as chisel, harrow or disk (Meurer et
402 al., 2018; West and Post, 2002). Hence when reducing soil tillage, there may be an additional
403 SOC storage in superficial soil layers, but no or little SOC sequestration for the land unit
404 considered if the whole soil profile is considered. This seems to be particularly the case in
405 humid and temperate conditions (e.g., Dimassi et al., 2014; VandenBygaart et al., 2010) as
406 opposed to drier climates such as the semi-arid Canadian Prairies (VandenBygaart et al.,
407 2010) or the Mediterranean regions (Blanco-Moure et al., 2013), where significant beneficial
408 effects of no-till relative to mouldboard ploughing are observed. However, the origin of this
409 variability and the underlying processes have not yet been explained (Luo et al., 2010; Meurer
410 et al., 2018; Virto et al., 2012) nor thoroughly studied. Helgason et al. (2014) showed that
411 under the cool and moist climatic conditions of Eastern Canada, the decomposition of ¹³C
412 barley residues was the same whether the residues were incorporated or not, whereas under

413 the semi-arid conditions of the Canadian Prairies, decomposition was greater when residues
414 were incorporated than left at the surface. Decomposition would be limited at the soil surface
415 due to drier conditions. Dimassi et al. (2014) also show that the response of SOC to no tillage
416 is dependent on climate, and in particular precipitation, with a greater response in drier
417 conditions. Changes in micro-environmental conditions induced by ploughing seem to be the
418 main mechanisms controlling the effects of tillage on SOC dynamics (Dimassi et al., 2014;
419 Oorts et al., 2007). Overall, these results also cast doubts on the direct mechanical effect of
420 tillage on SOC mineralization and raise concerns about the relations between physical
421 protection and tillage, in agreement with other studies suggesting that physical protection of
422 organic would only take place at very fine spatial scales ($< 100 \mu\text{m}$) (e.g., (Juarez et al.,
423 2013a). Part of SOC stock differences induced by conversion to no tillage can also be
424 explained by C inputs changes induced by no tillage implementation (Virto et al., 2012).

425

426 Conservation agriculture encompasses a range of cropping systems that propose alternative
427 management practices aiming at maintaining or improving the sustainability of agricultural
428 production, which rely on three pillars: reduced tillage, permanent soil cover, with the use of
429 cover crops and diversified rotations. In its simplest form, conservation agriculture often
430 refers to no-till systems which we covered in the previous paragraph. In its more complex
431 forms it comprises no-tillage with diversified rotations and cover crops which are conducted
432 between successive crops as well as in association with the cash crop. A recent meta-analysis
433 showed that, in a tropical context, such conservation agriculture cropping systems had the
434 potential to store additional carbon while with a large variability and with cases where no
435 increase in SOC stocks was measured (Powlson et al., 2016). Recent field studies (Autret et
436 al., 2016) and meta-analyses (Poeplau and Don, 2015) have clearly shown the potential of
437 cover crops to increase SOC stocks relative to their absence (Autret et al., 2016; Poeplau and

438 Don, 2015). Hence the potential of no-tillage to store SOC is limited while it is much larger
439 when cover crops are associated with no-tillage, i.e. in conservation agriculture. In a study
440 where C inputs and SOC stocks have either been measured or modelled, increases in OC
441 inputs due to alternative management were sufficient to explain the observed SOC stocks
442 changes (Autret et al., 2016). A similar observation was made in agroforestry systems
443 (Cardinael et al., 2015a; Cardinael et al., 2018). In addition, in a meta-analysis of the effects
444 of no tillage on SOC stocks increased OC inputs were the only factor explaining additional
445 SOC storage under not till (Virto et al., 2012). All together, these observations suggest that
446 increasing inputs is probably the best option to increase SOC stocks compared than
447 decreasing outputs by mineralisation through no tillage. This assumption however requires
448 further studies.

449 In addition to providing additional C inputs to the soil, the use of cover crops also involves
450 some diversification of the quality of the C inputs. The influence of C input quality on SOC
451 storage is still a matter of debate (Schmidt et al., 2011). Field studies suggest that the use of
452 legumes either as cover crops (e.g., Boddey et al., 2010) or as intercrop (e.g. Martins et al.,
453 2012) is particularly efficient in increasing SOC in no tillage systems. This would be
454 consistent with the idea that higher-quality residues are more efficiently utilized by the soil
455 microflora, resulting in greater production of microbial by-products and SOC formation
456 (Cotrufo et al., 2013).

457

458 *Irrigation.*

459 Several practices affect different components of the overall carbon balance. Fertilization
460 (Ladha et al., 2011), liming (Paradelo et al., 2015) and irrigation (Trost et al., 2013 ; Zhou et
461 al., 2016) increase primary production and thus increase inputs to soil, modify plant rooting
462 (fertilization and irrigation), and accelerate C and N mineralization. Their net effect on SOC

463 stocks is hence highly variable, and likely depends on local conditions. For example, from the
464 temperature and moisture dependence of SOM decay rates in current models such as RothC,
465 summer irrigation versus summer drought may increase yearly mineralization by as much as
466 50% in cool to warm regions. The meta-analysis performed by Trost et al. (2013) showed that
467 the effects of irrigation on SOC stocks depended on the climate and initial soil organic carbon
468 content. Irrigation had strong positive effects of SOC stocks in desert soils, positive ones in
469 semi-arid areas, and no consistent trend was observed in humid areas. While irrigation may
470 have similar effects on SOC decomposition in all situations, its effects on primary production
471 are likely to be much higher in arid and semi-arid areas compared to humid regions with dry
472 summers. Deep root irrigation is a practice which effect on SOC stocks warrants evaluation as
473 it may increase soil moisture in the vicinity of roots in the subsoil but not in the organic
474 matter rich topsoil, hence allowing to increase plant growth and OC inputs to soil, but have
475 limited effects on SOC mineralization. In the context of forecasted climate changes, the
476 effects of irrigation on SOC stocks and dynamics particularly clearly require more
477 assessments and research.

478

479 *Increasing below-ground inputs.*

480 Below ground OC inputs (roots and associated inputs) contribute more to soil carbon as
481 compared to above ground inputs (Balesdent and Balabane, 1992; Kätterer et al., 2011;
482 Menichetti et al., 2015; Rasse et al., 2005). This is ascribed to its different chemical nature
483 and because the C contained in fine roots, root hairs, associated mycorrhizae and root
484 exudates would enter the soil directly in sites (small pores, microaggregates), where it would
485 be stabilized by adsorption or physical protection (Rasse et al., 2005). This would suggest that
486 management practices that increase below ground C inputs would be particularly efficient in
487 enhancing SOC stocks. Increasing C belowground inputs to soil can be achieved through

488 cropping deep rooting crop varieties (Kell, 2012), deep-rooting perennials (Carter and
489 Gregorich, 2010), and agroforestry (Cardinael et al., 2018; Peichl et al., 2006). Plant breeding
490 should therefore assess the C storage potential of crop genotypes that have a high levels of
491 root biomass or rhizodeposition, and assess the cost and benefits of photosynthate allocation
492 to roots vs harvested organs (Kell, 2012). As previously mentioned (see section 4), the trade-
493 offs between increased below ground inputs and priming effect need to be assessed.

494

495 *Organic amendments*

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

506

507 The influence of residue quality on long-term SOC is still a matter of debate. Many
508 convergent studies have now revealed that the most labile and easy-degradable compounds
509 contribute more to SOM on the long-term than so-called "recalcitrant" materials (e.g., lignin-
510 rich), especially in clayey soils (Cotrufo et al. 2013). Three explanations have been proposed:
511 long-lasting SOM are essentially derived from microbial material (Kallenbach et al., 2015;
512 Miltner et al., 2012); easily degradable substrates are processed with a high microbial carbon

513 use efficiency (Wieder et al., 2014); soluble compounds migrate in soil between mineral
514 surfaces, where they can be protected. Since the quality of organic amendments is often
515 estimated from short-term incubations (Lashermes et al., 2009), the extrapolation to long-term
516 could be counter-intuitive. Such products should be described at least by two parameters in
517 the frame of C models.

518

519 Organic residues and wastes can be applied to soil, either as fresh organic matter, or after
520 composting, methanisation or even pyrolysis. An assessment of these pathways of organic
521 residues processing would require to compare their effects on soil organic carbon and
522 nitrogen on the basis of the same initial amount of “fresh” organic matter, which is seldom
523 performed. For example, Cardinael et al. (2015b), using a long term bare fallow experiment,
524 showed that the effect of fresh vs composted straw on SOC stocks after was the same after 52
525 years, showing here that there was no benefit of composting in terms of CO₂ removal from
526 the atmosphere. Similarly, Thomsen et al. (2013) have shown that the retention of C over
527 decades to centuries appears to be similar whether the initial turnover of plant biomasses
528 occurs in the soil, in the digestive tract of ruminants, in an anaerobic reactor, or in a
529 combination of the latter two. Sector scale budgets of C, but also of the associated N and P
530 are needed.

531

532 *Managing soil nitrogen*

533 The role of nitrogen input on SOC storage and sequestration is still debated. Nitrogen
534 availability has two opposite effects on SOC stocks. On the one hand, N can increase primary
535 production and thus increase the amount of above and below ground litter added to soil,
536 which can result in increased SOC (e.g. Campbell et al., 2000). In this case, the availability of
537 nitrogen can be a limiting factor to additional SOC storage, as discussed by van Groenigen et

538 al. (2017). On the other hand, increased N availability may also accelerate the rate of
539 biodegradation of both litter and indigenous soil organic matter (Melillo et al., 1982 ; Recous
540 et al., 1995) and thereby lead to enhanced loss of SOC. The balance between these processes
541 seems to depend on the ecosystem considered. In a meta-analysis, nitrogen fertilization was
542 found to reduce the rate at which SOC is declining in agricultural soils worldwide (Ladha et
543 al., 2011), i.e. it promoted SOC storage. Lu et al., (2011) observed a 3.48 % relative increase
544 of SOC stocks with N fertilization in agricultural soils in a meta-analysis with 340 paired
545 observations. However, grasslands receiving high nitrogen fertilization may have lower OC
546 content than less fertilized ones (Soussana et al., 2004). Lu et al. (2011) concluded from their
547 meta-analysis that N stimulation of SOC storage primarily occurred in plant pools and less in
548 soil pools. The small magnitude of the effect of N addition on SOC stocks was explained by
549 the higher stimulation of above ground biomass production than that of belowground biomass
550 while, as described previously above ground biomass contributes less to soil carbon compared
551 to below ground biomass. Furthermore, the dataset gathered by Lu et al. (2011) showed that
552 N addition stimulated soil organic matter mineralization. They suggested that earth system
553 models need to treat soil OC inputs from aboveground and belowground sources differentially
554 for soil C storage in response to N deposition and fertilization.

555

556 Regarding stabilization of organic matter, obviously, old SOM is N-rich, and soil
557 proteinaceous material belong to pools of SOM with decadal or centennial turnover times
558 (Bol et al., 2009). The role of proteinaceous compounds on SOM sorption and stabilization on
559 the long term has been hypothesised (Kleber et al., 2007), but the quantitative impact of N
560 input on the long term C stabilization still requires quantitative assessments. Kirkby et al.
561 (2014) demonstrated that the “stable” organic C pool, defined in their study as the SOC fine
562 fraction (< 0.4 mm) was increased with N additions, due to two processes: more fine-sized

563 SOC was formed from the added fresh organic matter, i.e. there was more litter
564 decomposition, but also less old organic matter was lost, i.e. less priming effect occurred (less
565 microbial nutrient mining) (Kirkby et al., 2014). Indeed, microorganisms were shown in other
566 studies to meet their nutrient requirements by mining N from stable SOM by inducing a
567 priming effect (Chen et al., 2014; Derrien et al., 2014).

568 Assessing the role of nitrogen on SOC storage, and the same comment applies to phosphorus,
569 requires research differentiating its effect on primary production and its allocation between
570 above and below ground biomass, litter decomposition, priming effect and long term SOC
571 stabilization.

572

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

574

575 *Plant secondary metabolites*

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

581

582 *Mineral amendments*

583 Fine crystallized-minerals are undoubtedly considered as the first factor of C stabilization in
584 soils (Mathieu et al., 2015). Extremely high SOC stabilization is found in andosols (Torn et
585 al., 1997) and is explained by the presence of very-fine aluminosilicates called allophanes,
586 which are derived from volcanic glasses. Adding fine minerals to soils is not a common
587 management practice. Although some soils have been ameliorated for a long time by addition

588 of clay-rich minerals (e.g., marls) the effects of this management practice on CO₂ balance
589 remains questionable due to the large amounts needed and the related energy consumption to
590 transport them. Basile-Doelsch et al. (2015) developed a new paradigm of co-stabilization of
591 OM with the poorly-crystallized minerals that result from the alteration of primary minerals.
592 In the light of this work, alumino-silicates such as those present in basalt rocks, which are
593 sometimes used as amendments of base-poor soils (Gilman et al., 2002), or clay refuses from
594 bauxite processing (Churchman et al., 2014) could be tested as OM stabilizers.

595

596 *Manipulating microbial physiology.*

597 Several organic cropping systems, characterized by a diversified rotation including legume
598 cover crops, exhibited similar or higher SOC stocks than their conventional counterparts,
599 while fresh OC inputs to soil were not higher and tillage was more frequent (Autret et al.,
600 2016; Gregorich et al., 2001; Syswerda et al., 2011) (a process not represented in Figure 4).
601 Kallenbach et al. (2015) recently showed that in an organic cropping system, soil
602 microorganisms had a higher carbon use efficiency and higher growth rates than under the
603 reference conventional system. As suggested by the authors, this should result in more
604 microbial necromass being formed per unit of C input. Microbial necromass represents a
605 significant fraction of soil organic matter and a major constituent of SOM stabilized in the
606 long term (Cotrufo et al., 2013; Grandy and Neff, 2008), which would explain the increased
607 or preserved SOC stocks cited above. The carbon use efficiency depends on the type of
608 microorganisms (i.e. fungi and actinomycetes vs bacteria, oligotrophs vs copiotrophs), and on
609 the quality of organic inputs (compound providing more available energy and with lower C:N
610 ratio are assimilated with a higher carbon use efficiency). The effects of cropping practices
611 such as cover crops, reduced fertilization, or organic fertilization on the carbon use efficiency

612 of microorganisms remain to be studied as well as the consequences of such changes in terms
613 of SOC stocks.

614

615 *Managing soil biodiversity*

616 A range of studies have shown that increasing the diversity of soil organisms and plants can
617 result in greater SOC stocks and more stabilized organic carbon. Plant diversity increases
618 SOC stocks and the magnitude of SOC storage is related to the abundance of fine roots
619 (Lange et al., 2015; Steinbeiss et al., 2008). Regarding the effects of earthworms on SOC
620 stocks, very contrasted results have been observed (Blouin et al., 2013) and a meta-analysis
621 showed that, in the short term, they increase SOC mineralization (Lubbers et al., 2013). In
622 fact, earthworms would have two opposite effects on SOC stocks, at different time scales.
623 They simultaneously increase the mineralization of both fresh and old soil organic matter (by
624 fragmentation, by their own respiration and their stimulation of soil microorganisms), and
625 incorporate fresh residues into aggregates, i.e., their casts (e.g. (Bossuyt et al., 2005)) and
626 bury carbon at depth (e.g., (Schon et al., 2015) which would increase their stabilization. The
627 simultaneous occurrence of these processes that impact SOC at different time scales has been
628 demonstrated in incubation experiments (Lubbers et al., 2017; Zhang et al., 2013).

629 A similar debate has taken place concerning mycorrhizae (Verbruggen et al., 2013), which
630 were found to increase the mineralization of litter (Cheng et al., 2012) in the short term, while
631 increasing soil aggregation and thus presumably the stabilization of organic matter in the long
632 term (Verbruggen et al., 2016), with opposite effects on SOC stocks depending on the time
633 scale of observation and the relative importance of the two processes (Verbruggen et al.,
634 2013). These results, along with the demonstration that soil organic matter with decadal
635 residence time is mostly microbial (microbial necromass and metabolites, (Liang and Balsler,
636 2008; Miltner et al., 2012), suggest that while increasing the abundance and diversity of

637 decomposers will increase decomposition rates of organic matter, it may result in increased
638 SOC stocks, and/or in a higher proportion of the SOC having long residence times. A recent
639 study by Sanderman et al. (2017) shows that increased productivity due to different rotations
640 in a long term experiment was associated with increased SOC stocks after 40 years, but
641 decreased turnover time of SOC, which supports the idea that increased microbial activity
642 promotes carbon storage.

643

644 These findings call for further research on the effects of agricultural practices that have
645 positive effects on the abundance and diversity of soil organisms in order to analyse the
646 consequences on SOC stabilization. SOC dynamics in intensive cropping systems could be
647 revisited: such systems may have higher C inputs to the soil than natural ecosystems, thanks
648 to their very high productivity and the return of crop remains to the soil, but lower soil C
649 content. The much higher decay rates of SOM in cropped systems (e.g. (Arrouays et al.,
650 1995) are not fully explained by tillage nor N inputs. These intensive cropping systems are
651 also characterized by decreased soil biodiversity, especially mycorrhizal and invertebrates,
652 due to the effects of the concurrent plant diversity reduction (monocultures or simple
653 rotations) and pesticides use. However, when comparing different cropping systems or land
654 uses it is difficult to disentangle the effects of fresh OC inputs to soil from that of modified
655 trophic network and decomposers communities or modified environmental conditions.

656

657 **7. PERSPECTIVE**

658

659 The vision emerging from recent studies on soil organic matter dynamics and on the
660 processes explaining its persistence show that there is still a need to appraise or reappraise

661 and understand the effects of cropping systems and practices on SOC storage and
662 sequestration, and that there is potential for innovation. Long term experiments, which are
663 indispensable, cannot however cover the huge diversity of management options available to
664 farmers. A participatory approach is then needed, which faces the difficulty to measure
665 reliably SOC stock changes at the field scale over only a few years, a time scale relevant to
666 the farmer (Perez et al., 2007). To this regard, since the residence time of SOM under the
667 tropics is *ca.* four times shorter than under temperate climates, and the effects of management
668 thus measurable much faster, medium-term experiments in tropical countries could provide
669 results of general interest even concerning colder climates, and should be clearly encouraged
670 (Milne et al., 2016). Besides, as mentioned in the introduction, the selection of management
671 practices to increase SOC stocks cannot be made solely on criteria based on the potential SOC
672 storage or sequestration. An increase in NPP can be obtained through irrigation or higher
673 addition of mineral fertilizers, which may compromise the sustainability of resources (water
674 use) and have adverse environmental impacts (altered water quality due to nitrate leaching, a
675 negative GHG balance, the increase in soil OC being offset by increased N₂O and CH₄
676 emissions (*e.g.* Schultz et al., 2009). SOC sequestration in agricultural soils must thus be
677 envisioned in a much broader perspective than considering only the global carbon cycle.
678 Furthermore, the feasibility of SOC storing management practices may be limited, such as for
679 instance, increasing crop residues return to the soil can be socially and economically very
680 difficult (*e.g.*, (Naudin et al., 2011). While a process-oriented approach shows the need to
681 reappraise or test a wide range of practices for their ability to sequester carbon in soils and for
682 the permanence and vulnerability of the storage, a much broader approach of these practices,
683 including environmental, agricultural, social and economic evaluations, is also needed to
684 ensure a sustainable management of agricultural soils.

685 The 4 per 1000 initiative promotes carbon storage in soils. Its Scientific and Technical
686 Committee made it clear that the aim is to increase SOC stocks compared to business as
687 usual, with no numerical target value (www.4p1000.org). The initiative remains very
688 ambitious, with its threefold objective of contributing to food security, to climate change
689 adaptation and to mitigation of climate change and with its commitment to the UN
690 Sustainable Development Goals. It has the merit of challenging the scientific community, and
691 in particular the soil organic matter scientific community, asking to clarify concepts and
692 vocabulary and make them known broadly, asking for quantitative estimates of the current
693 state of soil organic resources and of SOC storage potential in a wide variety of pedoclimatic
694 contexts, requiring to position SOC storage questions in a much broader perspective, and
695 revealing gaps in knowledge that need to be explored. The 4 per 1000 initiative is thereby
696 very stimulating for research.
697

698 **References**

- 699 Alcantara, V., Don, A., Vesterdal, L., Well, R., Nieder, R., 2017. Stability of buried carbon in
700 deep-ploughed forest and cropland soils - implications for carbon stocks. *Scientific Reports* 7,
701 1-12.
- 702 Alcantara, V., Don, A., Well, R., Nieder, R., 2016. Deep ploughing increases agricultural soil
703 organic matter stocks. *Global Change Biology* 22, 2939-2956.
- 704 Angers, D.A., Arrouays, D., Saby, N., Walter, C., 2011. Estimating and mapping the carbon
705 saturation deficit of French agricultural topsoils. *Soil Use and Management* 448-452, 448-
706 452.
- 707 Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-inversion tillage and organic carbon
708 distribution in soil profiles: a meta-analysis. *Soil Science Society of America Journal* 72,
709 1370-1374.
- 710 Angers, D.A., Mehuys, G.R., 1989. Effects of cropping on carbohydrate content and water
711 stable aggregation of a clay soil. *Canadian Journal of Soil Science* 69, 373-380.
- 712 Arrouays, D., Balesdent, J., Mariotti, A., Girardin, C., 1995. Modelling organic carbon
713 turnover in cleared temperate forest soils converted to maize cropping by using ¹³C natural
714 abundance measurements. *Plant and Soil* 173, 191-196.
- 715 Arrouays, D., Pelissier, P., 1994. Changes in carbon storage in temperate humic loamy soils
716 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.

767 Cardinael, R., Chevallier, T., Barthès, B., Saby, N., Parent, T.o., Dupraz, C., Bernoux, M.,
768 Chenu, C., 2015a. Impact of alley cropping agroforestry on stocks, forms and spatial
769 distribution of soil organic carbon - a case study in a Mediterranean context. *Geoderma* 259–
770 260 288–299.

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

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

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

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

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

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

788 Cheng, L., Booker, F.L., Tu, C., Burkey, K.O., Zhou, L., Shew, H.D., Ruffy, T.W., Hu, S.,
789 2012. Arbuscular mycorrhizal fungi increase organic carbon decomposition under elevated
790 CO₂. *Science* 337, 1084-1086.

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

794 Chenu, C., Le Bissonnais, Y., Arrouays, D., 2000. Organic matter influence on clay
795 wettability and soil aggregate stability. *Soil Science Society of America Journal* 64, 1479-
796 1486.

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

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

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

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

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

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

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

817 labile substrate destabilise old soil organic matter? *Soil Biology and Biochemistry* 76, 149-
818 160.

819 Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., Cohan, J.-P.,
820 2014. Long-term effect of contrasted tillage and crop management on soil carbon dynamics
821 during 41 years. *Agriculture, Ecosystems & Environment* 188, 134-146.

822 Don, A., Steinberg, B., Schoening, I., Pritsch, K., Joschko, M., Gleixner, G., Schulze, E.D.,
823 2008. Organic carbon sequestration in earthworm burrows. *Soil Biology & Biochemistry* 40,
824 1803-1812.

825 Dungait, J.A.J., Hopkins, D.W., Gregory, A.S., Whitmore, A.P., 2012. Soil organic matter
826 turnover is governed by accessibility not recalcitrance. *Global Change Biology* 18, 1781-
827 1796.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

865 Kallenbach, C.M., Grandy, A.S., Frey, S.D., Diefendorf, A.F., 2015. Microbial physiology
866 and necromass regulate agricultural soil carbon accumulation. *Soil Biology and Biochemistry*
867 91, 279-290.

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

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

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

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

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

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

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

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

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

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

895 Le Quéré, C., Moriarty, R., Andrew, R.M., Peters, G.P., Ciais, P., Friedlingstein, P., Jones,
896 S.D., Sitch, S., Tans, P., Armeth, A., Boden, T.A., Bopp, L., Bozec, Y., Canadell, J.G.,
897 Chevallier, F., Cosca, C.E., Harris, I., Hoppema, M., Houghton, R.A., House, J.I., Jain, A.K.,
898 Johannessen, T., Kato, E., Keeling, R.F., Kitidis, V., Klein Goldewijk, K., Koven, C., Landa,
899 C.S., Landschützer, P., Lenton, A., Lima, I.D., Marland, G., Mathis, J.T., Metzl, N., Nojiri,
900 Y., Olsen, A., Ono, T., Peters, W., Pfeil, B., Poulter, B., Raupach, M.R., Regnier, P.,
901 Rödenbeck, C., Saito, S., Salisbury, J.E., Schuster, U., Schwinger, J., Séférian, R.,
902 Segsneider, J., Steinhoff, T., Stocker, B.D., Sutton, A.J., Takahashi, T., Tilbrook, B., Van
903 Der Werf, G.R., Viovy, N., Wang, Y.-P.P., Wanninkhof, R., Wiltshire, A., Zeng, N., Le
904 Quéré, C., Moriarty, R., Andrew, R.M., Peters, G.P., Ciais, P., Friedlingstein, P., Jones,
905 S.D., Sitch, S., Tans, P., Armeth, A., Boden, T.A., Bopp, L., Bozec, Y., Canadell, J.G., Chini,
906 L.P., Chevallier, F., Cosca, C.E., Harris, I., Hoppema, M., Houghton, R.A., House, J.I., Jain,
907 A.K., Johannessen, T., Kato, E., Keeling, R.F., Kitidis, V., Klein Goldewijk, K., Koven, C.,
908 Landa, C.S., Landschützer, P., Lenton, A., Lima, I.D., Marland, G., Mathis, J.T., Metzl, N.,
909 Nojiri, Y., Olsen, A., Ono, T., Peng, S., Peters, W., Pfeil, B., Poulter, B., Raupach, M.R.,
910 Regnier, P., Rödenbeck, C., Saito, S., Salisbury, J.E., Schuster, U., Schwinger, J., Séférian,
911 R., Segsneider, J., Steinhoff, T., Stocker, B.D., Sutton, A.J., Takahashi, T., Tilbrook, B.,
912 Van Der Werf, G.R., Viovy, N., Wang, Y.-P.P., Wanninkhof, R., Wiltshire, A., Zeng, N.,
913 2015. Global carbon budget 2014. *Earth System Science Data* 7, 47-85.

914 Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. *Nature* 528, 60-
915 68.

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

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

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

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

926 Lubbers, I.M., van Groenigen, K.J., Fonte, S.J., Six, J., Brussaard, L., van Groenigen, J.W.,
927 2013. Greenhouse-gas emissions from soils increased by earthworms. *Nature Climate Change*
928 3, 187-194.

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

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

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

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

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

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

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

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

954 Milne, E., Adamat, R.A., Batjes, N.H., Bernoux, M., Bhattacharyya, T., Cerri, C.C., Cerri,
955 C.E.P., Coleman, K., Easter, M., Falloon, P., Feller, C., Gicheru, P., Kamoni, P., Killian, K.,
956 Pal, D.K., Paustian, K., Powlson, D.S., Rawajfih, Z., Sessay, M., Williams, S., Wokabi, S.,
957 2007. National and sub-national assessments of soil organic carbon stocks and changes: The
958 GEFSOC modelling system. *Agriculture, Ecosystems & Environment* 122, 3-12.

959 Milne, E., Aynekulu, E., Bationo, A., Batjes, N.H., Boone, R., Conant, R., Davies, J., Hanan,
960 N., Hoag, D., Herrick, J.E., Knausenberger, W., 2016. Grazing lands in Sub-Saharan Africa
961 and their potential role in climate change mitigation: What we do and don't know.
962 *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

1013 reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures.
1014 Synopsis of the study report, INRA (France), p. 80p.

1015 Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, M., Butault, J.-P., Chenu, C.,
1016 Colnenne-David, C., De Cara, S., Delame, N., Doreau, M., Dupraz, P., Favardin, P., Garcia-
1017 Launay, F., Hassouna, M., Hénault, C., Jeuffroy, M.-H., Klumpp, K., Metay, A., Moran, D.,
1018 Recous, S., Samson, E., Savini, I., Pardon, L., Chemineau, P., 2017. Identifying cost-
1019 competitive greenhouse gas mitigation potential of French agriculture. *Environmental Science*
1020 *& Policy* 77, 130-139.

1021 Peltre, C.m., Christensen, B.T., Dragon, S., Icard, C., Kätterer, T., Houot, S., 2012. RothC
1022 simulation of carbon accumulation in soil after repeated application of widely different
1023 organic amendments. *Soil Biology & Biochemistry* 52, 49-60.

1024 Perez, C., Roncoli, C., Neely, C., Steiner, J.L., 2007. Can carbon sequestration markets
1025 benefit low-income producers in semi-arid Africa? Potentials and challenges. . *Agricultural*
1026 *Systems* 94, 2-12.

1027 Pinheiro, M., Garnier, P., Beguet, J., Martin Laurent, F., Vieublé-Gonod, L., 2015. The
1028 millimetre-scale distribution of 2,4-D and its degraders drives the fate of 2,4-D at the soil core
1029 scale. *Soil Biology & Biochemistry* 88, 90-100.

1030 Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover
1031 crops - A meta-analysis. *Agriculture Ecosystems & Environment* 200, 33-41.

1032 Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.a., Sanchez, P.a., Cassman,
1033 K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. *Nature*
1034 *Climate Change* 4, 678-683.

1035 Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does
1036 conservation agriculture deliver climate change mitigation through soil carbon sequestration
1037 in tropical agro-ecosystems? *Agriculture, Ecosystems and Environment* 220, 164–174.

1038 Quinton, J.N., Govers, G., Oost, K.v., Bardgett, R.D., 2010. The impact of agricultural soil
1039 erosion on biogeochemical cycling. *Nature Geoscience* 3, 311-314.

1040 Rasse, D.P., Rumpel, C., Dignac, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms
1041 for a specific stabilisation. *Plant and Soil* 269, 341–356.

1042 Recous, S., Robin, D., Darwis, D., Mary, B., 1995. Soil inorganic N availability: Effect on
1043 maize residue decomposition. *Soil Biology and Biochemistry* 27, 1529-1538.

1044 Ruamps, L.S., Nunan, N., Chenu, C., 2011. Microbial biogeography at the soil pore scale.
1045 *Soil Biology & Biochemistry* 43, 280-286.

1046 Rumpel, C., Kogel-Knabner, I., 2011. Deep soil organic matter-a key but poorly understood
1047 component of terrestrial C cycle. *Plant and Soil* 338, 143-158.

1048 Saffih-Hdadi, K., Mary, B., 2008. Modeling consequences of straw residues export on soil
1049 organic carbon. *Soil Biology & Biochemistry* 40, 594-607.

1050 Sanderman, J., Berhe, A.A., 2017. The soil carbon erosion paradox. *Nature Climate Change*
1051 7, 317-319.

1052 Sanderman, J., Creamer, C., Baisden, W.T., Farrell, M., Fallon, S., 2017. Greater soil carbon
1053 stocks and faster turnover rates with increasing agricultural productivity. *Soil* 3, 1-16.

1054 Schimel, J.P., Schaeffer, S.M., 2012. Microbial control over carbon cycling in soil. *Frontiers*
1055 *in Microbiology* 348, 1-11.

1056 Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A.,
1057 Kleber, M., Kogel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P.,
1058 Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem
1059 property. *Nature* 478, 49-56.

1060 Schon, N.L., Mackay, A.D., Gray, R.A., Dodd, M.B., Van Koten, C., 2015. Quantifying dung
1061 carbon incorporation by earthworms in pasture soils. *European Journal of Soil Science* 66,
1062 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 Kreuziger, 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. Bentham, 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.

1113 Verbruggen, E., Jansa, J., Hammer, E.C., Rillig, M.C., de Vries, F., 2016. Do arbuscular
1114 mycorrhizal fungi stabilize litter-derived carbon in soil? *Journal of Ecology* 104, 261-269.
1115 Verbruggen, E., Veresoglou, S.D., Anderson, I.C., Caruso, T., Hammer, E.C., Kohler, J.,
1116 Rillig, M.C., 2013. Arbuscular mycorrhizal fungi--short-term liability but long-term benefits
1117 for soil carbon storage? *New Phytol* 197, 366-368.
1118 Virto, I., Barré, P., Burlot, A., Chenu, C., 2012. Carbon input differences as the main factor
1119 explaining the variability in soil organic C storage in no-tilled compared to inversion tilled
1120 agrosystems. *Biogeochemistry* 108, 17–26
1121 Wang, Z.G., Hoffmann, T., Six, J., Kaplan, J.O., Govers, G., Doetterl, S., Van Oost, K., 2017.
1122 Human-induced erosion has offset one-third of carbon emissions from land cover change.
1123 *Nature Climate Change* 7, 345–349.
1124 West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop
1125 rotation: a global data analysis. *Soil Science Society of America Journal* 66, 1930-1946.
1126 Wieder, W.R., Grandy, A.S., Kallenbach, C.M., Bonan, G.B., 2014. Integrating microbial
1127 physiology and physio-chemical principles in soils with the M**IC**robia**L**-M**IN**eral C**AR**bon
1128 S**T**abilization (MIMICS) model. *Biogeosciences* 11, 3899-3917.
1129 Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F.N., Herold,
1130 M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D.P., Dickie, A., Neufeldt, H., Sander,
1131 B.r.O., Wassmann, R., Sommer, R., Amonette, J.E., Falcucci, A., Herrero, M., Opio, C.,
1132 Roman-Cuesta, R.M., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino,
1133 M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.F.o., Baedeker, T., Sadler, M.,
1134 Vermeulen, S., Campbell, B.M., 2016. Reducing emissions from agriculture to meet the
1135 2°C target. *Global Change Biology* 22, 3859-3864.
1136 Yue, Y., Ni, J., Ciais, P., Piao, S., Wang, T., Huang, M., Borthwick, A.G., Li, T., Wang, Y.,
1137 Chappell, A., Van Oost, K., 2016. Lateral transport of soil carbon and land-atmosphere CO₂
1138 flux induced by water erosion in China. *Proc Natl Acad Sci U S A* 113, 6617-6622.
1139 Zhang, W., Hendrix, P.F., Dame, L.E., Burke, R.A., Wu, J., Neher, D.A., Li, J., Shao, Y., Fu,
1140 S., 2013. Earthworms facilitate carbon sequestration through unequal amplification of carbon
1141 stabilization compared with mineralization. *Nature Communication* 4:2576.
1142 Zhou, X., Zhou, L., Nie, Y., Fu, Y., Du, Z., Shao, J., Zheng, Z., Wang, X., 2016. Similar
1143 responses of soil carbon storage to drought and irrigation in terrestrial ecosystems but with
1144 contrasting mechanisms: A meta-analysis. *Agriculture, Ecosystems and Environment* 228, 70-
1145 81.
1146
1147

1148 **Tables captions**

1149 Table 1. Indicative model calculations of required changes in either plant material C input to
1150 the soil or mean mineralization rates, to reach a relative increment of SOC by +8% in twenty
1151 years (+4 per 1000 per year). Prediction using the RothC 26.3 default model parameters of
1152 SOC dynamics applied to A horizons.

1153

1154 Table 2. Effect of no tillage compared to full inversion tillage or mouldboard ploughing, i.e.
1155 conventional tillage) on SOC stocks reported by meta-analyses. In the dataset from West and
1156 Post (2002) pairs of plots may also differ in the rotation, 22 cm is the average depth sampled.
1157 The dataset from Meurer et al. 2018 is a sub-set of that of Haddaway et al. 2017.

1158

1159 **Figures captions**

1160 Figure 1: Schematic increase in SOC stocks following changes in land-use or management
1161 practices (increased OC inputs or decreased OC outputs). 1. Carbon storage in 20 years. 2.
1162 Maximum C storage. Mean monthly variations of SOC stocks are figured.

1163

1164 Figure 2: (a) Relationship between C inputs and SOC stocks at steady state for two different
1165 soils assuming a linear relationship between C inputs and SOC stocks; (b) Relationship
1166 between C inputs and SOC stocks at steady state assuming a saturation behaviour. (Figure
1167 adapted from Stewart et al., 2007).

1168

1169 Figure 3. A meta-analysis of natural abundance of ^{13}C in cropped soils shows that the
1170 residence time of SOC is approximately four times higher in the subsoil (30-100 cm depth)
1171 than in the topsoil (0-30 cm). (Balesdent et al. 2017).

1172

1173 Figure 4. Levers associated with agricultural practices that may influence SOC stocks: (1)
1174 increasing primary production (e.g. crop rotations, agroforestry, cover crops), (2) increasing
1175 biomass return to soil (crop residue return), (3) importing organic wastes to soil (manures,
1176 composts..), (4) avoiding fires, (5) grassland management (fertilization, grazing), (6)
1177 decreasing biodegradation and mineralisation rates (no tillage, water management), (7)
1178 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

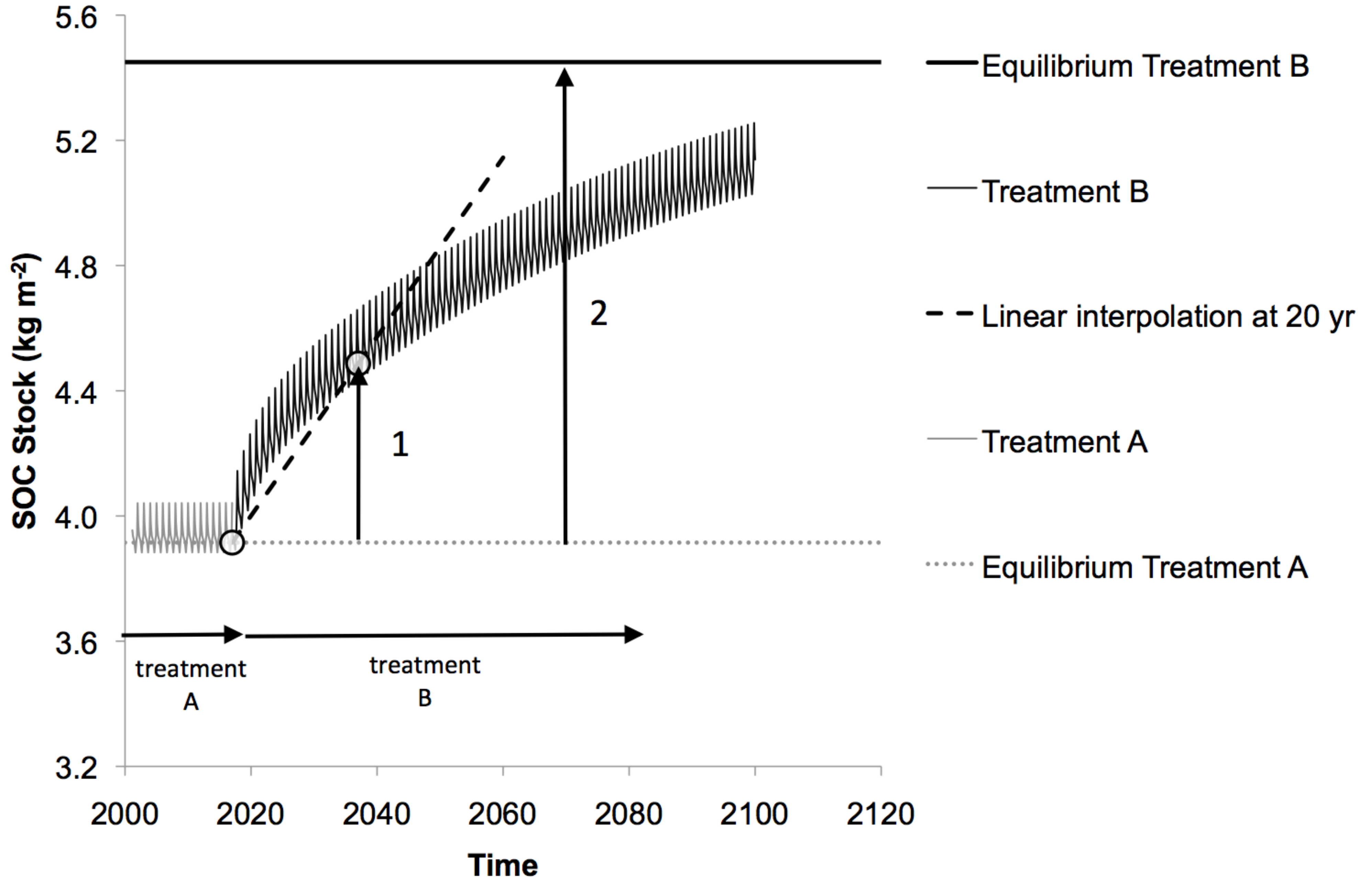
1185

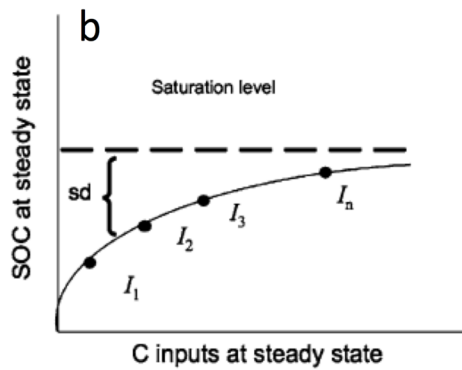
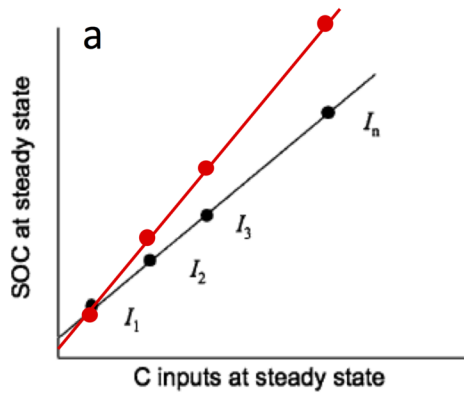
1186

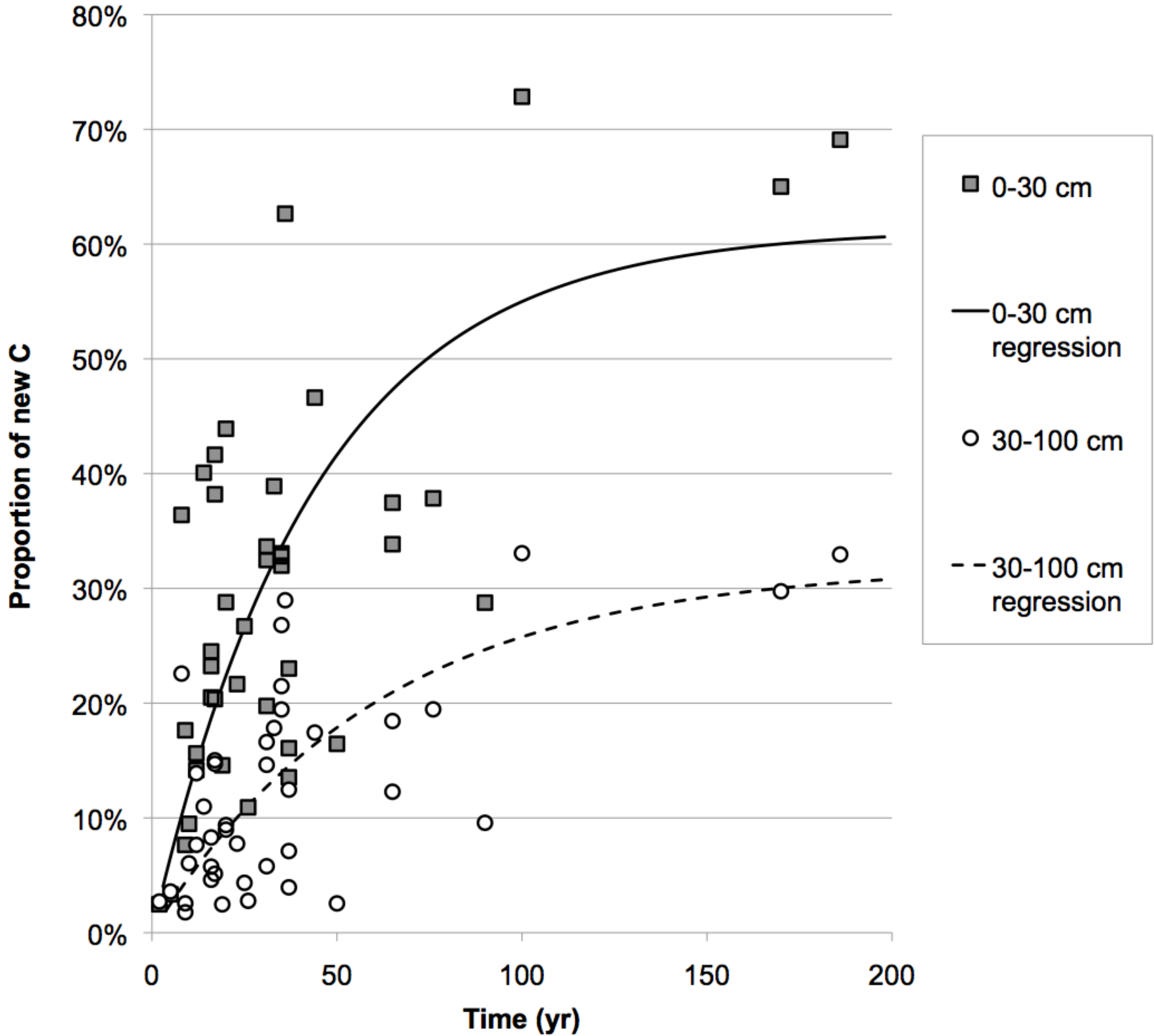
1187 Table 2 Effect of no-tillage (NT) compared to full inversion tillage or mouldboard ploughing, i.e. conventional tillage (FIT), on SOC stocks
 1188 reported by meta-analyses. In the dataset from West and Post (2002) pairs of plots may also differ in the rotation, 22 cm is the average depth
 1189 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







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 | | | | | | |
|--|--------------------|-------|-------|-------|-------|-------|-------|
| SOC increase after 20 years / kg m ⁻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 |

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