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1 **Title:** Soil carbon stocks under different land uses and the applicability of the soil
2 carbon saturation concept

3

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21 **Abstract**

22 Increasing soil organic carbon (SOC) stocks via land management has been
23 proposed as a temporary climate change mitigation measure. An upper limit of soil
24 stable SOC storage, which refers to the concepts of SOC saturation has been
25 proposed. Using systematic grid sampling of topsoil in mainland France and an
26 equation that predicts this SOC saturation, we derived estimates of the SOC
27 sequestration potential density (SOC_{spd}) for various land uses. First, using French
28 database and data from the literature we estimated the proportions of the SOC
29 stored in the fine fraction (SOC_{fine}) in total SOC for grassland (69%), cropland (85%)
30 and forest (66%). Then, SOC_{spd} was calculated as the difference between the
31 theoretical SOC saturation value and SOC_{fine} . The SOC_{spd} stocks for French topsoil
32 were estimated at about 1.1 Pg, in which cropland, forest and grassland accounted
33 for 66%, 17% and 17%, respectively. Varying the proportions of SOC_{fine} in the
34 calculations by assuming a possible range of 0.8-0.9 for cropland and 0.6-0.9 for
35 grassland and forest soils led to variations of total SOC_{spd} stocks of about 0.1 Pg for
36 each land use. Most importantly, we demonstrate that the distribution of SOC_{spd} in
37 forest soils is exactly centred at zero, which suggests that on average, forest topsoils
38 are saturated in SOC_{fine} , and thus Hassink's equation provides a valid estimate for
39 the SOC sequestration potential for French topsoil.

40 **Keywords**

41 Soil organic carbon; Soil carbon saturation; Carbon sequestration potential; Land
42 use; Forest soils

43 **1. Introduction**

44 Soil organic carbon (SOC) plays a major role in the global greenhouse gas balance
45 (Lal, 2004, 2010). Soils throughout the world store four times more SOC than the
46 biosphere and approximately two to three times more carbon than the atmosphere
47 (Batjes, 1996; Stockmann et al., 2015; Le Quéré et al., 2016). Thus, a relatively small
48 change in this reservoir may have a large effect on CO₂ balance. Anthropogenic
49 perturbations have strongly depleted SOC stocks (Bellamy et al., 2005; Sanderman
50 et al., 2017) contributing significantly to increased CO₂ concentration (Canadell et al.,
51 2007). Increasing SOC is beneficial not only for mitigating climate change but also for
52 restoring degraded soils with major potential impacts on crop yields, food security,
53 and the well-being of smallholder farmers (Smith et al., 2008, 2012; Chabbi et al.,
54 2017; Paustian et al., 2016). At the 21st session of the United Nations Framework
55 Convention on Climate Change (UNFCCC, COP21), a voluntary action plan, the “4
56 per 1000 Initiative: Soils for Food Security and Climate” was proposed
57 (<https://www.4p1000.org/>). The 4 per 1000 initiative is intended to foster food security
58 and reduce atmospheric CO₂ concentration by increasing the SOC stocks at an
59 annual rate of 0.4%.

60 Interest around the feasibility, range and duration of additional SOC sequestration
61 has rapidly risen (Lu et al., 2011; Smith et al., 2012; Bradford et al., 2016; Paustian et
62 al., 2016; Chabbi et al., 2017; Dignac et al., 2017; Minasny et al., 2017; van
63 Groenigen et al., 2017). But it has also generated controversy, such as the need for
64 additional nitrogen input to meet stoichiometric demand, the feasibility of
65 implementing changes in management, and the non-permanence of the SOC stocks
66 (Smith, 2005; van Groenigen et al., 2017; Poulton et al., 2018). However, there is a
67 general consensus regarding beneficial practices that may increase SOC (Smith et

68 al., 2008; Lal, 2010; Smith et al., 2012; Paustian et al., 2016; Chabbi et al., 2017;
69 Dignac et al., 2017; Minasny et al., 2017; Chenu et al., 2018).

70 Bonding of SOC to the fine mineral particles is considered one of the most significant
71 SOC stabilization mechanisms for mineral soils (Hassink, 1997; Baldock and
72 Skjemstad, 2000; Six et al., 2002), and as the amount of fine particles is finite, the
73 hypothesis of an upper limit of soil stable SOC storage, which refers to SOC
74 saturation, is generally accepted (Hassink, 1997; Baldock and Skjemstad, 2000; Six
75 et al., 2002; Stewart et al., 2007; Dignac et al., 2017). Hassink (1997) proposed an
76 equation to describe the relationship between maximum SOC storage in the fine
77 fraction, which is assumed to be more stable than the coarse SOC, and the soil fine
78 fraction ($<20 \mu\text{m}$, clay and fine silt) for world soils. In this context, the fine fraction
79 represents a proxy for the mineral surface. The SOC saturation deficit or SOC
80 sequestration potential (SOC_{sp}) can be calculated as the difference between the
81 theoretical SOC saturation and the SOC stored in the fine fraction (SOC_{fine}).

82 Here, we make a distinction between SOC sequestration, defined as long-term
83 stabilized SOC associated with the soil fine fraction, and soil SOC storage, which
84 refers to the whole-soil SOC content (including the coarse or sand-size fraction)
85 (Chenu et al., 2018). Recent discussions have emphasized that the saturation deficit
86 concept may not be suitable to estimate short- to medium-term (10-30 years) whole-
87 soil (including the sand-size fraction) SOC storage potential under varying agro- and
88 climatic conditions (Barré et al., 2017). Indeed, the SOC saturation concept only
89 applies to the soil fine fraction and is theoretically related to the inherent capacity of
90 soils to stabilize (sequester) SOC in the long term in the fine fraction (Hassink, 1997).
91 Other tools (e.g., data-driven approaches and process-based prediction models) may

92 be more appropriate to estimate the whole-soil SOC storage potential under varying
93 management and climatic conditions for a given period of time (Barré et al., 2017).

94 Changes in land cover and land use have a major effect on SOC stocks (Post and
95 Kwon, 2000; Guo and Gifford, 2002; Lal, 2010; Smith et al., 2012; Stockmann et al.,
96 2015). Forests and grasslands usually show the highest SOC stocks among land
97 covers (Carter et al., 1998; Post and Kwon, 2000; Conant et al., 2001; Guo and
98 Gifford, 2002; Soussana et al., 2004; McNally et al., 2017). Forest and grassland
99 soils are therefore often used as reference for the maximum reachable SOC stocks
100 and SOC saturation (Conant et al., 2001; Guo and Gifford, 2002; Lugato et al., 2014).

101 Here we analyse the statistical distribution of SOC sequestration potential density
102 (SOC_{spd}) from an unbiased sampling of topsoil in mainland France. Our objectives
103 were to apply the carbon saturation concept for French topsoil, to estimate their
104 SOC_{spd} , and to determine if some land uses could be used as a reference for
105 estimating soil SOC sequestration potential.

106 **2. Material and methods**

107 2.1. Sampling and measurements

108 Data come from the systematic grid of the French Soil Monitoring Network (RMQS).
109 This network is based on a 16 km x 16 km square grid and the sites are selected at
110 the center of each grid cell resulting in about 2000 soil sampling sites (Martin et al.,
111 2011). Twenty-five individual core samples were collected for topsoil (0-30 cm) based
112 on an unaligned sampling design within a 20 m x 20 m square, and then were mixed
113 into a composite sample for each site. In the south border of the 20 m x 20 m square,
114 a soil pit was dug to record main soil characteristics including bulk density with three
115 replicates. Soil organic carbon content was measured using an automated C-N

116 analyzer by the dry combustion method (Thermofisher NA 2000) and bulk density
117 was determined by taking samples of known volume and drying them to constant
118 weight. Particle-size analysis was determined using the pipette method. More details
119 about the sampling strategy are found in Chen et al. (2018).

120 2.2. Calculation of SOC sequestration potential

121 The SOC saturation of soil fine fraction (<20 μm , clay and fine silt) was calculated
122 according to the equation proposed by Hassink (1997):

$$123 \quad \text{SOC}_{sat} = 4.09 + 0.37 \times \text{fine fraction} \quad (1)$$

124 where SOC_{sat} is the SOC saturation (g kg^{-1}) and *fine fraction* is the content of soil
125 particle-size < 20 μm (%).

126 The SOC saturation deficit was calculated as the difference between SOC saturation
127 and the SOC stored in soil fine fraction (SOC_{fine}). The SOC_{fine} content of cropland
128 soils was assumed to comprise 85% of the total SOC based on previous studies
129 (Balesdent, 1996; Jolivet et al., 2003; Angers et al., 2011). We also summarized
130 previous studies from regions with similar climate (Table 1) and derived the
131 proportions of SOC_{fine} in the total SOC by weighted averaging (according to the
132 number of samples per study) for grassland ($69 \pm 9\%$) and forest ($66 \pm 2\%$).

133 The SOC saturation deficit or SOC sequestration potential (SOC_{sp}) was calculated as
134 follows:

$$135 \quad \text{SOC}_{sp} = \text{SOC}_{sat} - \text{SOC}_{fine} \quad (2)$$

136 where SOC_{sp} is the SOC sequestration potential (g kg^{-1}) and SOC_{fine} is SOC in fine
137 fraction (g kg^{-1}).

138 The SOC sequestration potential density was calculated using the following equation:

139
$$SOC_{spd} = p \times SOC_{sp} \times BD \times (100 - ce) \times 10^{-2} \quad (3)$$

140 where SOC_{spd} is the SOC sequestration potential density ($kg\ m^{-2}$) in topsoil layer (0-
141 30 cm), BD , SOC_{sp} and ce are the bulk density ($kg\ m^{-3}$), sequestration potential ($g\ kg^{-1}$
142 or ‰), ce is the percentage of coarse elements (>2 mm, ‰), and p is the thickness
143 (m) of topsoil horizon.

144 As the RMQS is a systematic grid covering the whole territory (mainland France), it
145 can be used in a straightforward and unbiased way to estimate mean values and
146 total SOC_{spd} stocks (Brus and de Gruijter, 1997). Using RMQS sites we calculated
147 the estimates of SOC_{spd} stocks at the national scale. Estimates of SOC_{spd} stocks
148 were calculated by multiplying the total area of each land use by its mean SOC_{spd}
149 (negative values were replaced by 0 as they have by definition no potential to
150 sequester SOC) of observed RMQS sites under cropland, forest and grassland.

151 2.3. Sensitivity analysis

152 As a large part of uncertainty comes from the parameter setting for the proportion of
153 SOC_{fine} in the total SOC for each land use, we first assessed the influence of
154 proportion setting on the estimates of French national SOC_{spd} stocks in topsoil.

155 Then, in order to assess how the distribution of SOC_{fine} proportion may change the
156 distribution of SOC_{spd} , we applied Gaussian distribution simulation (1000 times) for
157 the forest soils with SOC_{spd} around 0 (-0.5 to $0.5\ kg\ m^{-2}$). In the Gaussian distribution
158 simulation, the mean value was defined as 0.66 (mean value used for forest soils),
159 and three different standard deviation values (σ at 0.1, 0.2 and 0.3) were tested.

160

161 3. Results

162 3.1. SOC sequestration potential under land uses

163 The relative frequency distribution of SOC_{spd} was analysed for three main land uses:
164 forest, grassland and cropland (Fig. 1). Positive values indicate the potential to
165 sequester additional stable SOC, whereas negative values indicate seemingly
166 oversaturated soils, the implication of which is discussed later. Nearly 84% of
167 cropland soils are depleted in stable SOC, with a modal SOC_{spd} value of
168 approximately 4 kg m^{-2} (40 Tg ha^{-1}).

169 The relative frequency distribution of SOC_{spd} of forest soils is exactly centred at zero.
170 Its mean, modal and median values are 0.06 , 0 , and 0.28 kg m^{-2} , respectively. The
171 distribution is skewed and exhibits a tail for most negative values, which suggests
172 that some forest soils may be oversaturated in stable SOC.

173 Skewness is also observed for the relative frequency distribution of SOC_{spd} under
174 grassland. The distribution is centered at 2 kg m^{-2} with a sharp increase in the
175 frequency around this value, whereas its median value is close to zero (-1.40 kg m^{-2}).
176 Among the three frequency distributions, the values under forest are the most
177 scattered and show a large proportion of negative values.

178 3.2. SOC_{spd} sequestration potential density and soil fine fractions

179 The SOC_{spd} is related to the fine mineral particle fraction ($0\text{-}20 \mu\text{m}$) as per Hassink's
180 equation. There is a general increase in SOC_{spd} with an increase in fine fraction
181 content, but the magnitude differs between land uses (Fig. 2). Cropland soils show a
182 greater slope value (0.08) and Pearson correlation coefficient (0.47) of the fitted line
183 between SOC_{spd} and fine fraction content than forest and grassland soils. This result
184 suggests that the increase in SOC_{spd} with increasing fine fraction is highest for
185 cropland.

186 3.3. SOC_{spd} stocks and sensitivity analysis

187 The SOC_{spd} stocks in French topsoil were about 1.1 Pg, of which cropland, forest and
188 grassland accounted for 66%, 17% and 17%, respectively. Varying the proportion of
189 SOC_{fine} in the calculation (assuming a possible range of 0.8-0.9 for croplands and
190 0.6-0.9 for grasslands and forests) led to variations of total SOC_{spd} stocks of about
191 0.1 Pg for each land use (Fig. 3). Fig. 4 shows that the SOC_{spd} distribution is very
192 sensitive to variation in the proportion of SOC_{fine} used. The flatter and the wider is the
193 distribution of SOC_{fine}, the larger is the range of SOC_{spd} for simulated forest soils that
194 had a SOC_{spd} close to zero when using the fixed value of 0.66 for the SOC_{fine}
195 proportion.

196 **4. Discussion**

197 The observed differences among land uses in topsoil confirm the well-known effect of
198 SOC depletion with cultivation (Post and Kwon, 2000; Conant et al., 2001; Guo and
199 Gifford, 2002; McNally et al., 2017). The mean values that we obtained for cropland,
200 grassland and forest soils are consistent with trends of SOC associated with land use
201 change reported in the literature (Post and Kwon, 2000; Guo and Gifford, 2002).

202 Among the invoked limitations of the SOC saturation concept, is the lack of field
203 validation (O'Rourke et al., 2015). Our findings indicate that the SOC saturation
204 concept for the French climate is sensitive to land use. Similar ranges of SOC_{spd}
205 have been identified for cultivated soils using an entirely different and independent
206 data set (Angers et al., 2011) which indicates that our findings are robust.

207 Following a previous study (Angers et al., 2011), we postulated that part (15%) of the
208 SOC measured in cropland soil was not bound to minerals and was unprotected.
209 Similarly, we used lower values from the literature to estimate this proportion of
210 unprotected SOC in grassland and forest soils as a higher proportion of unbound

211 SOC is usually observed in these soils. Although we adapted the proportion to land
212 use, we may have under- or overestimated the protected SOC in some soils with
213 very high SOC contents. Moreover, our sensitivity analysis shows that SOC_{spd} is very
214 sensitive to the proportion of SOC_{fine} used in the calculations. Assuming that there is
215 a variation around the mean values we used, a large part of the dispersion in SOC_{spd}
216 under forest soils may be attributable to the variability in the proportion of SOC_{fine} .
217 This may also explain why we find some negative values of SOC_{spd} (oversaturation of
218 the fine fraction) which should not happen in theory.

219 To estimate stable SOC saturation, we employed an equation that was derived for
220 soils from around the world (Hassink, 1997). Therefore, some bias and uncertainty
221 may be associated with the derived estimates. The equation we used is linear;
222 however, as suggested by some authors (Stockmann et al., 2013), this relation may
223 follow a curve that reaches a plateau at high fine particle content.

224 Unlike many previous studies looking at national/regional estimates of SOC
225 sequestration, our results are statistically unbiased. Indeed, our sampling scheme,
226 which is based on a systematic grid for which the origin was not purposely chosen,
227 corresponds to the standards of an unbiased statistical sample. Apart from noticeable
228 exceptions (e.g., Bellamy et al., 2005, Wiesmeier et al., 2014), most of the broad-
229 scale inventory or monitoring schemes are based on purposive sampling that is
230 useful for understanding causes of variation but may be biased when applying
231 statistics to determine a mean value or a total stock at a national scale.

232 One striking finding is that SOC_{spd} under forest exhibits a peak relative frequency
233 distribution that is exactly centred at zero. The fact that the potential additional
234 sequestration is centered at zero under forest suggests that "on average" their fine

235 fraction is saturated. This does not mean that, for a specific pedo-climate context,
236 forest soils are saturated. However, French forest soils, considered as a whole,
237 provide an adequate reference to estimate the maximum sequestration potential
238 overall, for the French territory. The higher mean SOC_{spd} in grassland may result
239 from the fact that some grassland soils have been already degraded probably due to
240 SOC export from intensive grazing. This may also be related to the fact that
241 grassland soils are on average more clayey (25% clay or 48% fine fraction) than
242 forest soils (22% clay or 43% fine fraction), and, as we can see in Fig. 2, the SOC_{spd}
243 tends to increase with fine fraction content.

244 The SOC_{spd} stocks for French topsoil under the three main land uses was estimated
245 to be about 1.1 Pg. This potential additional SOC sequestration can be compared to
246 recent estimates of total SOC stocks in French topsoil of about 3.5 Pg (Martin et al.,
247 2011; Meersmans et al., 2012; Mulder et al, 2016). This potential additional amount
248 of SOC stocks represents 4.0 Pg CO₂ equivalent, that is about 12.6 times the French
249 annual CO₂ emission in 2013 (0.32 Pg) (Eurostat, 2015). Cropland has the highest
250 potential to sequester with nearly 66% of the total. The fact that our calculations
251 show that a large additional sequestration potential exists in theory does not
252 necessarily mean that it can be reached in practice. Innovative management
253 practices (Chenu et al., 2018) will need to be developed and proposed to take
254 advantage of this high sequestration potential. Many factors may limit both the
255 duration and potential of SOC sequestration. Among those factors limiting SOC
256 sequestration potential are for instance N and P availability and climatic or water
257 regime effects on net primary productivity and SOC mineralization and stabilization
258 (van Groenigen et al., 2017). It may be that under French climate, the conditions for
259 an optimal SOC sequestration cannot be reached. Moreover, some options for a

260 maximal SOC sequestration are clearly not realistic (e.g., converting all croplands to
261 grassland or forest) or may not be feasible according to technical, economic or social
262 constraints.

263 Finally, there is a need to refine our estimate of SOC in the fine fractions for French
264 soils in order to derive more reliable estimates of SOC_{spd} . Further, other approaches
265 to estimate the potential for additional SOC storage, such as data-driven or
266 mechanistic C models (Barré et al., 2017), need to be developed in order to improve
267 the national estimates, their driving factors, and identify suitable land management
268 practices.

269 **5. Conclusion**

270 We estimated SOC_{spd} using an unbiased sampling of topsoil in mainland France and
271 estimates of the proportion of SOC_{fine} compiled from the literature. Our results
272 showed that French topsoils have a large potential to sequester SOC (1.1 Pg) when
273 compared to the total SOC stocks (3.5 Pg). A sensitivity analysis suggested that
274 actual measurements of the proportion of SOC_{fine} would be helpful to decrease the
275 uncertainty of SOC_{spd} estimates. As the distribution of SOC_{spd} in forest soils is
276 centred at zero, we suggest that it may be used as a reference to estimate the
277 maximum SOC sequestration potential in France.

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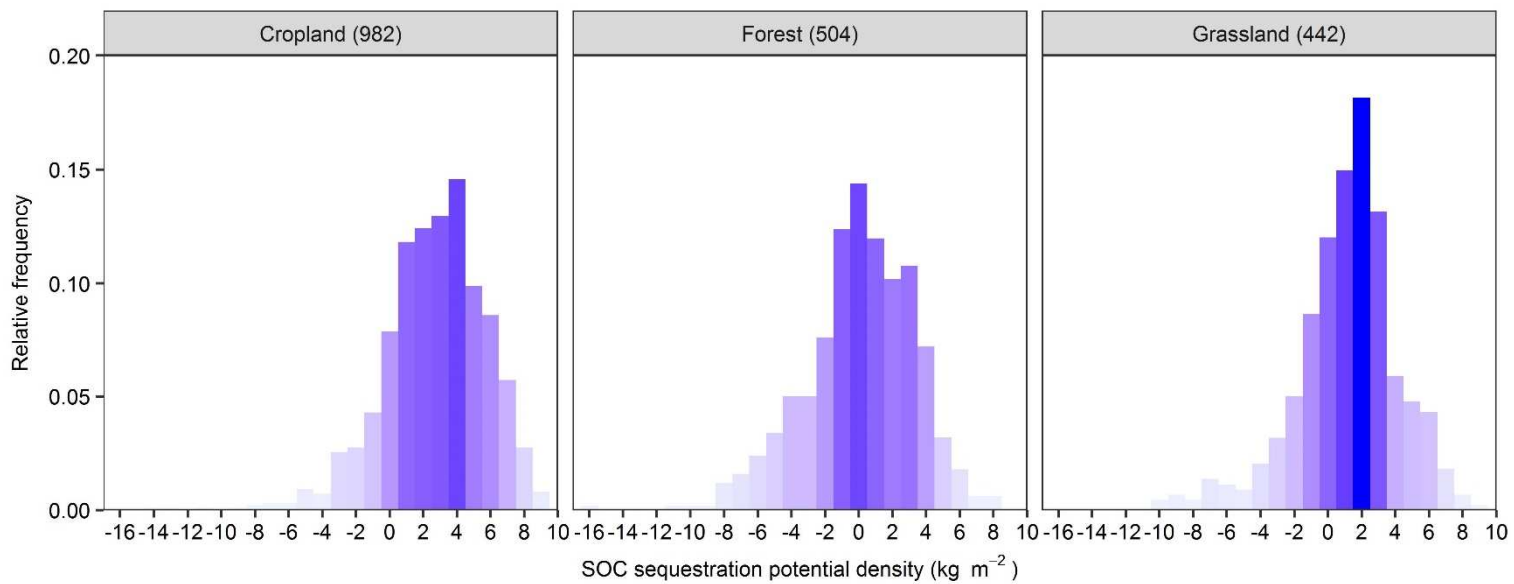
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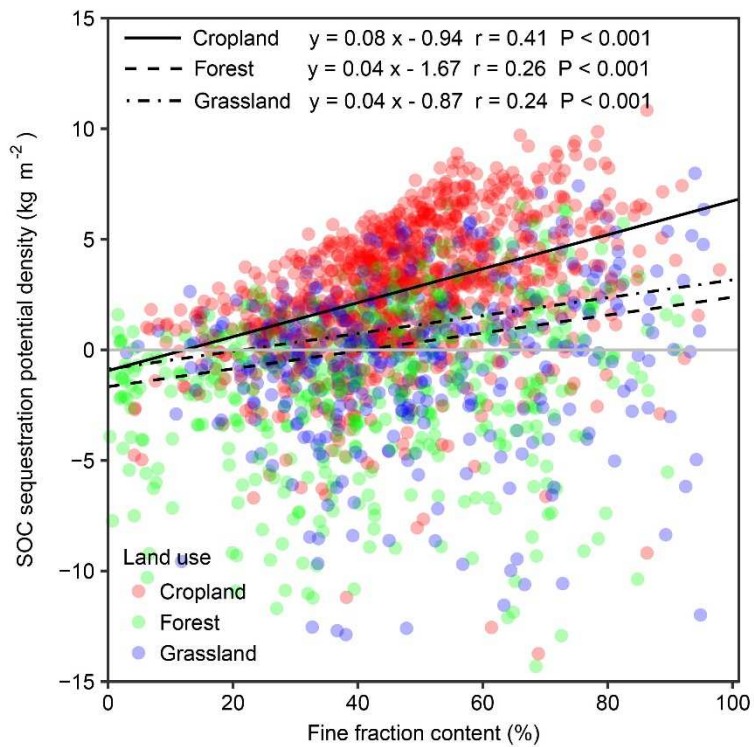
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463 Fig. 1. Relative frequency distribution of SOC_{spd} for three land uses in topsoil (0-30
464 cm). The number of samples is indicated for each land use.

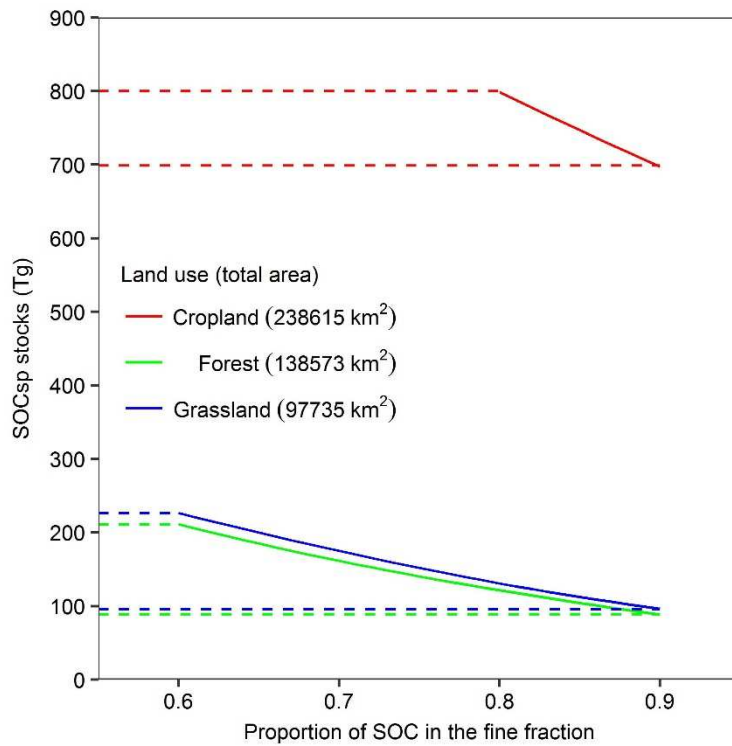


465 Fig. 2. Correlation between the fine fraction content and SOC_{spd}. Solid black lines
466 black dashed line and black dot dashed line dashed black lines are fitted lines for
467 cropland, forest and grassland, respectively.



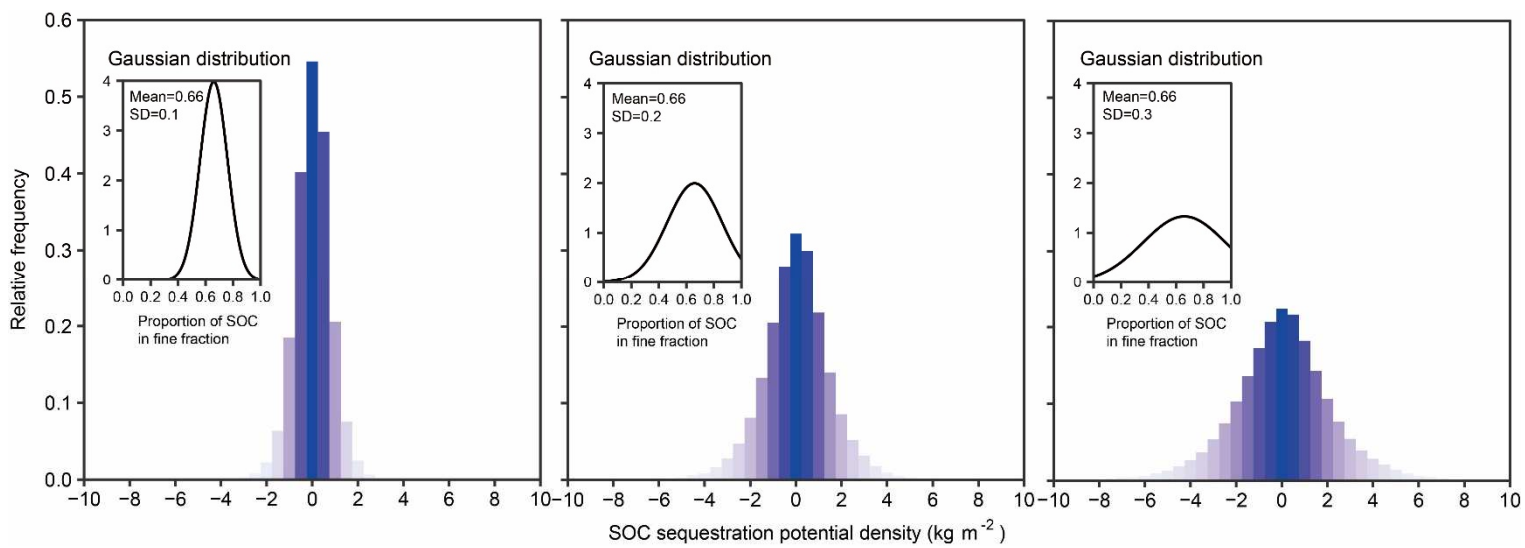
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469 Fig. 3. The influence of the proportion of SOC in the fine fraction on the national
470 estimates of SOC_{spd} stocks in French topsoil. Solid lines show how SOC_{spd} stocks
471 change with proportion of SOC_{fine} under three land uses and dashed lines are the
472 corresponding minimal and maximal SOC_{spd} stocks for each land use.



473

474 Figure 4. Sensitivity analysis: influence of the SOC_{fine} proportion distribution on
475 SOC_{spd}



476

477 Table 1. Proportion of SOC in fine fraction among total SOC for grassland and forest
 478 topsoil (after Chen et al., 2018)

Land use	Country	Sampling depth (cm)	Number of sampling sites	0-20 μm^{a}	0-50 μm^{b}	0-53 μm^{c}	0-63 μm^{d}	Reference
Grassland	USA	0-20	2			0.68		Cambardella and Elliott (1992)
	Canada	0-15	2			0.65		Carter et al. (1998)
	USA	0-20	4			0.80		Conant et al. (2003)
	Belgium	0-20	6		0.58			Accoe et al. (2004)
	France	0-30	2		0.85			Chenu et al. (2004)
	Germany	0-30	1			0.88		John et al. (2005)
	Switzerland	0-20	2				0.60	Leifeld and Fuhrer (2009)
	UK	0-18	1		0.69			Coppin et al. (2009)
	Germany	0-20	11				0.70	Wiesmeier et al. (2014)
Forest	Canada	0-15	1			0.69		Carter et al. (1998)
	France	0-30	1	0.66	0.67			Balesdent et al. (1998)
	France	0-24	5		0.68			Jolivet et al. (2003)
	Germany	0-24(30)	2	0.65				Rumpel et al. (2004)
	Germany	0-25	1			0.56		John et al. (2005)
	Germany	0-20	14				0.66	Wiesmeier et al. (2014)

479 ^a proportion of SOC in 0-20 μm among total SOC content;

480 ^b proportion of SOC in 0-50 μm among total SOC content;

481 ^c proportion of SOC in 0-53 μm among total SOC content;

482 ^d proportion of SOC in 0-63 μm among total SOC content.

