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## Additional soil organic carbon stocks in hedgerows in crop-livestock areas of western France

Valérie Viaud, Tom Künnemann

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## 10 Abstract

11 Mitigating climate change is a critical challenge, and establishing agroforestry systems is identified as  
12 an effective strategy to increase carbon (C) sequestration in agricultural areas. However, the C  
13 storage potential of agroforestry systems, especially hedge agroforestry, still needs to be quantified  
14 in temperate areas. This study was performed in three mixed crop-livestock areas of western France  
15 and focused on hedges planted 20 years ago and on hedges inherited from the traditional hedge  
16 landscape and planted 40-120 years ago. We quantified soil organic carbon (SOC) stocks to a depth of  
17 90 cm in 21 agricultural fields adjacent to a hedge, at 1, 3, 6 and 18 m from the hedge. Additional  
18 SOC storage by hedges were estimated in comparison to a reference plot, which corresponded to the  
19 18-m measurement. SOC storage dynamics was empirically modeled from the measurements. SOC  
20 distribution by particle-size fraction at 0-30 cm depth was also measured. Compared to those in a  
21 reference plot, SOC concentrations and stocks were significantly higher in the adjacent field up to 1  
22 m from the hedge at 0-60 cm depth, and up to 3 m from the hedge at 60-90 cm. However, 56-65% of  
23 the additional SOC was stored at 0-30 cm depth and within 1 m of the hedge. Additional SOC stocks  
24 equaled 30-50% of the C stored in non-harvested biomass. Estimates of SOC accumulation rates over  
25 30 years after tree planting ranged from 0.034-0.096 Mg C yr<sup>-1</sup> per 100 linear m of hedge. In the first  
26 30 cm, 59-85% of the additional SOC was stored in the labile particulate organic matter fraction. Our  
27 study demonstrated hedges' significant potential to store SOC locally around themselves; combined  
28 with other practices to store C, they could help increase C storage potential at the scale of an  
29 agricultural landscape. Results also highlight the high variability in hedge storage potential,  
30 depending on hedge characteristics and intrinsic soil properties, whose underlying controlling  
31 processes remain to be understood.

32

33 *Keywords:* agroforestry systems, shelterbelts, windbreaks, field margins, perennial vegetation, soil  
34 carbon sequestration

## 35 1 Introduction

36 The Intergovernmental Panel on Climate Change (IPCC) recently established that limiting global  
37 warming to 1.5°C above pre-industrial levels implies reaching net zero CO<sub>2</sub> emissions globally by ca.  
38 2050 (Masson-Delmotte et al., 2018). This ambitious goal of balancing anthropogenic greenhouse gas  
39 emissions with ecosystem sequestration of CO<sub>2</sub> is now required in most national and international  
40 climate policies. Soils are the largest terrestrial pool of organic carbon (C), and the IPCC highlights the  
41 relevance of sustainable land management solutions to help achieve this goal (IPCC, 2019). With a  
42 total estimated storage of 2400 Gt of organic C (to a depth of 2 m), soils store 2-3 times as much C as  
43 the atmosphere (Batjes, 1996). As emphasized in the “4 per 1000” initiative – “Soils for Food Security  
44 and Climate” – (<http://4p1000.org>), a slight change in soil organic C (SOC) stocks thus has a large  
45 impact on atmospheric CO<sub>2</sub> concentration. In this context, the major role of reforestation and  
46 planting of trees in agricultural areas is increasingly recognized as one of the most effective solutions  
47 for sequestering C (Zomer *et al.*, 2016; Bastin *et al.*, 2019). Establishing agroforestry systems is an  
48 effective way to plant trees while preserving most area for crop production and providing many  
49 agroecological functions (Moreno *et al.*, 2018; Shi *et al.*, 2018). These systems are complex  
50 agroecosystems that combine woody perennials (e.g. trees or shrubs) and crops or grasslands in the  
51 same land management unit (Nair, 1993). Agroforestry includes a wide range of land uses,  
52 agricultural practices and spatial arrangement of the woody and crop vegetation. Among this  
53 diversity, hedges are an agroforestry system consisting of linear rows of woody perennials planted on  
54 field margins, either on arable land, in ley-arable systems or on permanent grasslands. Despite their  
55 strong decline over the past several decades, due to land-use change and intensive management of  
56 agricultural areas, they remain a dominant agroforestry pattern in many parts of the world and  
57 specifically in northwestern Europe (Baudry *et al.*, 2000; Carlier and Moran, 2019). Recent  
58 agricultural and environmental policies, as well as development of the local fuelwood industry, have  
59 renewed the interest in hedges and prompted new planting and sustainable management of new  
60 and older hedge networks, particularly by emphasizing their role in regulating the global C cycle.

61 The C sequestration potential of agroforestry systems in plant parts and soils has been estimated in  
62 studies in tropical and temperate areas, and reported in recent reviews (Kumar and Nair, 2011;  
63 Lorenz and Lal, 2014; Cardinael et al., 2019) and meta-analyses (Chatterjee et al., 2018; De Stefano  
64 and Jacobson, 2018; Feliciano et al., 2018; Shi et al., 2018). Estimates of SOC accumulation in soils in  
65 agroforestry systems vary widely at the global scale (30-300 Mg C ha<sup>-1</sup> yr<sup>-1</sup> to a depth of 100 cm  
66 (Feliciano *et al.*, 2018)), depending on biophysical context, land use and type of agroforestry system.  
67 On average, Shi et al. (2018) report that SOC stocks are 19% higher than those in crop or grassland  
68 soils. Multiple mechanisms and processes are responsible for the higher SOC stocks in agroforestry  
69 systems than in mono-cropping systems. Trees can increase SOC stocks by increasing aboveground  
70 and belowground organic matter inputs into soils. Belowground biomass represents a particularly  
71 large C input into the soil by incorporating dead roots and exudates, and deep roots can significantly  
72 increase SOC stocks in soil layers deeper than 30 cm (Upson and Burgess, 2013; Germon *et al.*, 2016).  
73 The lower intensity of human management (e.g. tillage) next to the trees than to crops can also favor  
74 SOC stabilization and protection (Udawatta et al., 2008). Variability in an agroforestry system's  
75 potential to sequester SOC is expected, however, depending on inherent soil properties, the age of  
76 the woody perennials, stand structure and management practices, which influence tree productivity  
77 and resulting C inputs into the soil (Albrecht and Kandji, 2003).

78 The distribution of SOC among particle-size fractions also provides important insight into how  
79 agroforestry systems influence the quality and long-term stability of organic matter in soils.  
80 Particulate organic matter (POM), is sensitive to changes in land management practices than total  
81 SOC and is used mainly as indicator of change in the soil ecosystem (Kaschuk *et al.*, 2010). This  
82 fraction tends to respond the most to in-field agroforestry systems (Mao *et al.*, 2012; Baah-  
83 Acheamfour *et al.*, 2015; Ramesh *et al.*, 2015), and may therefore provide early information about  
84 effects of agroforestry on SOC dynamics. However, they generally have a shorter turnover time than  
85 other fractions (Balesdent *et al.*, 2000).

86 Although the potential for hedge systems to store C is acknowledged (Falloon *et al.*, 2004; Follain *et*  
87 *al.*, 2007; Thiel *et al.*, 2015), they have been studied less often than in-field agroforestry, and  
88 quantitative estimates of SOC storage potential remain rare, especially in the European temperate  
89 areas. In addition, data from control plots without trees are not always available, so while SOC stocks  
90 under hedges can be estimated, the additional SOC storage compared to SOC stocks of adjacent  
91 fields cannot always be calculated. Walter *et al.* (2003) estimated SOC stocks for seven hedges,  
92 residuals from traditional “bocage” landscape in Brittany (France). These hedges stored an additional  
93 1-30 Mg C ha<sup>-1</sup> in the first 30 cm in an area 5 m wide on either side of the hedge (i.e. 0.1-3.0 Mg C per  
94 100 linear m (100 m<sup>-1</sup>)), without considering their potential role in controlling soil erosion. Among the  
95 studies available, few knew when the hedges had been planted, which is necessary to estimate  
96 storage dynamics as a function of hedge age. In their review, Arrouays *et al.* (2002) considered the  
97 maximum additional SOC stock at equilibrium in the presence of hedges as 5 Mg C ha<sup>-1</sup> in the first 30  
98 cm, in a landscape with a hedge density of 100 m ha<sup>-1</sup>. Using an exponential equation, they estimated  
99 the mean additional SOC storage rate constant as 0.025 yr<sup>-1</sup>, and the mean net SOC storage rate over  
100 20 years as 0.1 Mg C 100 m<sup>-1</sup> yr<sup>-1</sup>. Using a model, Falloon *et al.* (2004) predicted a mean SOC  
101 accumulation rate of 0.62 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for a 2 m wide hedge in England (i.e. 0.0124 Mg C 100 m<sup>-1</sup>  
102 yr<sup>-1</sup>). Dhillon and Van Rees (2017), studying six hedges planted with different tree species in the  
103 Canadian Prairies measured an additional SOC stock of 5.8-38.0 Mg C ha<sup>-1</sup> at 0-50 cm depth (0.5-3.7  
104 Mg C 100 m<sup>-1</sup>) for hedges ranging in age from 18-31 years. Overall, studies show that larger SOC  
105 stocks are generally measured near hedges than in adjacent plots, but the additional quantities  
106 stored vary greatly.

107 The objective of this study was to assess the contribution of hedge systems to SOC storage. For this,  
108 (1) we quantified SOC stocks and estimated storage dynamics in hedge systems from soil sampling in  
109 three study areas of western France under contrasting soil conditions and for two classes of hedge  
110 age and (2) we assessed potential impacts of hedges on SOC biogeochemical composition in topsoil  
111 using early indicator of SOC response to changes in land management (i.e. POM). This study was

112 based on the hypothesis that SOC stocks next to hedges are larger than those in adjacent fields at  
113 distances beyond which the hedges can influence SOC stocks.

114

## 115 2 Materials and methods

### 116 2.1 Study areas

117 The study was performed in three areas of northwestern France: the “Pays du Roi Morvan” (MO)  
118 next to Gourin (48°08'24.5"N, 3°36'44.2"W), the “Pays des Mauges” (MA) next to Maulevrier  
119 (47°00'36.1"N, 0°44'49.6"W) and the “Pays Vallée de la Sarthe” (SA) next to Le Mans (48°00'52.1"N,  
120 0°13'36.7"E) (Figure 1). The climate in all areas is classified as temperate oceanic (Köppen  
121 classification) but is wetter in MO than in MA or SA (Table 1). Mean SOC concentration is also higher  
122 in MO (Table 1). In each area, we selected hedges from farmers interested in implementing  
123 sustainable management plans for hedges and advised by the Chambers of Agriculture of the  
124 Brittany and Pays de la Loire regions. These hedges are pruned on average every 15 years for fuel  
125 wood production. We distinguished “young” hedges, which had been planted 20 years ago on field  
126 margins that had never had trees and from which wood had never been harvested, from older  
127 hedges, which had been planted 45-120 years ago and which may have experienced several pruning  
128 management cycles. MO, MA and SA contained four (MO1-MO4), five (MA1-MA5) and three (SA1 to  
129 SA3) hedges, respectively. Where possible, the impact of hedges on SOC stocks was assessed on both  
130 sides of hedges, yielding a total of 21 fields adjacent to these hedges. The plots we selected also had  
131 relatively flat topography, to avoid asymmetric soil erosion processes on the two sides, which could  
132 interfere with SOC storage. Vegetation composition, pruning management, soils and adjacent land  
133 use of the hedges were recorded (Table 2).

134

## 2.2 Carbon stocks in aboveground and belowground biomass

C content in biomass was estimated as an indicator in this study to compare to SOC stocks in soils. For each of the 12 hedges, aboveground biomass was estimated using allometric equations. To date, there is no specific equation for estimating the biomass of hedge trees, so for high-stem trees or stems of coppices, we used an equation of Deleuze *et al.* (2014) parameterized for 28 species in French forests.

$$V_t = \frac{H_t * DBH^2}{4 \pi \left(1 - \frac{1.3}{H_t}\right)^2} \times \left( a + b \frac{\sqrt{1.3}}{H_t} + c \frac{H_t}{DBH} \right) \quad (1)$$

where  $V_t$  (m<sup>3</sup>) is total volume of aboveground biomass;  $DBH$  (m) is trunk or stem diameter at 1.30 m (Diameter at Breast Height);  $H_t$  (m) is total trunk height; and  $a$  (unitless),  $b$  (m<sup>0.5</sup>) and  $c$  (unitless) are parameters defined by tree species.

We used the mean values of parameters  $a$ ,  $b$  and  $c$  of Deleuze *et al.* (2014) for deciduous trees: 0.522, 0.661 m<sup>0.5</sup>, and -0.002, respectively. For the trunk of pollard trees, we used another equation of Deleuze *et al.* (2014):

$$V = 0.7 \frac{\pi DBH^2}{4} H \quad (2)$$

where  $V$  (m<sup>3</sup>) is volume of the trunk and  $H$  (m) is trunk height.

Aboveground biomass equaled the total volume of the tree multiplied by the wood density (dry weight per unit volume). Wood density and aboveground biomass C content were assumed to equal 0.546 Mg dry matter m<sup>-3</sup> and 0.475 Mg C Mg<sup>-1</sup> dry matter, according to means calculated by Lousteau (2004) for deciduous trees in France. C stock in aboveground biomass was expressed in Mg C 100 m<sup>-1</sup> of hedges. To estimate belowground biomass, we used a root-expansion factor, defined as the ratio of total biomass to belowground biomass. As recommended by Lousteau (2004) for deciduous trees, we set the root-expansion factor to 1.28.



157 Since most hedges were multispecies, to represent their biomass well, the trunk height and diameter  
158 of each tree planted on a section of each hedge were measured (Table 3). The volume of each tree  
159 was estimated from Eq. 1 or 2. The total volume of the section of the hedge equaled the sum of  
160 individual tree volumes. For pollard trees and coppices, most aboveground biomass is periodically  
161 harvested and used as fuelwood. The C contained in the fraction of harvested and burned biomass  
162 was thus considered as temporarily stored. Relying on field measurements conducted by the  
163 Chambers of Agriculture (unpublished data), we assumed that only 30% of the C stock in the  
164 aboveground biomass is perennial. Since we obtained one estimate per hedge, these data were not  
165 analyzed statistically.

166

### 167 *2.3 Soil sampling protocol and soil analyses*

168 The soil sampling protocol was defined to capture the spatial distribution of SOC stocks in each of the  
169 21 adjacent fields, with sampling points at varying distances from hedges (Figure 2). The soils were  
170 sampled in April 2018, before fertilization and tillage operations for annual crop seeding occurred.  
171 Sampling points were located along three transects perpendicular to the hedge, at fixed distances  
172 from the tree trunks: 1, 3, 6, and 18 m. Root density and the presence of a bank along most hedges  
173 prevented sampling any closer to the trees. At each distance, soil was sampled with a manual auger  
174 from three depths: 0-30, 30-60 and 60-90 cm. For a given distance and depth, the three samples  
175 collected from the three transects were bulked. The composite sample was sieved at 2 mm, air dried  
176 and stored at room temperature. Subsamples were analyzed for particle-size distribution (pipette  
177 method, NF X31-107 (AFNOR, 2003)) and SOC concentration (dry combustion, NF ISO 10694 (AFNOR,  
178 1995)). For the distances 1 and 18 m from the hedge, subsamples from the 0-30 cm depth were  
179 analyzed to determine the C concentration of particle-size fractions, according to a procedure  
180 adapted from Balesdent *et al.* (2000): the soil sample (25 g) was suspended in 100 mL of deionized  
181 water by shaking it along with glass beads for 12 h and then wet-sieved to 53  $\mu\text{m}$  to separate the

182 POM (53-2000  $\mu\text{m}$ ) from the mineral-associated organic matter (MAOM) fraction ( $< 53 \mu\text{m}$ ),  
183 consisting of clay and silt particles. Organic C concentrations in the fractions were determined by dry  
184 combustion (NF ISO 10694 (AFNOR, 1995)), and the SOC concentration in each fraction was  
185 calculated ( $\text{g C kg}^{-1}$  soil).

186 At each sampling point and depth, bulk density was estimated using the pedotransfer functions. We  
187 tested five pedotransfer functions including different numbers of soil parameters (Table 3). The  
188 quality of prediction of these pedotransfer functions was assessed by measuring bulk density in each  
189 field sample 1 and 18 m from the hedge: undisturbed soil was sampled using a manual core sampler  
190 15 cm high with an 8 cm internal diameter. The samples were weighed and dried at  $105 \text{ }^\circ\text{C}$  for 48 h to  
191 determine gravimetric water content and bulk density. Comparison between observed and predicted  
192 values of bulk density was performed using several complementary indices: the mean prediction  
193 error (MPE), the standard deviation of the prediction error (SDPE), the root mean square prediction  
194 error (RMSPE), and the prediction coefficient of determination ( $R^2$ ).

195 SOC stock ( $\text{Mg C ha}^{-1}$ ) for each layer sampled was calculated using the following equation:

$$196 \quad S_z = OC_z \cdot \rho_z \cdot h_z \cdot \left(1 - \frac{Vce_z}{100}\right) \cdot 10^{-1} \quad (3)$$

197 Where  $S_z$  is the SOC stock ( $\text{Mg ha}^{-1}$ ) in layer  $z$ ,  $OC_z$  is the SOC concentration ( $\text{g kg}^{-1}$ ) of fine earth in  
198 layer  $z$ ,  $\rho_z$  is bulk density of fine earth of layer  $z$  ( $\text{g cm}^{-3}$ ),  $h_z$  is the thickness (cm) of layer  $z$ ,  $Vce_z$  is the  
199 volumetric fraction of coarse elements ( $> 2\text{mm}$ ) in layer  $z$ .

200 SOC stock was then calculated for each soil profile by summing the SOC stocks through the soil  
201 profile. The SOC stocks were then adjusted for an equivalent soil mass (Ellert and Bettany, 1995;  
202 Wendt and Hauser, 2013) to enable comparison among distances from the hedge regardless of  
203 differences in bulk density. Based on previous studies in northwestern France (Walter *et al.*, 2003;  
204 Lacoste *et al.*, 2014), we assumed that SOC stock measured 18 m from the hedge was not affected by  
205 hedges; it was therefore considered as the reference SOC stock of the field.

206

#### 207 2.4 SOC data analyses

208 Statistical analyses were performed using R version 3.6.0 (R Core Team, 2018), with differences  
209 considered significant at  $p < 0.05$ . When the data were not normally distributed, the inter-decile  
210 interval (D1-D9) was used to quantify the error. In the analyses, the statistical individual was the  
211 field, (i.e. one side of a hedge). Since SOC concentration measured in each sampling plot may have  
212 been influenced both by agricultural practices in the field and the hedge, each field adjacent to a  
213 hedge was considered a replicate.

214 For each depth, we determined the influence of the distance from the hedge and of hedge age on  
215 SOC concentrations, SOC stocks and SOC distribution in particle-size fractions. We considered age as  
216 a qualitative factor with two classes: young (20 years) and old ( $\geq 40$  years). The sampling design  
217 exhibited specific features: sampling locations were nested by fields, fields nested by hedges, and  
218 hedges nested by study sites. To analyze this design, we fit mixed-linear models testing the effects of  
219 distance, age class and their interaction on the SOC concentrations and SOC stocks of the soil layers:  
220 distance and age class were the main fixed effects, with study area, and fields as a random effect (R  
221 package nlme (Pinheiro *et al.*, 2018)). The Shapiro-Wilk test was used to check the normality of data  
222 distributions. Data were log-transformed when necessary. When the required assumptions were  
223 met, ANOVA was performed on these models, and the Tukey HSD test was used for post-hoc  
224 pairwise comparisons (R package multcomp (Bretz *et al.*, 2011)). When ANOVA assumptions were  
225 not met, we performed the non-parametric Friedman test (R package agricolae (de Mendiburu,  
226 2017)).

227 For the distances at which SOC stocks differed significantly from those measured 18 m from the  
228 hedge, we calculated the additional SOC stock due to the hedge ( $\text{Mg C ha}^{-1}$ ) as the SOC stock  
229 measured at the given distance minus the reference SOC stock in the field.

$$230 \quad \Delta S_d^f = S_d^f - S_{18}^f \quad (4)$$

231 where  $\Delta S$  is additional SOC stock ( $\text{Mg C ha}^{-1}$ ) at distance  $d$  from the hedge (with  $d = 1, 3$  or  $6$  m) in  
232 field  $f$ ,  $S_d^f$  is SOC stock ( $\text{Mg C ha}^{-1}$ ) measured at distance  $d$  in field  $f$ , and  $S_{18}^f$  is the reference SOC stock  
233 ( $\text{Mg C ha}^{-1}$ ) in field  $f$  measured 18 m from the hedge.

234 Total additional SOC stock in the field ( $\text{Mg C } 100 \text{ m}^{-1}$  of hedge) was calculated by summing SOC stocks  
235 over the distance affected by the hedge, assuming that SOC stock was homogeneously distributed  
236 within 1 m of the hedge and then decreased exponentially from 1 m to the longest distance affected  
237 by the hedge. A statistical analysis similar to that presented above and accounting for the specific  
238 sampling design was implemented to determine the influence of hedge age on additional SOC stocks.

239 Assuming a first-order one-compartment model, based on a first-order exponential decay function,  
240 mean SOC stock accumulation rate  $F$  ( $\text{Mg C } 100 \text{ m}^{-1} \text{ yr}^{-1}$ ) for a period  $T$  (yr) after hedge planting was  
241 calculated by the following equation:

$$242 \quad F(T) = \frac{C_{\text{hedge}}(T) - C_{\text{ref}}(T)}{T} = \Delta \left( \frac{1 - \exp(-kT)}{T} \right) \quad (5)$$

243 where  $C_{\text{hedge}}(T)$  ( $\text{Mg C } 100 \text{ m}^{-1}$ ) is SOC stock under the hedge at  $T$ ,  $C_{\text{ref}}(T)$  is the reference SOC stock at  
244  $T$  ( $\text{Mg C } 100 \text{ m}^{-1}$ ), the range  $\Delta$  is the difference in SOC stock at equilibrium between the hedge and  
245 the reference plot ( $C_{\text{eq\_hedge}} - C_{\text{eq\_ref}}$ ) ( $\text{Mg C } 100 \text{ m}^{-1}$ ), and  $k$  is the decay rate constant ( $\text{yr}^{-1}$ ).

246 We assumed that SOC stocks at 1 m from hedges planted more than 100 years ago had reached  
247 equilibrium; the range  $\Delta$  was thus derived from the additional SOC stocks estimated for these  
248 hedges.  $F$  was calculated from the additional SOC stocks estimated for young hedges; given  $F$  and  $\Delta$ ,  
249 parameter  $k$  was derived from our dataset. We simulated mean annual SOC accumulation rates over  
250 15 and 30 years (i.e. one and two pruning management cycles, respectively).

251

## 252 3 Results

### 253 3.1 Carbon stocks in aboveground and belowground biomass

254 In the study areas, estimated C stocks in the aboveground biomass of hedges ranged from 1.2-21.6  
255 Mg C 100 m<sup>-1</sup> depending on hedge management, tree density and age class (Table 4). They ranged  
256 from 0.7-6.1 Mg C 100 m<sup>-1</sup> in belowground biomass. The largest perennial stocks (10.1-15.2 Mg C 100  
257 m<sup>-1</sup>) were estimated for older high-stem hedges.

258

### 259 3.2 SOC concentrations

260 Mean SOC concentrations at 0-30 cm depth were 3.7, 2.1 and 1.6 g C kg<sup>-1</sup>, in MO, MA and SA,  
261 respectively. SOC concentrations decreased significantly with increasing depth at all distances from  
262 the hedge.

263 Hedge age class and its interaction with distance from the hedge had no significant impact on SOC  
264 concentrations, which depended significantly only on distance for all depths and all study areas  
265 (Table 5). In the 0-30 and 30-60 cm layers, SOC concentration was significantly higher 1 m from the  
266 hedge than that 3, 6 or 18 m from the hedge. Mean SOC concentrations were 30.7 g kg<sup>-1</sup> for soils  
267 sampled 1 m from the hedge and 22.3 g C kg<sup>-1</sup> for the other distances at 0-30 cm depth; they were  
268 11.9 g C kg<sup>-1</sup> 1 m from the hedge and 6.5 g C kg<sup>-1</sup> for the other distances at 30-60 cm (Figure 3). In the  
269 60-90 cm layer, mean SOC concentration measured 1 m from the hedge was significantly higher than  
270 that 6 and 18 m from the hedge, while that 3 m from the hedge was intermediate (5.1, 2.9 and 2.7 g  
271 C kg<sup>-1</sup>, at 1, 3 and ≥ 6 m from the hedge, respectively). SOC concentration 1 m from the hedge varied  
272 the most.

273

274           3.3   *SOC stocks*

275   The quality of the fit of the pedotransfer function for bulk density are presented in Table 3. To  
276   compute SOC stocks, we took on the predictions of the function from Manrique and Jones (1991),  
277   which presented the best fit to measured data.

278   SOC stocks decreased significantly with increasing depth at all distances from the hedge. Hedge age  
279   class and its interaction with distance had no significant impact on SOC stocks, which depended  
280   significantly only on distance for all depths and all study areas (Table 5). In the 0-30 and 30-60 cm  
281   layers, SOC stock was significantly larger 1 m from the hedge than that 3, 6 or 18 m from the hedge  
282   (Figure 4). Mean SOC stocks were 84.8 Mg C ha<sup>-1</sup> for soils sampled 1 m from the hedge and 63.2 Mg C  
283   ha<sup>-1</sup> for the other distances in the 0-30 cm layer; they were 46.8 Mg C ha<sup>-1</sup> 1 m from the hedge and  
284   31.5 Mg C ha<sup>-1</sup> for the other distances in the 30-60 cm layer. In the 60-90 cm horizon, mean SOC  
285   stock was significantly larger 1 m from the hedge (23.8 Mg C ha<sup>-1</sup>) than that 6 and 18 m from the  
286   hedge (14.2 Mg C ha<sup>-1</sup>), while that 3 m from the hedge was intermediate (14.5 Mg C ha<sup>-1</sup>).

287

288           3.4   *Additional SOC storage around hedges*

289   Since study area had a statistically significant influence on additional SOC storage by hedges, results  
290   from MO area were analyzed separately from those from SA and MA area. Additional SOC storage by  
291   hedges at 1 and 3 m from the hedge (where hedges significantly influenced SOC concentrations and  
292   stocks) varied greatly between distances and among depths (Table 6). Hedge age class had no  
293   significant effect on additional SOC stocks except in the first 30 cm 3 m from the hedge, with mean  
294   additional SOC stock significantly larger for old hedges (34.4 Mg C ha<sup>-1</sup>, all areas combined) than  
295   young ones (17.9 Mg C ha<sup>-1</sup>, all areas combined). In a depth of 0-30 cm, hedges in MO had  
296   significantly larger mean additional SOC stock (49.0 Mg C ha<sup>-1</sup>) than those in SA and MA. Mean  
297   additional SOC stock at 0-30 cm depth up to 3 m from the hedge ranged from 0.54 Mg C 100 m<sup>-1</sup> for  
298   young hedges in MA and SA to 2.64 Mg C 100 m<sup>-1</sup> for old hedges in MO (Table 6). In the 0-90 cm

299 layer, it ranged from 0.81-4.71 Mg C 100 m<sup>-1</sup>. Additional SOC stock in the 0-30 cm layer equaled 30 to  
300 50% of the total additional SOC stock in the soil profile.

301

### 302 3.5 SOC storage dynamics

303 Estimates of parameters  $\Delta$  and  $k$ , as well as of net annual storage fluxes for 15 and 30 years after  
304 hedge planting, varied with depth and among study areas (Table 8). Median reference C stocks at 0-  
305 90 cm depth were 151.5 and 82.2 Mg C ha<sup>-1</sup> in MO and MA-SA, respectively (i.e. 9.1 and 4.9 Mg C,  
306 respectively in a 100 m × 6 m area, which corresponds to the area of influence on both sides of the  
307 hedge). Thus, our results indicated that annual additional SOC storage equals 1.3% and 0.9% of the  
308 reference stock in a 100 m × 6 m area, which corresponds to the influence of hedges in MO and  
309 MA/SA, respectively, 15 years after hedge planting. Assuming a landscape composed of 1 ha square  
310 fields (100 m × 100 m) enclosed by hedges (400 m of hedges around each field), hedges would  
311 increase initial SOC stocks at the field scale by 0.15% and 0.10% per year in MO and MA-SA,  
312 respectively, after 15 years (mean annual SOC accumulation rate over 15 years estimated for 100 m  
313 of hedge multiplied by 4, and divided by 2, because each field is only concerned by one side of  
314 hedge). Assuming 5 ha square fields (223.6 m × 223.6 m) enclosed by hedges, hedges would increase  
315 initial SOC stocks at the field scale by 0.07% and 0.05% per year in MO and MA-SA, respectively, after  
316 15 years.

317

### 318 3.6 Distribution of SOC in particle-size fractions

319 Distribution of C in particle-size fractions was assessed only in the first 30 cm 1 and 18 m from the  
320 hedge (Figure 5). In all study areas, mean SOC concentration in the POM fraction was significantly  
321 higher 1 m than 18 m from the hedge ( $p < 0.001$  in MA and SA,  $p < 0.001$  in MO). In MA and SA, mean  
322 SOC concentration in the MAOM fraction was similar 1 and 18 m from the hedge. Conversely, in MO,

323 it was significantly higher 1 m than 18 m from the hedge ( $p < 0.01$ ). On average, the POM fraction  
324 contained 59% and 85% of additional SOC stored in the first 30 cm 1 m from the hedge in MO and  
325 MA/SA, respectively. Age class had no significant effect on SOC concentrations in POM or MAOM  
326 fractions.

327

## 328 4 Discussion

### 329 4.1 *Spatial and depth distribution of SOC around hedges*

330 The general objective was to quantify additional SOC storage due to hedges in mixed crop-livestock  
331 agricultural landscapes of western France, given the range of climate conditions and soil  
332 characteristics (primarily reference SOC stock) in this area. Our study was performed in areas where  
333 many hedges, traditional landscape structures, have been razed since the 1940s; however, new  
334 dynamics of hedge planting have emerged there in the past 20 years. Simultaneous study of hedges  
335 with contrasting planting age enabled us to assess dynamics of SOC storage around hedges.

336 As expected, higher SOC concentrations were measured in MO than in the two other areas. These  
337 concentrations were slightly higher than those reported in national soil observation databases for  
338 these areas (Table 1).

339 In the hedge systems studied, the 0-90 cm soil profile stored a substantial amount of C: additional  
340 SOC stocks in soils equaled 30-50% of the C stored in non-harvested biomass. Soils under hedges  
341 generally had higher SOC concentrations and larger SOC stocks than the adjacent agricultural fields  
342 did. Similar trends have been observed for hedges (Walter *et al.*, 2003; Follain *et al.*, 2007; Lacoste *et*  
343 *al.*, 2014; Dhillon and Van Rees, 2017; Pardon *et al.*, 2017) and in other agroforestry systems in which  
344 trees are incorporated into fields (Shi *et al.*, 2018).



345 Like Bambrick *et al.* (2010) and Cardinael *et al.* (2015), who studied intercropping agroforestry  
346 systems, our sampling strategy was designed to capture the spatial extent and depth distribution of  
347 trees' impact on additional SOC storage. While additional SOC stocks accumulated mainly in the first  
348 30 cm and laterally within 1 m of each side of the hedge, where they represented 55-65% of the total  
349 additional SOC stored, hedge influence on SOC concentrations and stocks extended at least 1 m at 0-  
350 60 cm depth and up to 3 m at 60-90 cm depth. These results suggest that hedges add significant  
351 amounts of organic matter to the soil at depth and relatively distant from the tree line, presumably  
352 derived from roots and rhizodeposits (Lorenz and Lal, 2014) or from surface litter, roots and leaching  
353 of dissolved organic C (Usselman *et al.*, 2007). Although these deep SOC stocks were small, and  
354 organic matter input into deep soil layers may increase C losses through a priming effect (Cheng *et al.*  
355 *et al.*, 2014), they may be critical to a long-term increase in SOC stocks when soil depth does not limit  
356 root development. Indeed, deep SOC stocks generally have higher residence time than shallower  
357 stocks and may be less vulnerable to land-use change (Balesdent *et al.*, 2017).

358 One limitation of our study is that our sampling strategy was not designed to fully assess uncertainty  
359 in SOC stocks evaluation, and especially uncertainty associated with bulk density estimation. As  
360 reported in several papers (e.g. Wiesmeier *et al.*, 2012; von Haden *et al.*, 2020), bulk density is a  
361 critical parameter for the accurate estimation of SOC stocks at the scale of hedges or fields. Bulk  
362 density varies much in space at the field or hedge scale. Specific evaluation of bulk density variability.  
363 This study could therefore be strengthened in the future by implementing an exhaustive  
364 uncertainty analysis.

365

#### 366 4.2 Additional SOC storage by hedges

367 We observed high variability in additional SOC storage potential within and between study areas. MO  
368 had additional SOC storage potential three times as high as that in MA and SA, which may be  
369 explained in part by higher biomass production and presumably higher C inputs into the soil from

370 litter and roots for the hedges sampled. However, this result questions the concept of SOC saturation  
371 limit and its definition (Hassink, 1997; Stewart *et al.*, 2007), since the agricultural fields with the  
372 largest reference SOC stocks had the highest potential to store SOC, regardless of soil texture.  
373 Further characterization of SOC would be required to investigate the high potential of soils for C  
374 storage in MO area.

375 Overall, the additional SOC stocks estimated in MA and SA were lower than those reported in most  
376 studies, while those in MO were in the same order of magnitude as the highest values observed in  
377 similar contexts. Indeed, the largest mean additional SOC stock estimated for old hedges in MO (4.71  
378 Mg C 100 m<sup>-1</sup>) was similar to those reported in the review of Arrouays *et al.* (2002), who estimated  
379 maximum additional SOC storage by hedges as 5 Mg C 100 m<sup>-1</sup>. The mean annual SOC accumulation  
380 rate estimated over 30 years for the entire soil profile in MA and SA (0.034 Mg C 100 m<sup>-1</sup> yr<sup>-1</sup>) was  
381 lower than those estimated by Dhillon and Van Rees (2017) for hedges ca. 30 years old in the  
382 Canadian Prairies (0.07-0.19 Mg C 100 m<sup>-1</sup> yr<sup>-1</sup>); in contrast, the rate estimated for MO (0.096 Mg C  
383 100 m<sup>-1</sup> yr<sup>-1</sup>) did lay within the range they estimated. In the first 0-30 cm, the mean SOC accumulation  
384 rate estimated over 30 years in MO (0.029 Mg C 100 m<sup>-1</sup> yr<sup>-1</sup>) was consistent with results of a recent  
385 study of the C storage potential of soils in France (0.72 Mg C ha<sup>-1</sup> yr<sup>-1</sup>, over a 5 m width, equals 0.036  
386 Mg C 100 m<sup>-1</sup> yr<sup>-1</sup> over 25 years at 0-40 cm depth) (Pellerin *et al.*, 2019). The mean SOC accumulation  
387 rate estimated over 15 years in MA and SA areas (0.008 Mg C 100 m<sup>-1</sup> yr<sup>-1</sup>) was also consistent with  
388 the value reviewed by for accumulation rates after conversion from cropland to hedgerow under  
389 temperate climate in Europe (0.15 Mg C ha<sup>-1</sup> yr<sup>-1</sup> equals 0.008 Mg C 100 m<sup>-1</sup> yr<sup>-1</sup> over 14 years on  
390 average at 0-30 cm depth) (Cardinael *et al.*, 2019). When considering the entire soil profile, the mean  
391 SOC accumulation rate in MA and SA was consistent with this estimate, but that of MO was higher  
392 than it. According to our estimations, at the landscape scale, the contribution of hedges to the  
393 mitigation of climate change by the storage of C in the soils is moderate compared to the guide value  
394 of 4‰. The annual additional SOC storage rate estimated in the study areas was of one order of  
395 magnitude lower. Additional SOC storage represented one third to two thirds of C perennial storage

396 in biomass. Besides, in addition to providing C inputs to the soil, enhancing soil fertility and climate  
397 change mitigation, hedges contributes to other environmental and agricultural benefits from farm- to  
398 landscape scale, which have to be considered together.

399 In addition to the hedge ages and soil-climate context that we studied, several other factors may  
400 have induced variability in the SOC storage potential of hedges. The hedges studied had a variety of  
401 management practices and were composed of a variety woody perennial species (Table 2). While the  
402 impact of these factors on SOC storage in agroforestry systems is recognized in the literature (Kumar  
403 and Nair, 2011; Adhikary *et al.*, 2017), our sample size was too small to assess the impact of these  
404 factors and their interactions with hedge age class or soil-climate conditions on SOC stocks, spatial  
405 distribution and quality. In a general perspective, however, we described the composition, structure  
406 and estimated C stocks in the biomass of hedges, which may help to compare our results to those  
407 from other agroecosystems or from the many studies that examine impacts of hedges or other  
408 agroforestry systems on SOC stocks. Likewise, although the study was performed on crop-livestock  
409 farms, whose crop rotations in sampled fields included annual crops and grasslands, the sampling  
410 strategy could not differentiate hedge impact on SOC storage as a function of land use in the  
411 adjacent field. Unlike Pellerin *et al.* (2019), who assumed that hedges associated with grasslands  
412 stored no additional SOC (but emphasized a lack of data about such hedges), we observed additional  
413 SOC storage under all of the hedges studied, including those in grasslands. However, additional  
414 quantitative data from grassland hedges will be necessary to validate these observations.

#### 415 *4.3 SOC in labile organic matter fractions*

416 We verified in this study that labile SOC in POM was an indicator sensitive to land-use change such as  
417 hedge planting. Additional SOC was located mainly in the labile fractions of POM, which is not closely  
418 associated with soil minerals, but rather dominated by relatively fresh, undecomposed plant  
419 residues. It may also include fungal hyphae, seeds, spores and exoskeletons (Baldock and Skjemstad,  
420 1999). This macro-organic matter decomposes faster than total soil organic matter, meaning that

421 additional SOC storage may be sustainable only if hedges maintain C inputs into the soil over time  
422 (i.e. they are managed sustainably and produce large amounts of biomass).

423 In MO, some additional SOC stocks were also located in the MAOM fraction, which suggests that SOC  
424 storage potential and its underlying processes differ between MO and MA or SA. In MO, specific  
425 climate conditions or land-use history may have influenced SOC stabilization and turnover in soils.  
426 Specific processes, unrelated or indirectly related to hedges, may act in the agricultural, soil and  
427 climate conditions of MO to stabilize organic matter added to the soil (Balesdent *et al.*, 2000; Chenu  
428 *et al.*, 2019). These processes need to be investigated adequately. Nonetheless, our results show that  
429 additional SOC storage by hedges may be related to hedge characteristics (e.g. age) but also depend  
430 greatly on the intrinsic characteristics of soil storage potential.

431

## 432 5 Conclusion

433 This study provided additional data on the potential of hedge agroforestry systems to increase SOC  
434 stocks in crop-livestock systems of western France, which combine annual crops and grasslands. SOC  
435 stocks under hedges were larger than those in adjacent agricultural fields, but varied greatly within  
436 and among the three study areas. While most additional SOC stocks were located in the first 30 cm  
437 and laterally up to 1 m from hedge, hedges can increase SOC stocks in the entire 0-90 cm soil profile  
438 and up to 3 m from the trees. Depending on the study area, most or nearly all additional SOC was  
439 stored in a labile fraction. Overall, our results highlight the benefits of hedge systems in significantly  
440 increasing SOC accumulation locally around hedges. Sustainable SOC storage requires sustainable  
441 management of hedges to ensure regular C inputs into the soil. Combined with other agricultural  
442 practices and with other types of semi-natural and cultivated vegetation, they can help increase SOC  
443 storage in agricultural landscapes. Finally, this study also emphasizes the need for future research to

444 investigate the respective control of climate, soil and management factors on SOC storage processes  
445 in agroforestry systems.

446

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## 453 **Appendix A. Supplementary data**

454 Supplementary material related to this article can be found in the online version.

455

## 456 **References**

- 457 Adhikary, P.P., Hombegowda, H.C., Barman, D., Jakhar, P., Madhu, M., 2017. Soil erosion control and  
458 carbon sequestration in shifting cultivated degraded highlands of eastern India: performance  
459 of two contour hedgerow systems. *Agrofor. Syst.* 91, 757-771.
- 460 AFNOR, 1995. NF ISO 10694. Soil Quality — Determination of Organic and Total Carbon after Dry  
461 Combustion (Elementary Analysis).
- 462 AFNOR, 2003. NF X31-107. Soil Quality - Particle Size Determination by Sedimentation - Pipette  
463 Method.
- 464 Albrecht, A., Kandji, S.T., 2003. Carbon sequestration in tropical agroforestry systems. *Agric. Ecosyst.*  
465 *Environ.* 99, 15-27.

466 Alexander, E.B., 1980. Bulk densities of California soils in relation to other soil properties. *Soil Sci.*  
467 *Soc. Am. J.* 44, 689-692.

468 Arrouays, D., Balesdent, J., Germon, J.C., Payet, P.A., Soussana, J.F., Stengel, P., 2002. Contribution à  
469 la lutte contre l'effet de serre, Stocker du carbone dans les sols agricoles de France ? Synthèse.  
470 In: INRA (Ed.), Expertise collective, Paris, p. 36.

471 Baah-Acheamfour, M., Chang, S.X., Carlyle, C.N., Bork, E.W., 2015. Carbon pool size and stability are  
472 affected by trees and grassland cover types within agroforestry systems of western Canada.  
473 *Agric. Ecosyst. Environ.* 213, 105-113.

474 Baldock, J.A., Skjemstad, J.O., 1999. Role of the mineral phase for stabilization of organic matter in  
475 soils and sediments. *Abstr. Pap. Am. Chem. Soc.* 217, U838–U838.

476 Balesdent, J., Basile-Doelsch, I., Chadoeuf, J., Cornu, S., Fekiacova, Z., Fontaine, S., Guenet, B., Hatte,  
477 C., 2017. Turnover of deep organic carbon in cultivated soils: an estimate from a review of  
478 isotope data. *Biotechnologie, Agronomie, Société et Environnement / Biotechnology,*  
479 *Agronomy, Society and Environment* 21, 181-190.

480 Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical  
481 protection and tillage. *Soil Tillage Res.* 53, 215-230.

482 Bambrick, A.D., Whalen, J.K., Bradley, R.L., Cogliastro, A., Gordon, A.M., Olivier, A., Thevathasan,  
483 N.V., 2010. Spatial heterogeneity of soil organic carbon in tree-based intercropping systems in  
484 Quebec and Ontario, Canada. *Agrofor. Syst.* 79, 343-353.

485 Bastin, J.-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C.M., Crowther,  
486 T.W., 2019. The global tree restoration potential. *Science* 365, 76-79.

487 Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. *Eur. J Soil Sci.* 47, 151-163.

488 Baudry, J., Bunce, R.G.H., Burel, F., 2000. Hedgerows: An international perspective on their origin,  
489 function and management. *J. Environ. Manag.* 60, 7-22.

490 Bretz, F., Hothorn, T., Westfall, P., 2011. Multiple comparisons using R. Chapman and Hall/CRC, New-  
491 York.

492 Cardinael, R., Chevallier, T., Barthès, B.G., Saby, N.P.A., Parent, T., Dupraz, C., Bernoux, M., Chenu, C.,  
493 2015. Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil  
494 organic carbon — A case study in a Mediterranean context. *Geoderma* 259-260, 288-299.

495 Cardinael, R., Umulisa, V., Toudert, A., Olivier, A., Bockel, L., Bernoux, M., 2019. Revisiting IPCC Tier 1  
496 coefficients for soil organic and biomass carbon storage in agroforestry systems (vol 13,  
497 124020, 2018). *Environ. Res. Letters* 14

498 Carlier, J., Moran, J., 2019. Hedgerow typology and condition analysis to inform greenway design in  
499 rural landscapes. *J. Environ. Manag.* 247, 790-803.

500 Chatterjee, N., Nair, P.K.R., Chakraborty, S., Nair, V.D., 2018. Changes in soil carbon stocks across the  
501 Forest-Agroforest-Agriculture/Pasture continuum in various agroecological regions: A meta-  
502 analysis. *Agric. Ecosyst. Environ.* 266, 55-67.

503 Cheng, W.X., Parton, W.J., Gonzalez-Meler, M.A., Phillips, R., Asao, S., McNickle, G.G., Brzostek, E.,  
504 Jastrow, J.D., 2014. Synthesis and modeling perspectives of rhizosphere priming. *New Phytol.*  
505 201, 31-44.

506 Chenu, C., Angers, D.A., Barre, P., Derrien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic  
507 stocks in agricultural soils: Knowledge gaps and potential innovations. *Soil Tillage Res.* 188, 41-  
508 52.

509 de Mendiburu, F., 2017. agricolae: Statistical Procedures for Agricultural Research. [https://CRAN.R-](https://CRAN.R-project.org/package=agricolae)  
510 [project.org/package=agricolae](https://CRAN.R-project.org/package=agricolae)

511 De Stefano, A., Jacobson, M.G., 2018. Soil carbon sequestration in agroforestry systems: a meta-  
512 analysis. *Agrofor. Syst.* 92, 285-299.

513 Deleuze, C., Morneau, F., Renaud, J.P., Vivien, Y., Rivoire, M., Santenoise, P., Longuetaud, F., Mothe,  
514 F., Hervé, J.C., Vallet, P., 2014. Estimer le volume total d'un arbre, quelles que soient l'essence,  
515 la taille, la sylviculture, la station. *Rendez-vous Techniques ONF*, 22-32 <hal-01143797>.

516 Dhillon, G.S., Van Rees, K.C.J., 2017. Soil organic carbon sequestration by shelterbelt agroforestry  
517 systems in Saskatchewan. *Can. J. Soil Sci.* 97, 394-409.

518 Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under  
519 contrasting management regimes. *Can. J. Soil Sci.* 75, 529-538.

520 Falloon, P., Powlson, D., Smith, P., 2004. Managing field margins for biodiversity and carbon  
521 sequestration: a Great Britain case study. *Soil Use Manage.* 20, 240-247.

522 Federer, C.A., 1983. Nitrogen mineralization and nitrification: Depth variation in four New England  
523 forest soils. *Soil Sci. Soc. Am. J.* 47, 1008-1014.

524 Feliciano, D., Ledo, A., Hillier, J., Nayak, D.R., 2018. Which agroforestry options give the greatest soil  
525 and above ground carbon benefits in different world regions? *Agric. Ecosyst. Environ.* 254, 117-  
526 129.

527 Follain, S., Walter, C., Legout, A., Lemerrier, B., Dutin, G., 2007. Induced effects of hedgerow  
528 networks on soil organic carbon storage within an agricultural landscape. *Geoderma* 142, 80-  
529 95.

530 Germon, A., Cardinael, R., Prieto, I., Mao, Z., Kim, J., Stokes, A., Dupraz, C., Laclau, J.P., Jourdan, C.,  
531 2016. Unexpected phenology and lifespan of shallow and deep fine roots of walnut trees  
532 grown in a silvoarable Mediterranean agroforestry system. *Plant Soil* 401, 409-426.

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

535 IPCC, 2019. Climate change and land. An IPCC Special Report on Climate Change, Desertification,  
536 Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in  
537 Terrestrial Ecosystems.

538 IUSS Working Group WRB. 2015. World Reference Base for Soil Resources 2014, update 2015  
539 International soil classification system for naming soils and creating legends for soil maps.  
540 World Soil Resources Reports No. 106. FAO, Rome

541 Kaschuk, G., Alberton, O., Hungria, M., 2010. Three decades of soil microbial biomass studies in  
542 Brazilian ecosystems: Lessons learned about soil quality and indications for improving  
543 sustainability. *Soil Biol. Biochem.* 42, 1-13.



544 Kaur, R., Kumar, S., Gurung, H.P., 2002. A pedo-transfer function (PTF) for estimating soil bulk density  
545 from basic soil data comparison with existing PTFs. *Aust. J. Soil Res.* 40, 847-857.

546 Kumar, B.M., Nair, P.K.R., 2011. Carbon Sequestration Potential of Agroforestry Systems  
547 Opportunities and Challenges Preface. In: Kumar, B.M., Nair, P.K.R. (Eds.), *Carbon*  
548 *Sequestration Potential of Agroforestry Systems: Opportunities and Challenges*. Springer,  
549 Dordrecht, pp. V-VI.

550 Lacoste, M., Minasny, B., McBratney, A., Michot, D., Viaud, V., Walter, C., 2014. High resolution 3D  
551 mapping of soil organic carbon in a heterogeneous agricultural landscape. *Geoderma* 213, 296-  
552 311.

553 Leonaviciute, N., 2000. Predicting soil bulk and particle densities by pedotransfer functions from  
554 existing soil data in Lithuania. *Geosgrafijos metrastis* 33, 317-330.

555 Lorenz, K., Lal, R., 2014. Soil organic carbon sequestration in agroforestry systems. A review. *Agron.*  
556 *Sustain. Dev.* 34, 443-454.

557 Lousteau, D., 2004. Rapport final du projet CARBOFOR. Séquestration de Carbone dans les grands  
558 écosystèmes forestiers en France. Quantification, spatialisation, vulnérabilité et impacts de  
559 différents scénarios climatiques et sylvicoles. INRA, Bordeaux, p. 138.

560 Manrique, L.A., Jones, C.A., 1991. Bulk-density of soils in relation to soil physical and chemical-  
561 properties. *Soil Sci. Soc. Am. J.* 55, 476-481.

562 Mao, R., Zeng, D.H., Li, L.J., Hu, Y.L., 2012. Changes in labile soil organic matter fractions following  
563 land use change from monocropping to poplar-based agroforestry systems in a semiarid region  
564 of Northeast China. *Environ. Monit. Assess.* 184, 6845-6853.

565 Masson-Delmotte, V., Zhai, P., Matthews, H.-O., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock,  
566 T., Tignor, M., Waterfield, T., 2018. Global Warming of 1.5°C. An IPCC Special Report on the  
567 impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse  
568 gas emission pathways, in the context of strengthening the global response to the threat of  
569 climate change, sustainable development, and efforts to eradicate poverty [ (eds.)].

570 Moreno, G., Aviron, S., Berg, S., Crous-Duran, J., Franca, A., de Jalon, S.G., Hartel, T., Mirck, J.,  
571 Pantera, A., Palma, J.H.N., Paulo, J.A., Re, G.A., Sanna, F., Thenail, C., Varga, A., Viaud, V.,  
572 Burgess, P.J., 2018. Agroforestry systems of high nature and cultural value in Europe: provision  
573 of commercial goods and other ecosystem services. *Agrofor. Syst.* 92, 877-891.

574 Nair, P.K.R., 1993. *An introduction to agroforestry*. Springer Netherlands.

575 Pardon, P., Reubens, B., Reheul, D., Mertens, J., De Frenne, P., Coussement, T., Janssens, P.,  
576 Verheyen, K., 2017. Trees increase soil organic carbon and nutrient availability in temperate  
577 agroforestry systems. *Agric. Ecosyst. Environ.* 247, 98-111.

578 Pellerin, S., Bamière, L., Launay, C., Martin, R., Schiavo, M., Angers, D., Augusto, L., Balesdent, J.,  
579 Basile-Doelsch, I., Bellassen, V., Cardinael, R., Cécillon, L., Ceschia, E., Chenu, C., Constantin, J.,  
580 Darroussin, J., Delacote, P., Delame, N., Gastal, F., Gilbert, D., Graux, A.-I., Guenet, B., Houot,  
581 S., Klumpp, K., Letort, E., Litrico, I., Martin, M., Menasseri, S., Mézière, D., Morvan, T., Mosnier,  
582 C., Roger-Estrade, J., Saint-André, L., Sierra, J., Théron, O., Viaud, V., Gâteau, R., Le Perchec,  
583 S., Savini, I., Réchauchère, O., p., 2019. Stocker du carbone dans les sols français, Quel  
584 potentiel au regard de l'objectif 4 pour 1000 et à quel coût ? Synthèse du rapport d'étude,  
585 INRA (France) INRA, p. 114.

586 Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., and R Core Team. 2018. nlme: Linear and Nonlinear  
587 Mixed Effects Models. R package version 3.1-140.

588 Ramesh, T., Manjaiah, K.M., Mohopatra, K.P., Rajasekar, K., Ngachan, S.V., 2015. Assessment of soil  
589 organic carbon stocks and fractions under different agroforestry systems in subtropical hill  
590 agroecosystems of north-east India. *Agrofor. Syst.* 89, 677-690.

591 Saby, N., Foucaud Lemerceir, B., Arrouays, D., Lemenager, S., Louis, B., Millet, F., Paroissien, J.-B.,  
592 Schellenberger, E., Squidant, H., Swiderski, C., Toutain, B., Walter, C., Bardy, M., 2014. Le  
593 programme Base de Données des Analyses de Terre (BDAT) : Bilan de 20 ans de collecte de  
594 résultats d'analyses. *Etude et Gestion des Sols* 21, 141-150.

595 Shi, L.L., Feng, W.T., Xu, J.C., Kuzyakov, Y., 2018. Agroforestry systems: Meta-analysis of soil carbon  
596 stocks, sequestration processes, and future potentials. *Land Degrad. Dev.* 29, 3886-3897.

597 Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., Six, J., 2007. Soil carbon saturation: concept,  
598 evidence, and evaluation. *Biogeochemistry* 86, 19-31.

599 R Core Team, 2018. R: A language and environment for statistical computing URL [http://www.R-](http://www.R-project.org/)  
600 [project.org/](http://www.R-project.org/). R Foundation for Statistical Computing, Vienna, Austria.

601 Thiel, B., Smukler, S.M., Krzic, M., Gergel, S., Terpsma, C., 2015. Using hedgerow biodiversity to  
602 enhance the carbon storage of farmland in the Fraser River delta of British Columbia. *J. Soil*  
603 *Water Conserv.* 70, 247-256.

604 Udawatta, R.P., Kremer, R.J., Adamson, B.W., Anderson, S.H., 2008. Variations in soil aggregate  
605 stability and enzyme activities in a temperate agroforestry practice. *Appl. Soil Ecol.* 39, 153-  
606 160.

607 Upson, M.A., Burgess, P.J., 2013. Soil organic carbon and root distribution in a temperate arable  
608 agroforestry system. *Plant Soil* 373, 43-58.

609 Uselman, S.M., Qualls, R.G., Lilienfein, J., 2007. Contribution of Root vs. Leaf Litter to Dissolved  
610 Organic Carbon Leaching through Soil Current address: Synergy Resource Solutions, Inc., 5393  
611 Hamm Rd., Belgrade, MT 59714. *Soil Sci. Soc. Am. J.* 71, 1555-1563.

612 von Haden, A.C., Yang, W.H., DeLucia, E.H., 2020. Soils' dirty little secret: Depth-based comparisons  
613 can be inadequate for quantifying changes in soil organic carbon and other mineral soil  
614 properties. *Glob. Chang. Biol.* 26, 3759-3770.

615 Walter, C., Merot, P., Layer, B., Dutin, G., 2003. The effect of hedgerows on soil organic carbon  
616 storage in hillslopes. *Soil Use Manage.* 19, 201-207.

617 Wendt, J.W., Hauser, S., 2013. An equivalent soil mass procedure for monitoring soil organic carbon  
618 in multiple soil layers. *Eur. J. Soil Sci.* 64, 58-65.

619 Wiesmeier, M., Spörlein, P., Geuß, U., Hangen, E., Haug, S., Reischl, A., Schilling, B., Lützow, M.,  
620 Kögel-Knabner, I., 2012. Soil organic carbon stocks in southeast Germany (Bavaria) as affected  
621 by land use, soil type and sampling depth. *Glob. Chang. Biol.* 18, 2233-2245

622 WRB, I.W.G., 2007. World Reference Base for Soil Resources 2006, first update 2007. World Soil  
623 Resources Reports No 103. FAO, Rome.

624 Zomer, R.J., Neufeldt, H., Xu, J.C., Ahrends, A., Bossio, D., Trabucco, A., van Noordwijk, M., Wang,  
625 M.C., 2016. Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of  
626 agroforestry to global and national carbon budgets. *Sci. Rep.* 6, 12.

627

628 **Figure captions**

629 Figure 1. Locations of the three study areas sampled in northwestern France.

630 Figure 2. Sampling design in hedge plots.

631 Figure 3. Boxplots of soil organic carbon (SOC) concentrations as a function of depth (0-30, 30-60, 60-  
632 90 cm) for each distance from a hedge (1, 3, 6, 18 m). Whiskers equal 1.5 times the interquartile  
633 range. Significantly different SOC concentrations per horizon are followed by different letters, and p-  
634 values are specified.

635 Figure 4. Boxplots of soil organic carbon (SOC) stocks as a function of depth (0-30, 30-60, 60-90 cm)  
636 for each distance from a hedge (1, 3, 6, 18 m). Whiskers equal 1.5 times the interquartile range.  
637 Significantly different SOC concentrations per depth are followed by different letters, and p-values  
638 are specified.

639 Figure 5. Boxplots of soil organic carbon (SOC) concentrations in the particle-size fractions  
640 (particulate organic matter (POM) and mineral-associated organic matter (MAOM)) 1 and 18 m from  
641 a hedge at 0-30 cm depth in MO and the two other areas (MA and SA). Whiskers equal 1.5 times the  
642 interquartile range. Significantly different SOC concentrations per fraction are followed by different  
643 letters, and p-values are specified.

644 **Table 1.** Characteristics of climate and soils in the three study areas: Pays du Roi Morvan (MO), Pays des Mauges (MA) and Pays Vallée de la Sarthe (SA). SOC  
 645 = soil organic carbon

Study area	Mean annual temperature (°C) <sup>a</sup>	Mean annual rainfall (mm) <sup>a</sup>	Mean annual potential evapotranspiration (mm) <sup>a</sup>	Mean SOC concentration (g kg <sup>-1</sup> ) <sup>b</sup>	Class of soil pH in water	Soil texture <sup>c</sup>
MO	11.5	967	700	30.2	6 – 7	Loam
MA	11.3	740	834	14.5	6 – 7	Loam
SA	11.0	693	785	14.6	6 – 7	Loam

646 <sup>a</sup> 1990-2018, Météo-France

647 <sup>b</sup> GISSol database <https://webapps.gissol.fr/geosol/> (Saby *et al.*, 2014) Average values available at the spatial resolution of the 'canton' (french administrative unit corresponding to several  
 648 municipalities). We have selected the value for the 'canton' covering the largest area of our study site.

649 <sup>c</sup> USDA classification

650

651 **Table 2.** Description of the hedge agroforestry plots from the three study areas: Pays du Roi Morvan (MO), Pays des Mauges (MA) and Pays Vallée de la  
 652 Sarthe (SA)

Plot	Hedge characteristics			Soil characteristics			Land use in the adjacent fields at the time of sampling		
	Tree species	Years since planting	Years since last pruning	Vegetation structure	Soil type <sup>a</sup>	Soil depth (cm)	Topsoil texture <sup>b</sup>	Field 1	Field 2
MO1	<i>Castanea sativa</i>	60	30	Coppice	Cambisol	> 90	Silty loam	Maize	(Not sampled)
MO2	<i>Elderberry, Quercus robur, Carpinus betulus, Corylus avellana</i>	20	- <sup>c</sup>	Mixed <sup>d</sup>	Luvisol	> 90	Silty loam	Temporary grassland <sup>e</sup>	Temporary grassland
MO3	<i>Castanea sativa, Corylus avellana</i>	60	-	Coppice	Cambisol	> 90	Loam	Long-term grassland <sup>f</sup>	(Not sampled)
MO4	<i>Quercus robur, Fraxinus excelsior, Fagus sylvatica</i>	45	-	High stem	Cambisol	55	Loam	Temporary grassland	Temporary grassland
MA1	<i>Robinia Pseudacacia</i>	60	25	Coppice	Luvisol	> 90	Loam	Long-term grassland	Temporary grassland
MA2	<i>Quercus robur</i>	120	-	High stem	Luvisol	> 90	Loam	Long-term grassland	Wheat
MA3	<i>Carpinus betulus, Quercus robur, Sorbus aucuparia</i>	20	-	Mixed	Luvisol	> 90	Silty clay	Temporary grassland	Temporary grassland

MA4	<i>Carpinus betulus</i>	20	-	Coppice	Luvisol	> 90	Loam	Wheat	Wheat
MA5	<i>Carpinus betulus, Ulmus minor</i>	20	-	Mixed	Luvisol	> 90	Loam	Temporary grassland	Temporary grassland
SA1	<i>Corylus avellana, Acer campestre, Crataegus monogyna</i>	60	15	Coppice	Colluvic regosol	> 90	Sandy loam	Long-term grassland	Rapeseed
SA2	<i>Quercus robur</i>	120	120	High stem	Luvisol	75	Silty loam	Oat	Temporary grassland
SA3	<i>Quercus robur, Crataegus monogyna</i>	120	120	High stem	Luvisol	> 90	Silty loam	Rapeseed	(Not sampled)

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653 <sup>a</sup> IUSS Working Group WRB (2015)

654 <sup>b</sup> USDA texture class for the 0-30 cm soil layer

655 <sup>c</sup> never pruned

656 <sup>d</sup> mixing of high-stem trees, pollard trees and shrubs

657 <sup>e</sup> Temporary grassland inserted in a crop rotation and lasting 1-4 years

658 <sup>f</sup> Grassland lasting more than 8 years, either permanent or occasionally reseeded.



659

660 Table 3. Pedotransfer functions tested in this study for the prediction of bulk density in each sampling locations, and quality of the fit: R<sup>2</sup>, mean prediction  
 661 error (MPE), standard deviation of the prediction error (SDPE), and root mean square prediction error (RMSPE) are used to compare measured bulk density  
 662 values and values predicted by the functions.

Reference	Function	R <sup>2</sup>	MPE	SDPE	RMSPE
Leonavičiūtė (2000)	$\rho = 1.70398 - 0.00313 \text{ silt} + 0.00261 \text{ clay} - 0.11245 \text{ OC}$	0.12	0.172	1.10	1.11
Alexander (1980)	$\rho = 1.660 - 0.308 (\text{OC})^{1/2}$	0.61	0.008	0.17	0.05
Manrique and Jones (1991)	$\rho = 1.660 - 0.318 (\text{OC})^{1/2}$	0.65	0.005	0.14	0.03
Federer (1983)	$\ln(\rho) = -2.31 - 1.079 \ln(\text{OM}) - 0.113[\ln(\text{OM})]^2$	0.51	0.061	0.41	0.41
Kaur et al. (2002)	$\ln(\rho) = 0.313 - 0.191 \text{ OC} + 0.02102 \text{ clay} - 0.000476 \text{ clay}^2 - 0.00432 \text{ silt}$	0.12	0.461	2.99	3.02

663  $\rho$  bulk density (g.cm<sup>-3</sup>), *silt* 2- to 50- $\mu$ m fraction (%), *clay* 0- to 2- $\mu$ m fraction (%), *OC* soil organic carbon concentration (%), *OM* organic matter content (g.g<sup>-1</sup>)

664

665 **Table 4.** Estimated aboveground and belowground biomass and carbon (C) stocks in sampling plots from the three study areas: Pays du Roi Morvan (MO),  
 666 Pays des Mauges (MA) and Pays Vallée de la Sarthe (SA).

Plot	Length of hedge sampled (m)	Number of trees sampled	Belowground biomass (Mg C 100 m <sup>-1</sup> )						
			Aboveground biomass (Mg C 100 m <sup>-1</sup> )			100 m <sup>-1</sup>		Total C stock in non-harvested biomass (Mg C 100 m <sup>-1</sup> )	Mean C storage rate in non-harvested biomass since hedge planting (Mg C 100 m <sup>-1</sup> yr <sup>-1</sup> )
			Dry matter	C stock	C stock in non-harvested biomass	Dry matter	C stock		
MO1	14.0	4	19.7	9.4	2.8	5.5	2.6	5.4	0.09
MO2	30.0	14	5.3	2.5	2.5	1.5	0.7	3.2	0.16
MO3	20.0	8	45.5	21.6	6.5	12.7	6.1	12.6	0.21
MO4	25.0	16	25.0	11.9	11.9	7.0	3.3	15.2	0.34
MA1	13.5	9	5.4	2.6	0.8	1.5	0.7	1.5	0.03
MA2	25.0	3	16.5	7.9	7.9	4.6	2.2	10.1	0.08
MA3	41.0	11	3.8	1.8	1.8	1.1	0.5	2.3	0.11
MA4	27.0	4	2.5	1.2	0.4	0.7	0.3	0.7	0.04
MA5	36.0	13	9.7	4.6	4.6	2.7	1.3	5.9	0.30
SA1	50.0	28	5.3	2.5	0.8	1.5	0.7	1.5	0.03
SA2	40.0	6	17.8	8.5	8.5	5.0	2.4	10.9	0.09

SA3 20.0 4 21.5 10.2 10.2 6.0 2.9 13.1 0.11

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667

668 **Table 5.** ANOVA or Friedman’s test on the effect of distance on the log-transformation of soil organic  
 669 carbon (SOC) concentrations and SOC stocks in each of the three soil layers sampled.

Soil property	Soil depth	Method	Statistical results			
				Distance	Residuals	
SOC concentration	0-30 cm	ANOVA	Degrees of freedom	3	79	
			Sum of squares	1.04	1.77	
			F value	11.21		
			Pr (> F)	6.37 10 <sup>-6</sup>		
	30-60 cm	ANOVA	Degrees of freedom	3	79	
			Sum of squares	2.46	3.92	
			F value	11.32		
			Pr (> F)	7.18 10 <sup>-6</sup>		
	60-90 cm	Friedman	Q value	7.7		
			Pr(>Q)	0.039		
	SOC stock	0-30 cm	Friedman	Q value	11.55	
				Pr(>Q)	9.07 10 <sup>-3</sup>	
30-60 cm		Friedman	Q value	11.94		
			Pr(>Q)	1.87 10 <sup>-3</sup>		
60-90 cm		Friedman	Q value	9.52		
			Pr(>Q)	0.02		
0-90 cm		ANOVA	Degrees of freedom	3	63	
			Sum of squares	0.27	0.03	
			F value	9.149		

Pr (> F)

$5.6 \cdot 10^{-5}$

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670 **Table 6.** Mean (and 95% confidence interval) of local additional soil organic carbon (SOC) stocks (Mg C ha<sup>-1</sup>) at 1 and 3 m from the hedge by hedge age class  
 671 and study area (Pays du Roi Morvan MO, Pays des Mauges MA and Pays Vallée de la Sarthe SA), calculated as SOC stocks at the given distance minus the  
 672 reference SOC stock (18 m from the hedge).

		Additional SOC stocks (Mg C ha <sup>-1</sup> )					
Study area	Soil depth (cm)	Young hedges (< 20 years old)		Old hedges (40-120 years old)		All hedges	
		1 m	3 m	1 m	3 m	1 m	3 m
MA and SA	0-30	17.0 (2.4-24.2)	0 <sup>a</sup>	19.7 (8.2- 28.4)	0 <sup>a</sup>	17.4 (3.5 - 27.6)	0 <sup>a</sup>
	30-60	4.9 (0.2-6.6)	0 <sup>a</sup>	5.5 (3.7-10.6)	0 <sup>a</sup>	5.5 (1.4-10.1)	0 <sup>a</sup>
	60-90	3.1 (1.2-4.3)	0.3 (0.1-3.2)	3.7 (1.0-7.8)	1.4 (0.1-3.7)	3.2 (0.7-7.0)	1.15 (0.1-3.6)
MO	0-30	26.8 <sup>b</sup>	0 <sup>a</sup>	60.1 (34.7-86.3)	0 <sup>a</sup>	49.0 (26.5-84.1)	0 <sup>a</sup>
	30-60	15.0 <sup>b</sup>	0 <sup>a</sup>	54.3 (13.6-86.7)	0 <sup>a</sup>	38.6 (9.1-84.4)	0 <sup>a</sup>
	60-90	7.05 <sup>b</sup>	4.5 <sup>b</sup>	7.0 (2.8-11.6)	0.1	7.1 (2.8-11.5)	1.3 (0.2-6.7)

673 <sup>a</sup> Additional SOC stock was considered to be zero since the statistical analysis testing the influence of the distance from the hedge on SOC stocks showed no  
 674 significant difference in this soil layer between SOC stocks measured 3 m from the hedge and the reference SOC stocks.

675 <sup>b</sup> Two data points

676 **Table 7.** Mean (and 95% confidence interval) of additional soil organic carbon (SOC) stocks (Mg C per  
 677 100 linear m) by hedge age class and study area (Pays du Roi Morvan MO, Pays des Mauges MA and  
 678 Pays Vallée de la Sarthe SA), summed over the influence distance of hedges and including both sides  
 679 of the hedge.

Study area	Soil depth (cm)	Additional SOC stocks (Mg C 100 m <sup>-1</sup> )		
		Young hedges (< 20 years old)	Old hedges (40-120 years old)	All hedges
MA and SA	0-30	0.54 (0.09-0.99)	0.91 (0.34-1.30)	0.77 (0.08-0.83)
	0-90	0.81 (0.17-1.34)	1.40 (0.66-1.89)	1.19 (0.13-0.94)
MO	0-30	1.10 <sup>a</sup>	2.64 (1.36-3.99)	2.34 (0.56-1.96)
	0-90	2.20 <sup>a</sup>	4.71 (1.76-7.31)	4.21 (0.85-3.65)

680 <sup>a</sup> Two data points

681

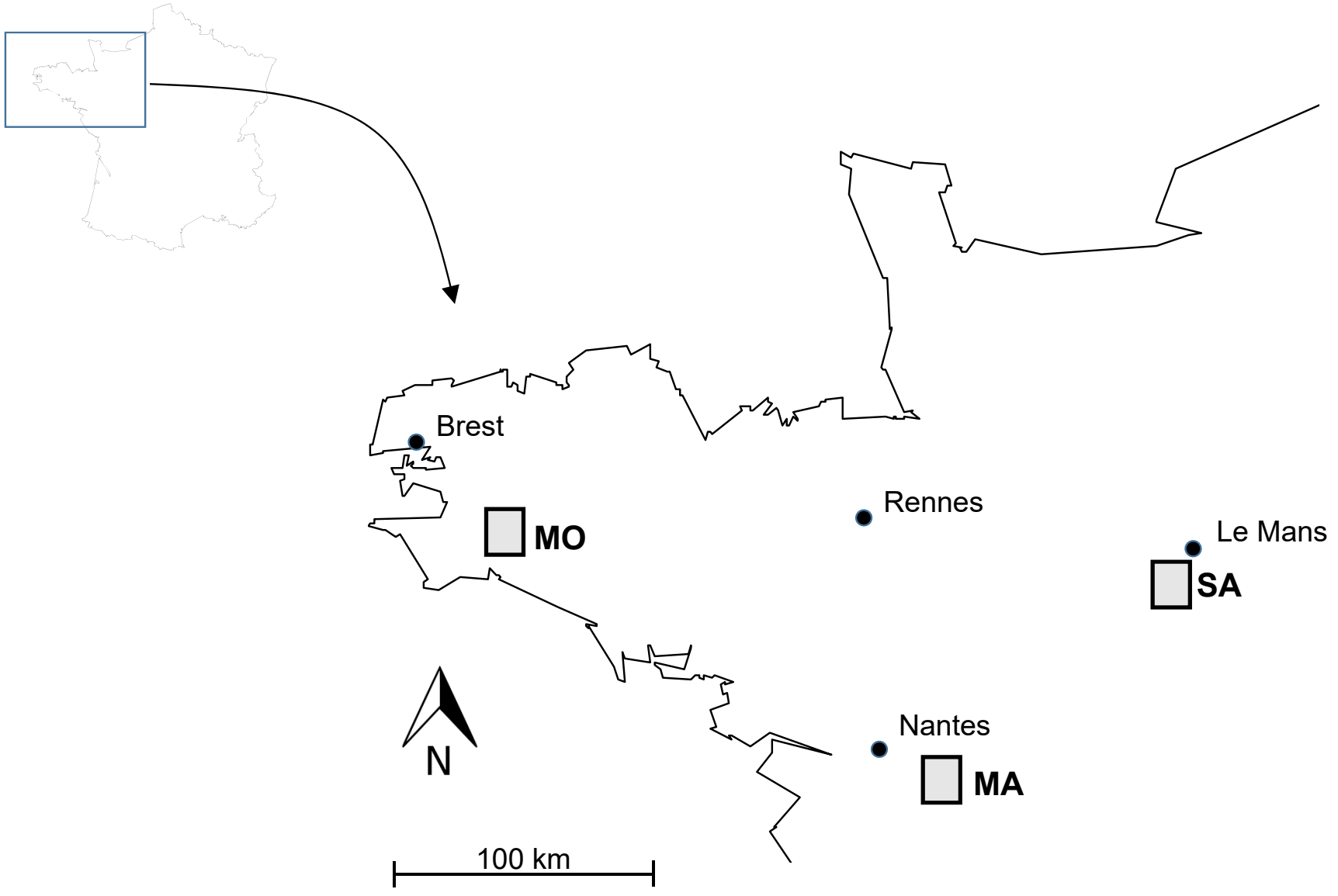
682 **Table 8.** Estimated parameters of the exponential model used to simulate additional soil organic carbon (SOC) storage dynamics by hedges and mean annual  
 683 SOC accumulation rates for at 0-30 and 0-90 cm depth, by study area (Pays du Roi Morvan MO, Pays des Mauges MA and Pays Vallée de la Sarthe SA), and  
 684 for all areas combined.

		0-30 cm			0-90 cm		
		All areas combined	MO	MA and SA	All areas combined	MO	MA and SA
Model parameters	Range $\Delta$ (Mg C 100 m <sup>-1</sup> )	1.54	2.64	0.91	2.60	4.71	1.40
	Decay rate constant k (yr <sup>-1</sup> )	0.014	0.015	0.029	0.027	0.031	0.043
	Initial accumulation rate (Mg C 100 m <sup>-1</sup> yr <sup>-1</sup> )	0.014	0.039	0.009	0.070	0.148	0.060
	Mean annual SOC accumulation rate over 15 years after planting (Mg C 100 m <sup>-1</sup> yr <sup>-1</sup> )	0.013	0.035	0.008	0.058	0.118	0.044
	Mean annual SOC accumulation rate over 30 years after planting (Mg C 100 m <sup>-1</sup> yr <sup>-1</sup> )	0.010	0.029	0.005	0.039	0.096	0.034

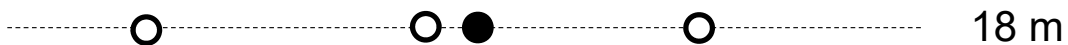
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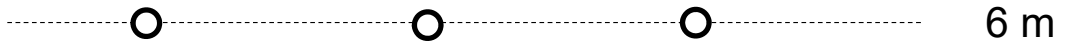




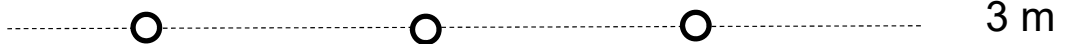
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18 m



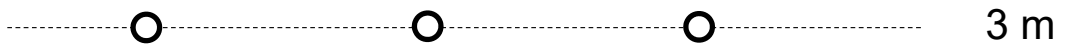
6 m



3 m



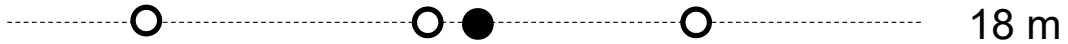
1 m  
0 m  
1 m



3 m



6 m

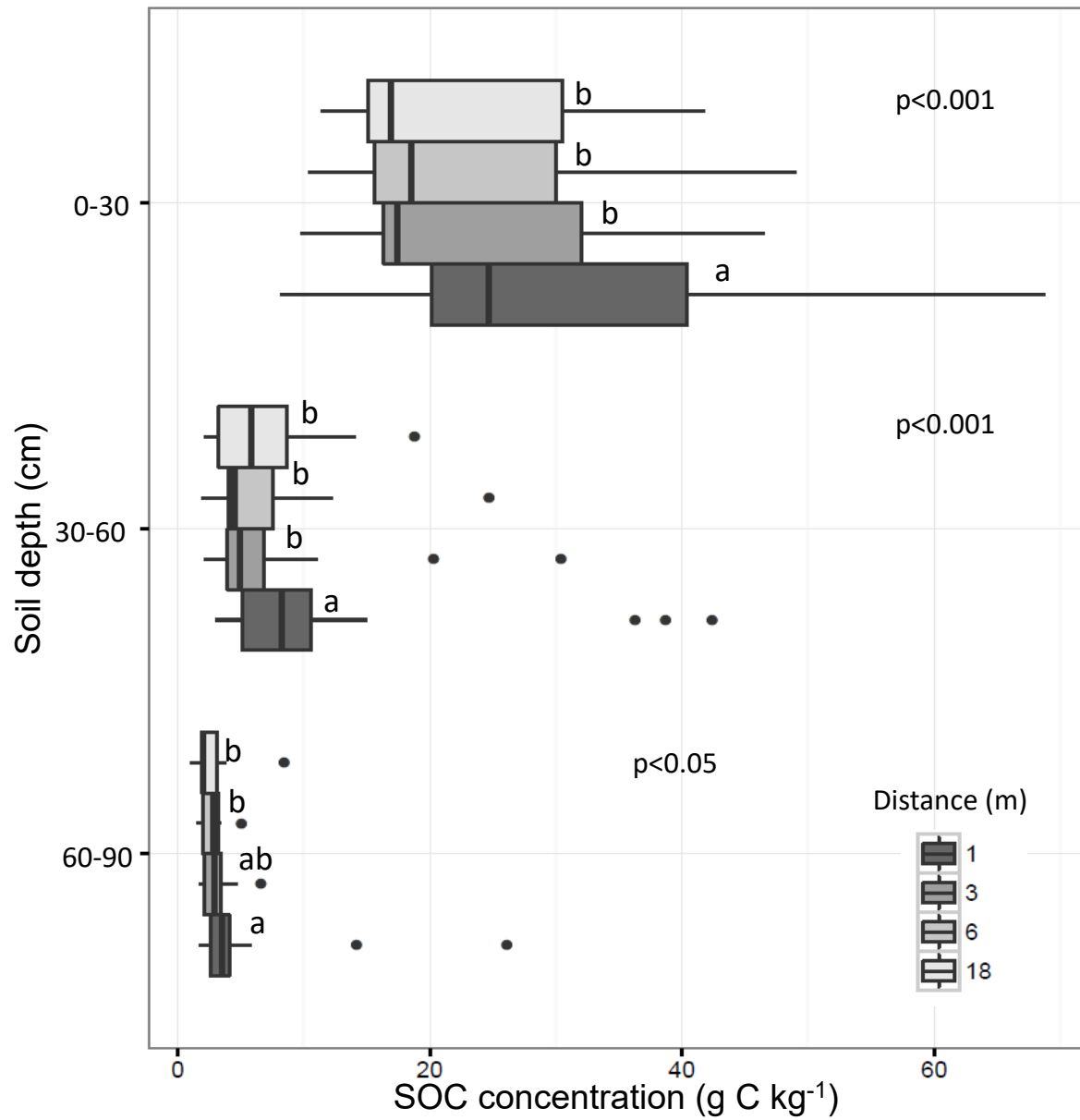


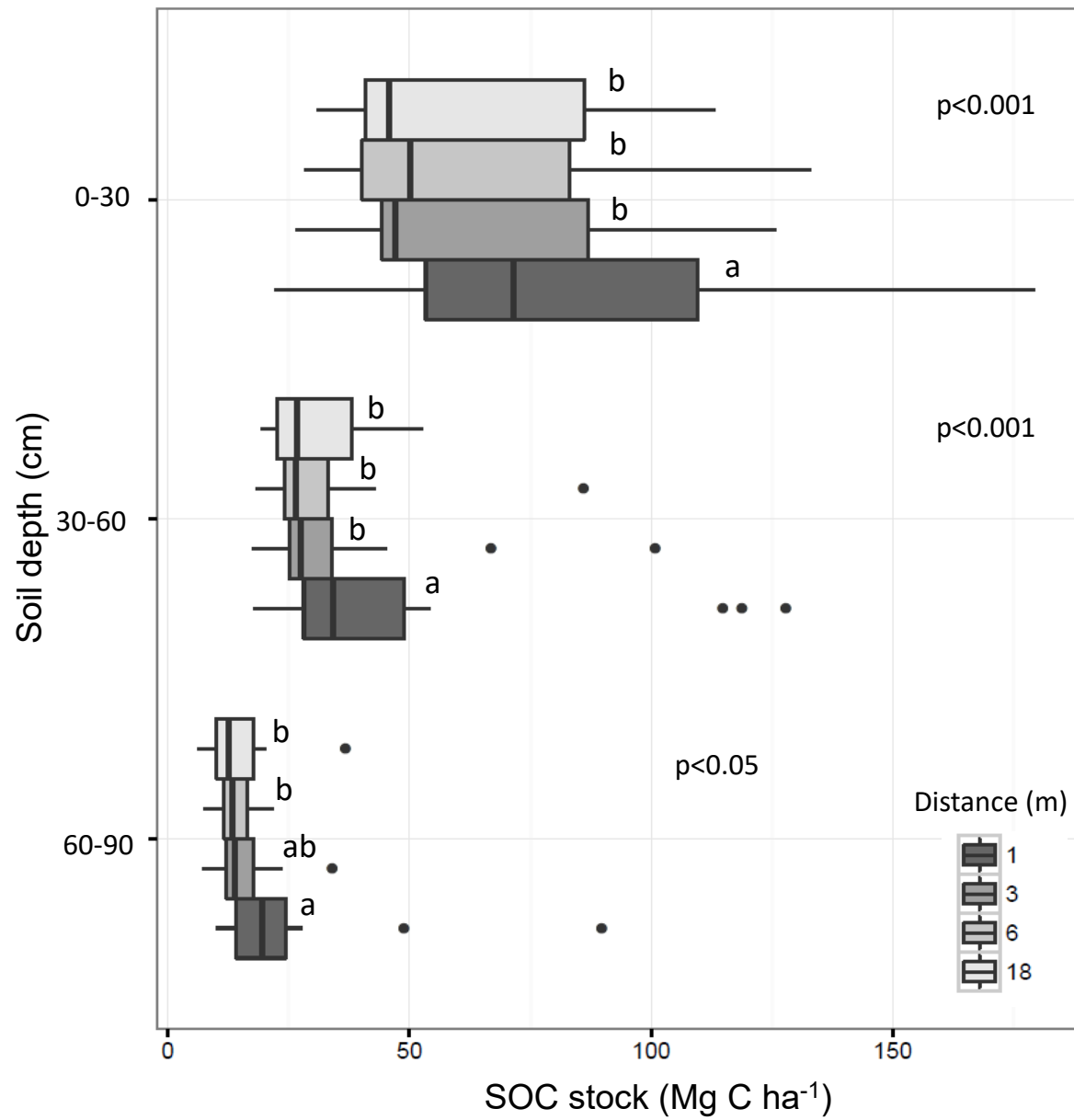
18 m

**FIELD 2**

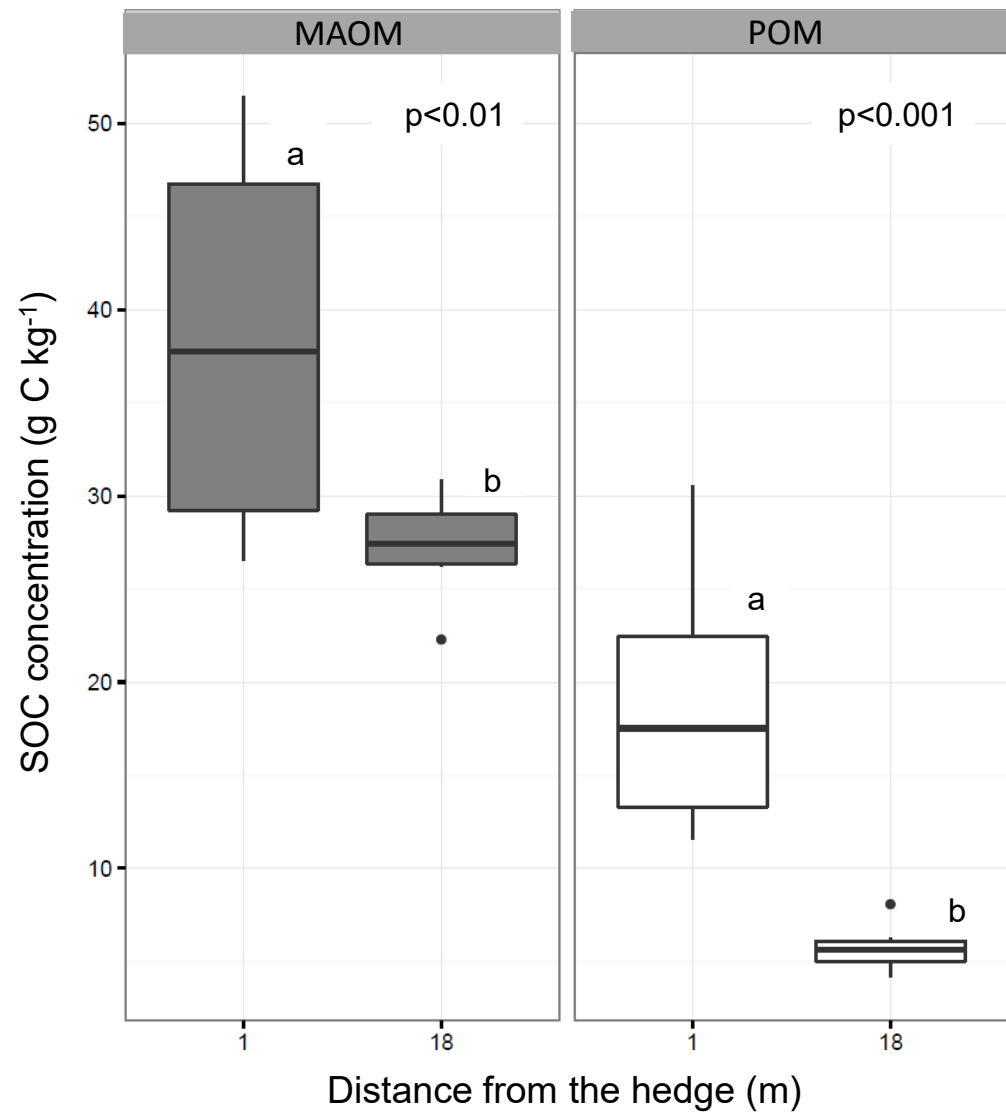
**HEDGE**

- Sampling for soil analyses with manual auger
- Sampling for bulk density with manual core sampler





### MO



### MA and SA

