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1 **Increased soil organic carbon stocks under agroforestry: a survey of six different sites in**
2 **France**

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13

14 **ABSTRACT**

15 Agroforestry systems are land use management systems in which trees are grown in
16 combination with crops or pasture in the same field. In silvoarable systems, trees are
17 intercropped with arable crops, and in silvopastoral systems trees are combined with pasture
18 for livestock. These systems may produce forage and timber as well as providing ecosystem
19 services such as climate change mitigation. Carbon (C) is stored in the aboveground and
20 belowground biomass of the trees, and the transfer of organic matter from the trees to the soil
21 can increase soil organic carbon (SOC) stocks. Few studies have assessed the impact of
22 agroforestry systems on carbon storage in soils in temperate climates, as most have been

23 undertaken in tropical regions. This study assessed five silvoarable systems and one
24 silvopastoral system in France. All sites had an agroforestry system with an adjacent, purely
25 agricultural control plot. The land use management in the inter-rows in the agroforestry systems
26 and in the control plots were identical. The age of the study sites ranged from 6 to 41 years after
27 tree planting. Depending on the type of soil, the sampling depth ranged from 20 to 100 cm and
28 SOC stocks were assessed using equivalent soil masses. The aboveground biomass of the trees
29 was also measured at all sites. In the silvoarable systems, the mean organic carbon stock
30 accumulation rate in the soil was 0.24 (0.09-0.46) Mg C ha⁻¹ yr⁻¹ at a depth of 30 cm and 0.65
31 (0.004-1.85) Mg C ha⁻¹ yr⁻¹ in the tree biomass. Increased SOC stocks were also found in deeper
32 soil layers at two silvoarable sites. Young plantations stored additional SOC but mainly in the
33 soil under the rows of trees, possibly as a result of the herbaceous vegetation growing in the
34 rows. At the silvopastoral site, the SOC stock was significantly greater at a depth of 30 to 50
35 cm than in the control. Overall, this study showed the potential of agroforestry systems to store
36 C in both soil and biomass in temperate regions.

37

38 **Keywords:** Alley cropping, Soil organic carbon storage, Equivalent soil mass, Aboveground
39 biomass, Belowground biomass

40

41 **1. Introduction**

42 Soils play an essential role in the global carbon budget (Houghton, 2007). Currently, the land
43 sink (including soil and vegetation) absorbs about 30% of the carbon (C) emitted to the
44 atmosphere through the burning of fossil fuel and cement production (Le Quéré et al., 2014).
45 Since 1850, the depletion of soil organic carbon (SOC) in cultivated lands has transferred about

46 70 Gt C to the atmosphere (Amundson, 2001; Lal, 2004a). The potential of these SOC depleted
47 soils as future C sinks through SOC sequestration has now been recognized (Paustian et al.,
48 1997; Freibauer et al., 2004; Smith, 2004). In France, SOC stocks have been estimated at 3.1-
49 3.3 Gt C in the top 30 cm of soils (Arrouays et al., 2001; Martin et al., 2011). Based on the SOC
50 saturation capacity (Hassink, 1997), assuming that the quantity of stable SOC is limited by the
51 amount of fine particles, Angers et al. (2011) found that the median saturation deficit of French
52 arable topsoils was 8.1 g C kg⁻¹ soil. About 70% of French agricultural topsoils are, therefore,
53 unsaturated in SOC and have the potential for additional SOC storage. Increasing SOC stocks
54 is often seen as a win-win strategy (Lal, 2004a; Janzen, 2006) as it allows the transfer of CO₂
55 from the atmosphere to the soil while improving soil quality and fertility (Lal, 2004b).

56 Several agricultural practices have been developed to increase SOC stocks. For instance, the
57 introduction of cover crops (Constantin et al., 2010; Poeplau and Don, 2015) or grasslands
58 (Conant et al., 2001; Soussana et al., 2004) in the cropping sequence has proven effective. The
59 effect of no-till farming on SOC stocks is disputed and highly variable (Luo et al., 2010; Virto
60 et al., 2012; Dimassi et al., 2013) and seems to depend on the amount of C transferred from the
61 crops to the soil (Virto et al., 2012). Agroforestry is a general term for agroecosystems in which
62 trees are intercropped with crops or pasture (Nair, 1993). Silvoarable systems intercrop trees
63 and arable crops and silvopastoral systems combine trees, pasture and livestock. These are
64 recognized as possible land use management systems that can maintain or increase SOC stocks,
65 both in tropical (Albrecht and Kandji, 2003) and temperate regions (Peichl et al., 2006;
66 Bambrick et al., 2010; Wotherspoon et al., 2014). However, most studies only consider the
67 surface soil layers (to a depth of < 20 or 30 cm) whereas trees grown in agroforestry can be
68 very deep rooted (Mulia and Dupraz, 2006; Cardinael et al., 2015a) and affect deep SOC stocks.
69 A recent study in the Mediterranean region of France showed that an 18-year-old silvoarable
70 system with hybrid walnuts intercropped with durum wheat increased SOC stocks by 0.25 ±

71 0.03 Mg C ha⁻¹ yr⁻¹ in the 0-30 cm layer and by 0.35 ± 0.04 Mg C ha⁻¹ yr⁻¹ from 0 to 100 cm
72 compared to an adjacent agricultural plot (Cardinael et al., 2015b). Furthermore, although trees
73 affect the spatial distribution of organic matter inputs to the soil (Rhoades, 1997), sampling
74 protocols have not always taken account of the potential impact on the spatial distribution of
75 SOC stocks. Some authors showed that SOC stocks were greater in the tree rows than in the
76 inter-rows, and found no gradients within the inter-rows (Peichl et al., 2006; Upson and
77 Burgess, 2013). Bambrick et al., (2010) found that the spatial distribution of SOC stocks varied
78 with the time after tree planting. Few studies have estimated SOC storage in agroforestry
79 systems in temperate conditions (Howlett et al., 2011; Mosquera Losada et al., 2011; Upson
80 and Burgess, 2013) and these studies sometimes do not have control plots without trees for
81 comparison, making it difficult to evaluate the precise effect of agroforestry on SOC stocks
82 (Pellerin et al., 2013).

83 This study set out i) to quantify organic carbon stocks in soils and in the tree biomass in six
84 agroforestry systems with adjacent agricultural control plots under different soil and climate
85 conditions in France, ii) to study the spatial distribution of SOC stocks as a function of the
86 distance from individual trees and the tree rows and iii) to estimate the SOC stock accumulation
87 rates for these agroforestry systems.

88

89 **2. Materials and methods**

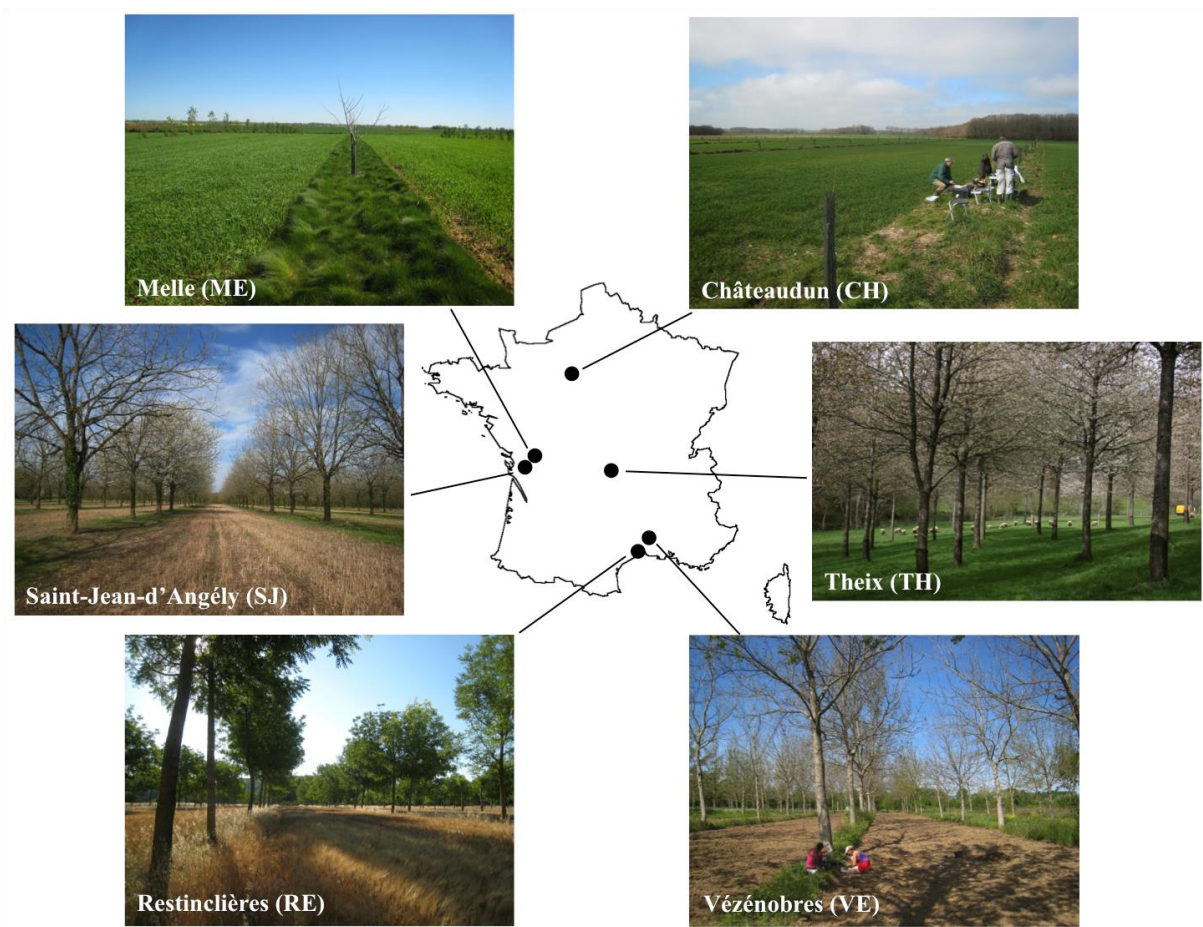
90 *2.1 The six agroforestry sites*

91 Each study site had an agroforestry system and an adjacent agricultural control plot. Before tree
92 planting, the agroforestry plot was part of the agricultural plot, with the same soil use and
93 management (crop rotation, fertilization, soil tillage). After tree planting, the soil management
94 of the agroforestry inter-rows and of the agricultural plot remained identical. Rows of trees

95 were planted in the agroforestry fields, with natural or sown grasses between the trees. Five
96 sites, Restinclières (RE), Châteaudun (CH), Melle (ME), Saint-Jean d'Angély (SJ), and
97 Vézénobres (VE), were silvoarable systems with no grazing. Only one site, Theix (TH), was a
98 silvopastoral system with regular grazing. Four sites were owned and managed by farmers and
99 Restinclières (RE) and Theix (TH) were experimental research sites.

100

101



102

103 **Figure 1.** Location and description of the six study cases under agroforestry systems sampled
104 in France.

105

106

107

108 **Table 1** Site characteristics.

109

Site	Mean annual temperature (°C)	Mean annual rainfall (mm)	Soil type (FAO)	Soil depth (cm)	Soil texture clay/silt/sand (g kg ⁻¹)		Soil pH in water
					Agroforestry	Control	
CH	11.1	595	Luvisol	0-30	200/700/100	190/710/100	7.0
ME	11.7	810	Luvisol	0-30	240/660/100	260/630/110	5.8
SJ	12.9	850	Luvisol	0-20	560/370/70	500/410/90	7.7
VE	14.5	1037	Fluvisol	0-30	110/410/480	90/370/540	8.3
				30-60	100/440/460	80/370/550	8.3
RE	15.4	873	Fluvisol	0-30	173/406/421	176/413/411	8.0
				30-50	178/416/406	177/421/402	8.1
				50-70	250/501/249	243/507/250	8.2
				70-100	309/582/109	307/586/107	8.3
TH	7.7	800	Andosol	0-20	340/300/360	380/360/260	6.5
				20-50	320/280/400	360/380/260	6.5

110 CH: Châteaudun, ME: Melle, SJ: Saint-Jean-d'Angély, VE: Vézénobres, RE: Restinclières, TH: Theix.

111

112

113 **Table 2** Description of the agroforestry plots.

Site	Tree species	Age (yrs)	Density (trees ha ⁻¹)	Distance between trees in tree rows (m)	Width of inter-rows (m)	Width of tree rows (m)	Area occupied by tree rows in the AF plot (%)	Crops
CH	Hybrid walnut	6	34	10	24	2	8	wheat, rapeseed
ME	Hybrid walnut	6	35	8	27	2	7	wheat, rapeseed, sunflower
SJ	Black walnut	41	102	7	12	2	14	sunflower, wheat, barley
VE	Hybrid walnut	18	100	10	9	2	18	rapeseed, wheat, potato, garlic
RE	Hybrid walnut	18	110	4-12	11	2	16	durum wheat, rapeseed, chickpea
TH	Wild cherry	26	200	7	No row	No row	No row	ryegrass, fescue

114 CH: Châteaudun, ME: Melle, SJ: Saint-Jean-d'Angély, VE: Vézénobres, RE: Restinclières, TH: Theix.

115 The CH silvoarable site was located in Châteaudun (Fig. 1), in the department of Eure-et-Loir
116 (longitude 1°17'58'' E, latitude 48°06'08'' N, elevation 147 m a.s.l.). The mean temperature
117 was 11.1°C and the mean annual rainfall 595 mm (years 2001-2013, INRA CLIMATIK,
118 <https://intranet.inra.fr/climatik>). The soil was a silty loam Luvisol (IUSS Working Group WRB,
119 2007) (Table 1). Hybrid walnut trees (*Juglans regia* × *nigra* cv. NG23) were planted in
120 February 2008 at a density of 34 trees ha⁻¹. The trees were planted 10 m apart within the rows,
121 with 26 m between rows. A mix of ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca*
122 *arundinacea* Schreb.) was sown in August 2007 in two meter wide strips along the tree rows
123 before the trees were planted. After tree planting, wheat (*Triticum aestivum* L. subsp. *aestivum*)
124 and rapeseed (*Brassica napus* L.) were grown in rotation in the control plot and in the inter-
125 rows (Table 2). The mean fresh grain yield was 7.5-8 t ha⁻¹ for wheat, and 3.8 t ha⁻¹ for rapeseed.
126 All crop residues were left in the field after harvest. The agroforestry inter-rows and the control
127 plot were ploughed every three years to a depth of 22 cm and harrowed to 8 cm the other years.

128 The ME silvoarable site was located in Melle (Fig. 1), in the department of Deux-Sèvres
129 (longitude 0°10'37'' W, latitude 46°11'54'' N, elevation 107 m a.s.l.). The mean temperature
130 was 11.7°C and the mean annual rainfall 810 mm (years 1990-2013, INRA CLIMATIK,
131 <https://intranet.inra.fr/climatik>). The soil was a silty loam Luvisol (IUSS Working Group WRB,
132 2007) (Table 1). Hybrid walnut trees (*Juglans regia* × *nigra* cv. NG23) were planted in 2008 at
133 a density of 35 trees ha⁻¹. The trees were planted 8 m apart within the rows, with 29 m between
134 rows. Sheep fescue (*Festuca ovina* L.) was sown in 2008 in two meter wide strips along the
135 tree rows before the trees were planted. After tree planting, wheat (*Triticum aestivum* L. subsp.
136 *aestivum*), rapeseed (*Brassica napus* L.) and sunflower (*Helianthus annuus* L.) were grown in
137 rotation in the control plot and in the inter-rows (Table 2). The mean fresh grain yield was 8-
138 8.5 t ha⁻¹ for wheat, 3.3 t ha⁻¹ for rapeseed and 2.5 t ha⁻¹ for sunflower. Crop residues were
139 usually exported, but this was counterbalanced by the application of manure in both the

140 agroforestry inter-rows and the control plot (the farmer was unable to specify the application
141 rates, but they were similar for both plots). Before the spring crop (sunflower), a winter cover
142 crop was sown to prevent soil erosion and nitrate leaching. This cover crop was a mix of radish
143 (*Raphanus sativus* L.), phacelia (*Phacelia tanacetifolia* Benth.) and mustard (*Sinapis alba* L.).
144 The soil was ploughed every year to a depth of 20 cm in both the agroforestry inter-rows and
145 the control plot. The agroforestry system was established on a moderate slope, while the control
146 plot was flat.

147 The SJ silvoarable site was located in Saint-Jean-d'Angély (Fig. 1), in the department of
148 Charente-Maritime (longitude 0°13'57'' W, latitude 46°00'39'' N, elevation 152 m a.s.l.). The
149 mean temperature was 12.9°C and the mean annual rainfall 850 mm (years 1990-2013, INRA
150 CLIMATIK, <https://intranet.inra.fr/climatik>). The soil was a carbonated silty clay Luvisol
151 (IUSS Working Group WRB, 2007) (Table 1). Black walnut trees (*Juglans nigra* L.) were
152 planted in 1973 at a density of 102 trees ha⁻¹. The trees were planted 7 m apart within the tree
153 rows, with 14 m between rows. The rows of trees were two meters wide, and covered by
154 spontaneous herbaceous vegetation. After tree planting, sunflower (*Helianthus annuus* L.),
155 wheat (*Triticum aestivum* L. subsp. *aestivum*) and barley (*Hordeum vulgare* L.) were grown in
156 rotation in the control plot and in the inter-rows (Table 2). Crop residues were left in the field
157 after harvest. The soil was ploughed every three years to a depth of 10-20 cm in both the
158 agroforestry inter-rows and the control plot.

159 The VE silvoarable site was located in Vézénobres (Fig. 1), in the department of Gard
160 (longitude 4°06'37'' E, latitude 46°00'39'' N, elevation 102 m a.s.l.). The climate was sub-
161 humid Mediterranean with a mean temperature of 14.5°C and a mean annual rainfall of 1037
162 mm (mean 1995-2007, experimental site weather station). The soil was a deep sandy loam
163 alluvial Fluvisol (IUSS Working Group WRB, 2007) (Table 1) originating from deposits from
164 the granitic Cevennes mountain range and was, therefore, not calcareous. Hybrid walnut trees

165 (*Juglans regia* × *nigra* cv. NG23) were planted in 1995 at a density of 100 trees ha⁻¹. The trees
166 were planted 10 m apart with the rows, with 10 m between rows. The tree rows were two meters
167 wide and were covered by spontaneous herbaceous vegetation. In the inter-rows, rapeseed
168 (*Brassica napus* L.) and wheat (*Triticum aestivum* L. subsp. *aestivum*) were grown in rotation
169 until 2010 (Table 2). In 2011, the farm changed over to organic farming and potatoes were
170 planted (*Solanum tuberosum* L.). In 2012 garlic (*Allium sativum* L.) was grown in the inter-
171 rows. In 2013 the inter-rows were left fallow and in 2014 sunflower (*Helianthus annuus* L.)
172 was sown. The same crops were grown in the control plot, except in 2011 when wheat (*Triticum*
173 *aestivum* L. subsp. *aestivum*) was sown and in 2012 when the control was left fallow. The soil
174 was occasionally ploughed to a depth of 20 cm in both the agroforestry inter-rows and the
175 control plot.

176 The RE site was located in Prades-le-Lez, at the Restinclières experimental site (Fig. 1), in the
177 department of Hérault (longitude 04°01' E, latitude 43°43' N, elevation 54 m a.s.l.). A full
178 description of this site is given in the study by Cardinael et al. (2015b). The climate was sub-
179 humid Mediterranean with a mean temperature of 15.4°C and a mean annual rainfall of 873
180 mm (years 1995–2013, experimental site weather station). The soil was a deep carbonated
181 sandy loam Fluvisol (IUSS Working Group WRB, 2007) (Table 1). Hybrid walnut trees
182 (*Juglans regia* × *nigra* cv. NG23) were planted in 1995 and the density was 110 trees ha⁻¹ at the
183 time of the study (Table 2). The trees were planted 4 to 8 m apart along the rows with 13 m
184 between rows. The two meter wide tree rows were covered by spontaneous herbaceous
185 vegetation. They were mainly intercropped with durum wheat (*Triticum turgidum* L. subsp.
186 *durum*) but also with rapeseed (*Brassica napus* L.) and chickpea (*Cicer arietinum* L.). The soil
187 was regularly ploughed to a depth of 20 cm in both the agroforestry inter-rows and the control
188 plot.

189 The TH silvopastoral site was located at the Theix experimental site (Fig. 1), in the department
190 of Puy-de-Dôme (longitude 3°01'39'' E, latitude 45°42'58'' N, elevation 829 m a.s.l.). The
191 mean temperature was 7.7°C and the mean annual rainfall 800 mm (years 1990-2013, INRA
192 CLIMATIK, <https://intranet.inra.fr/climatik>). The soil was a clay loam Andosol (IUSS
193 Working Group WRB, 2007) (Table 1). Wild cherry trees (*Prunus avium* L.) were planted in
194 1988 at a density of 200 trees ha⁻¹ on a natural permanent pasture. The trees were planted 7 m
195 apart and the soil was uniformly covered by a permanent pasture, mainly ryegrass (*Lolium*
196 *perenne* L.) and fescue (*Festuca* sp.), in both the control and agroforestry plots (Table 2). There
197 was no distinction between tree rows and inter-rows in terms of soil cover and management.
198 The pasture was regularly grazed by sheep in both the control and agroforestry plots.

199

200 2.2 Soil sampling protocol

201 The sampling protocol was defined to allow for the spatial distribution of SOC stocks owing to
202 the presence of trees and rows of trees, with sampling points at varying distances from the trees.
203 The agroforestry designs varied between sites with different distances between the trees within
204 the rows and between the rows. The sampling protocol was flexible to take account of these
205 differences but consistent enough to allow comparisons between sites. A sampling pattern was
206 defined with sampling points in transects around one tree. This was a rectangle with dimensions
207 $\frac{L}{2} \times \frac{d}{2}$, where L is the distance between tree rows and d is the distance between trees in the rows
208 (Fig. 2). This pattern is a quarter of the Voronoi polygon which is the elementary space defined
209 by the half distances between the sampled tree and its neighbors, as commonly used to estimate
210 root biomass (Levillain et al., 2011; Picard et al., 2012). At all sites, nine soil samples per
211 pattern were taken at fixed positions around the trees, at 1, 2 and 3 m in the tree row, in the
212 inter-row in front of the tree, and in the inter-row between two trees. If $L \geq 8$ m, soil samples

213 were additionally taken at mid-distance $\frac{L}{2}$, and, if $L \geq 16$ m, soil samples were also taken at $\frac{L}{4}$. If
214 $d \geq 8$ m, soil samples were also taken at $\frac{d}{2}$. This sampling pattern was applied three times in the
215 agroforestry plots at all sites. Two sampling patterns were oriented north of the tree rows (if the
216 rows were oriented east-west) or west of the rows (if the rows were oriented north-south) and
217 one sampling pattern was oriented south or east, respectively. Thirty-six sampling points were,
218 therefore, defined for the agroforestry plot at the CH site, twenty-four at the SJ site, thirty at the
219 VE site, and twenty-seven at the TH site (Table 3). In the control plots, a simpler sampling
220 pattern was applied in triplicate. This pattern was a rectangle with dimensions $\frac{L}{2} \times \frac{d}{2}$, with soil
221 samples taken at each corner (12 sampling points).

222 At the ME site, the agricultural control plot was flat, whereas the agroforestry plot was on a
223 moderate slope. The SOC-rich topsoil in the agroforestry plot might, therefore, have been
224 eroded before the start of the experiment. To take account of this topography difference, six
225 soil samples from the middle of the inter-row (two sampling positions for each of the three
226 sampling patterns) were used as an alternate arable control. Because the inter-rows were 27 m
227 wide and the 6-year-old trees were only 3 m high, the soil in the middle of the inter-rows had
228 probably not yet been affected by the presence of trees. 30 sampling points were defined in the
229 agroforestry plot and 6 in the control plot (Table 3).

230 The RE site had been the subject of a previous study (Cardinael et al., 2015b) to map SOC
231 stocks at plot scale. The sampling protocol at this site was, therefore, very dense: 100 soil
232 samples were taken from the agroforestry plot and 93 from the control plot (Table 3). Sampling
233 points were located every 5 m along a regular grid (25×25 m), and at 1, 2 and 3 m around nine
234 walnut trees, in the inter-rows and in the tree rows.

235 The sampling depths were 30 cm at the CH and ME sites, 20 cm at the SJ site, 60 at the VE
236 site, 100 at the RE site and 50 cm at the TH site. At the SJ site, the sampling depth corresponded

237 to the maximum soil depth. Soil samples were taken every 10 cm depth from the surface, except
 238 at the RE site (at 10 cm and every 20 cm from 10 cm).

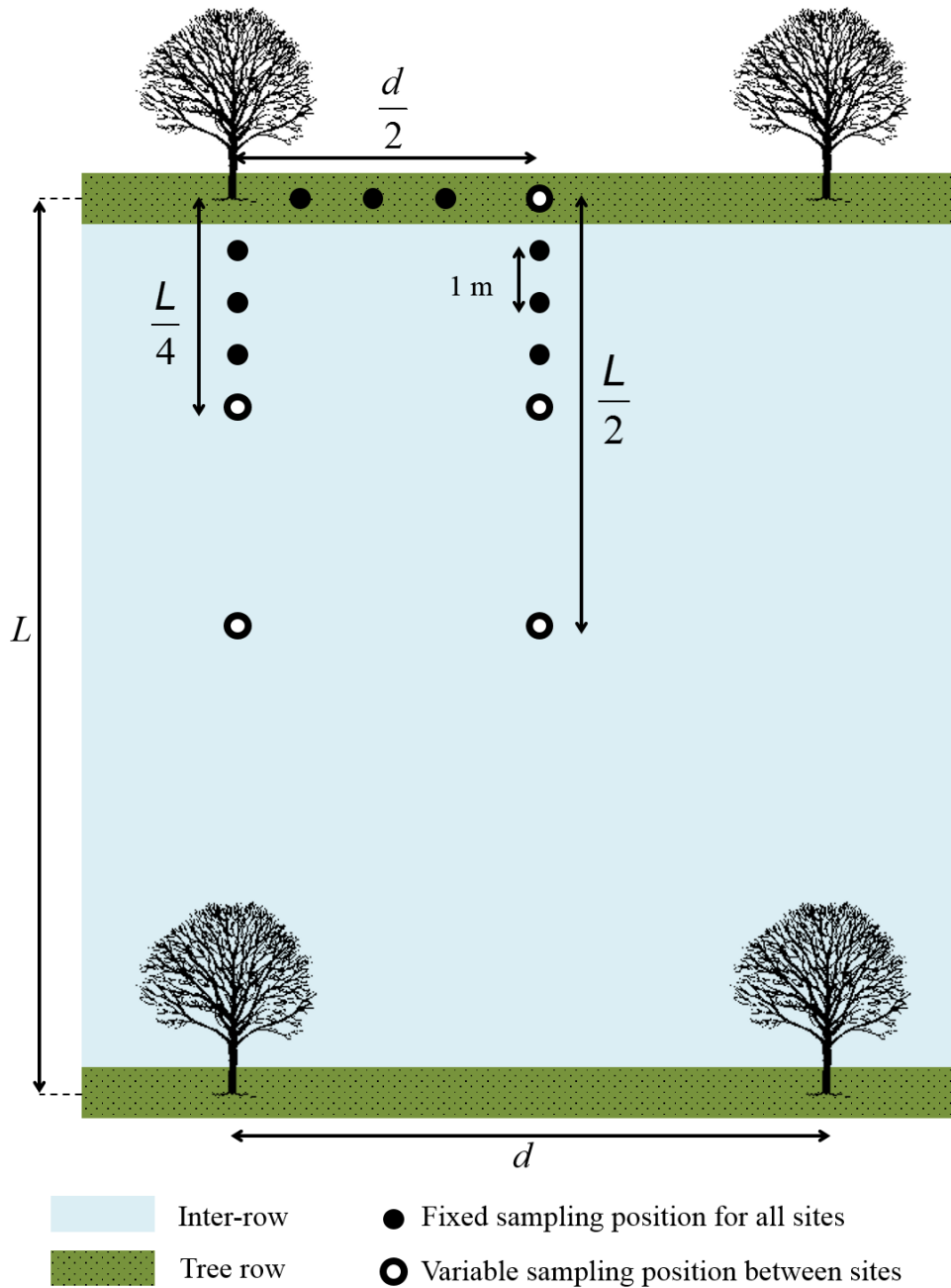


Figure 2. Sampling pattern for the agroforestry sites (except for the RE site). L is the distance between tree rows, d is the distance between trees on the rows.

243 *2.3 Bulk density measurement*

244 The soil samples were collected in April 2014 at all sites, except at the RE site which was
245 sampled in May 2013. Soil samples were taken every 10 cm from the surface using a 500-cm³
246 cylinder, except at the RE site where soil samples were taken every 20 cm depth after the top
247 10 cm. After air-drying in the lab, the soil samples were oven-dried at 105°C for 48 hours,
248 sieved to 2 mm and weighed without coarse particles > 2 mm. The bulk density (g cm⁻³) was
249 calculated as the ratio of the dry mass of fine soil (< 2 mm) to the cylinder volume.

250

251 *2.4 Organic carbon analysis*

252 The soil samples were dried at 40°C and ball milled until they passed through a 200 µm mesh
253 sieve. The presence of inorganic carbon was tested with HCl. If the soil contained inorganic
254 carbon, carbonates were removed by acid fumigation, as described in Harris et al. (2001). This
255 was the case for samples from the SJ and RE sites. 30 mg of soil were placed in open Ag-foil
256 capsules. The capsules were then placed in the wells of a microtiter plate and 50 µL of
257 demineralized water was added to each capsule. The microtiter plate was placed in a vacuum
258 desiccator with a beaker filled with 100 mL of concentrated HCl. The samples were exposed to
259 HCl vapor for 8 h and then dried at 40°C for 48 h. The capsules were then enclosed in a bigger
260 tin capsule. All samples were analyzed for organic carbon concentration using a CHN elemental
261 analyzer (Carlo Erba NA 2000, Milan, Italy).

262

263 *2.5 SOC stock calculation*

264 The SOC stock at soil sample level (mg C cm⁻³) is defined as the product of the SOC
265 concentration (mg C g⁻¹) and the bulk density (g cm⁻³) and is then calculated for each soil profile

266 (kg C m⁻²) by summing the SOC stocks in the samples through the profile. For each site, the
267 SOC stocks were calculated on an equivalent soil mass (ESM) basis (Ellert and Bettany, 1995)
268 to enable comparison between all locations (control, tree rows, inter-rows) even where the soil
269 bulk density varied within the same site. SOC stocks in the agroforestry plot (Mg C ha⁻¹) were
270 calculated by adding the tree row and inter-row SOC stocks, weighted by their respective
271 relative surface areas:

$$272 \text{ SOC stock}_{\text{Agroforestry}} = \frac{p \times \text{SOC stock}_{\text{Tree row}} + (100 - p) \times \text{SOC stock}_{\text{Inter-row}}}{100} \quad (1)$$

273

274 where p is the percentage of tree row surface area in the agroforestry plot (Table 2).

275

276 The delta SOC stock (Mg C ha⁻¹) at a given depth was expressed as the difference in the SOC
277 stock between the agroforestry and the control plot:

$$278 \Delta_{\text{SOC stock}} = \text{SOC stock}_{\text{Agroforestry}} - \text{SOC stock}_{\text{Control}} \quad (2)$$

279

280 The SOC stock accumulation rates under an agroforestry system at a given depth was calculated
281 by dividing the delta SOC stock by the number of years since tree planting.

282

283

284 *2.6 Tree aboveground and belowground biomass*

285 At each site, 10 to 20 trees were measured to estimate the aboveground biomass. As the trees
286 in the farmers' fields could not be felled, the aboveground biomass was estimated by
287 multiplying the volume of the trunk and branches by the wood density, using the global wood
288 density database (Chave et al., 2009). The trunk volume was estimated as the sum of the volume
289 of three truncated cones, from the soil surface up to 1.30 m, from 1.30 m to the first branch and

290 from the first branch to the top of the tree. The trunk diameter was measured 5 cm above the
291 soil surface, at 1.30 m (Diameter at Breast Height, DBH) and below the first branch. The total
292 height (H_{tot}) and merchantable height (H) of the trees were also measured. The volume of the
293 first order branches (branches arising directly off the trunk) was also estimated by measuring
294 the diameter of the branches at the trunk and the length of the branches and branch volumes
295 were calculated as cone volumes. For the RE site, three trees were felled to measure the trunk
296 and branch biomass directly. The carbon concentrations of the trunk and branches of the
297 *Juglans regia* × *nigra* cv. NG23 were measured. As it was not possible to sample wood from
298 the tree trunks at the other sites, the C concentrations were considered to be the same for *Prunus*
299 *avium* and *Juglans nigra*. This simplification was possible because these trees are slow growing
300 species and there is usually little variation in their wood C concentration (462.7 to 499.7 mg C
301 g^{-1} DM) (Lamlom and Savidge, 2003). It was also assumed that young and old trees had the
302 same wood density and C concentration.

303 So far as we are aware, there is no allometric equation for estimating the belowground biomass
304 of temperate agroforestry trees and so the equation proposed by Cairns et al. (1997) for
305 temperate forests was used:

$$306 \quad \text{RB} = e^{-1.3267+0.8877 \times \ln(\text{AB})+0.1045 \times \ln(\text{Age})} \quad (3)$$

307 where RB is the total root biomass (Mg C ha^{-1}), AB is the aboveground biomass (Mg C ha^{-1})
308 and Age is the age of the plantation (yr).

309

310 2.7 Statistical analyses

311 The influence of the sampling location in the inter-rows (in front of a tree or between two trees)
312 on the SOC concentration, bulk density and SOC stock was determined using mixed effects

313 models. This analysis was done at each site using the *nlme* package (Pinheiro et al., 2013). An
314 ANOVA was performed on these models. Mixed effects models were then fitted for each site
315 using the whole soil data set. The SOC concentration, bulk density and SOC stock were
316 compared as a function of depth, location (control, tree row, inter-row) and distance from the
317 closest tree. An ANOVA was performed on these models. The SOC stock were compared
318 between tree rows and inter-rows, between inter-rows and the control plot and between the
319 agroforestry plot and the control plot. The statistical analyses were performed using R version
320 3.1.1 (R Development Core Team, 2013), at a significance level of < 0.05 .

321

322 **3. Results**

323 *3.1 Soil bulk density*

324 At all sites, the soil bulk density increased significantly with increasing soil depth (Table 3, S1).
325 In the top 30 cm, the bulk density ranged from 0.7 to 1.6 g cm⁻³ depending on the site. There
326 was no significant difference in bulk density between the tree row and the inter-row except in
327 the top 10 cm at the ME, SJ and RE sites, where it was lower in the tree row than in the inter-
328 row and in the control (Table 3, S1). There was no significant difference between the control
329 and the inter-row at any depth, except at the RE site where the bulk density was higher in the
330 top 10 cm in the control plot (Table 3, S1).. The distance from the closest tree had no significant
331 effect on the bulk density except at the SJ site (Table S1). There was no significant difference
332 in the inter-row between samples collected in front of a tree or between two trees at any of the
333 sites or at any depth (p-value ≥ 0.18), except at the ME site (p-value = 0.03) (Table S1).

334

335

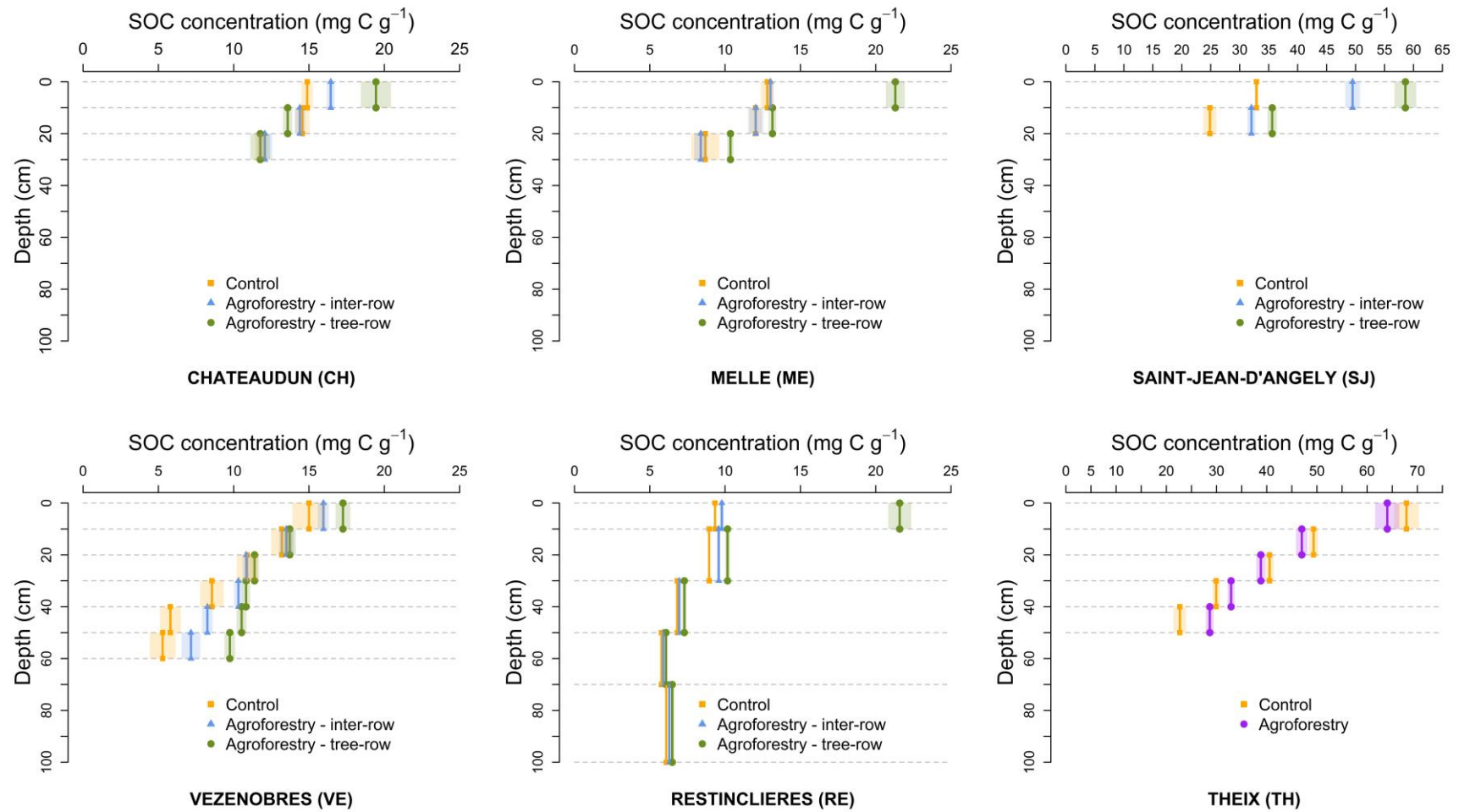
336 **Table 3** Mean soil bulk density (g cm^{-3}) and mean soil organic carbon (SOC) concentrations (mg C g^{-1}) with associated standard errors.

Site	Soil depth (cm)	Number of soil samples			Bulk density (g cm^{-3})			SOC concentration (mg C g^{-1})		
		Tree row	Inter-row	Control	Tree row	Inter-row	Control	Tree row	Inter-row	Control
CH	0-10	12	24	12	1.09 ± 0.03	1.10 ± 0.02	1.18 ± 0.02	19.44 ± 1.00	16.44 ± 0.26	14.88 ± 0.38
	10-20	12	24	12	1.12 ± 0.02	1.13 ± 0.02	1.16 ± 0.03	13.58 ± 0.31	14.39 ± 0.34	14.56 ± 0.48
	20-30	12	24	12	1.15 ± 0.02	1.20 ± 0.01	1.25 ± 0.02	11.76 ± 0.65	12.07 ± 0.48	11.78 ± 0.35
ME	0-10	12	18	6	1.04 ± 0.03	1.27 ± 0.02	1.31 ± 0.01	21.30 ± 0.63	13.01 ± 0.19	12.80 ± 0.43
	10-20	12	18	6	1.28 ± 0.02	1.29 ± 0.02	1.37 ± 0.03	13.14 ± 0.26	12.03 ± 0.50	12.02 ± 0.40
	20-30	12	18	6	1.21 ± 0.01	1.34 ± 0.01	1.35 ± 0.02	10.35 ± 0.21	8.38 ± 0.44	8.68 ± 0.93
SJ	0-10	8	16	12	0.67 ± 0.03	0.76 ± 0.02	0.78 ± 0.01	58.60 ± 1.88	49.49 ± 1.28	32.89 ± 0.33
	10-20	8	16	12	0.84 ± 0.03	0.78 ± 0.03	0.88 ± 0.04	35.60 ± 0.82	32.01 ± 0.67	24.86 ± 1.12
VE	0-10	12	18	10	1.06 ± 0.04	0.98 ± 0.03	0.91 ± 0.02	17.25 ± 0.49	15.95 ± 0.37	15.00 ± 1.11
	10-20	12	18	10	1.12 ± 0.02	1.18 ± 0.02	1.24 ± 0.03	13.72 ± 0.40	13.50 ± 0.49	13.19 ± 0.70
	20-30	12	18	10	1.16 ± 0.03	1.25 ± 0.01	1.31 ± 0.02	11.38 ± 0.30	10.83 ± 0.25	10.89 ± 0.68
	30-40	12	18	10	1.29 ± 0.04	1.39 ± 0.02	1.47 ± 0.04	10.82 ± 0.27	10.31 ± 0.29	8.55 ± 0.78
	40-50	12	18	10	1.30 ± 0.05	1.37 ± 0.03	1.34 ± 0.03	10.52 ± 0.33	8.25 ± 0.35	5.79 ± 0.69
	50-60	12	18	10	1.36 ± 0.04	1.39 ± 0.04	1.37 ± 0.06	9.74 ± 0.35	7.16 ± 0.62	5.28 ± 0.86
RE	0-10	40	60	93	1.10 ± 0.02	1.23 ± 0.03	1.41 ± 0.01	21.59 ± 0.76	9.78 ± 0.13	9.33 ± 0.06
	10-30	40	60	93	1.49 ± 0.01	1.60 ± 0.02	1.61 ± 0.00	10.16 ± 0.16	9.57 ± 0.12	8.94 ± 0.05
	30-50	40	60	93	1.71 ± 0.01	1.67 ± 0.02	1.73 ± 0.00	7.29 ± 0.15	6.95 ± 0.11	6.82 ± 0.10
	50-70	40	60	93	1.73 ± 0.01	1.77 ± 0.01	1.80 ± 0.00	6.07 ± 0.11	5.89 ± 0.07	5.77 ± 0.06
	70-100	40	60	93	1.68 ± 0.00	1.71 ± 0.00	1.74 ± 0.00	6.49 ± 0.16	6.29 ± 0.06	6.09 ± 0.06
TH	0-10		27	10		0.75 ± 0.02	0.69 ± 0.02		64.00 ± 2.40	67.83 ± 2.45
	10-20		27	10		0.79 ± 0.01	0.75 ± 0.01		46.97 ± 1.15	49.31 ± 0.89
	20-30		27	10		0.80 ± 0.02	0.73 ± 0.02		38.82 ± 0.88	40.56 ± 0.86
	30-40		27	10		0.82 ± 0.01	0.78 ± 0.02		32.90 ± 0.70	29.92 ± 0.75
	40-50		19	10		0.80 ± 0.01	0.79 ± 0.03		28.65 ± 0.76	22.69 ± 1.25

338 At the TH silvopastoral site, no distinction was made between tree rows and inter-rows (uniform cover), values are for the whole agroforestry plot.

339 CH: Châteaudun, ME: Melle, SJ: Saint-Jean-d'Angély, VE: Vézénobres, RE: Restinclières, TH: Theix.

340



341

342 **Figure 3.** Soil organic carbon concentration (mg C g⁻¹) at the different sites. Transparent rectangles represent standard errors. At the TH
 343 silvopastoral site, no distinction was made between tree rows and inter-rows (uniform cover), values are for the whole agroforestry plot.

344 3.2 Soil organic carbon concentration

345 The SOC concentration decreased significantly with increasing soil depth, except in the
346 ploughed layer, where it was uniform (Table 3, S1). At all sites, the SOC concentration in the
347 top 10 cm was significantly higher in the tree row than in the inter-row (Fig. 3). However, there
348 was no significant difference in the inter-row between samples collected in front of a tree and
349 between two trees ($p\text{-value} \geq 0.32$) at any site and at any depth. The SOC concentration
350 depended significantly on the distance from the trees only at the oldest site (SJ, $p\text{-value} < 0.001$)
351 (Table S1). At sites CH, SJ and RE, the SOC concentration in the top 10 cm was significantly
352 higher in the inter-rows than in the control plot (Fig. 3, Table 3). At the VE and RE silvoarable
353 sites, the SOC concentration was significantly higher in the inter-row than in the control below
354 30 cm (Fig. 3, Table 3). At the TH silvopastoral site, the SOC concentration below 30 cm was
355 also significantly higher in the silvopasture than in the tree-less pasture (Fig. 3, Table 3).

356

357 3.3 Soil organic carbon stock

358 The SOC stock was mainly influenced by depth and location (Table S1). In the inter-row, there
359 was no significant difference between samples collected in front of a tree and between two trees
360 ($p\text{-value} \geq 0.30$). The distance from the closest tree had no significant effect on the SOC stock
361 ($p\text{-value} \geq 0.5$) except at the SJ site ($p\text{-value} = 0.005$) (Table S1). In the silvoarable systems,
362 the SOC stock was significantly higher in the tree rows than in the inter-rows in the top 10 cm,
363 even in young plantations (CH and ME sites) (Fig. 4). The SOC stock was also significantly
364 higher in the inter-rows than in the control at depths of 10 cm at the CH site, 20 cm at the SJ
365 site and 30 cm at the RE site, as happened for SOC concentration (Fig. 4). Unlike, at the VE
366 site, the SOC stock was higher in the inter-rows than in the control below 30 cm (Fig. 4). At

367 the TH silvopastoral site, the SOC stock below 30 cm was higher in the agroforestry plot than
368 in the control.

369 In the top 30 cm, the delta SOC stock between silvoarable systems and control plots was
370 significantly positive except at the ME and VE sites (Table 4). For the silvoarable sites, the
371 delta SOC stock ranged from 0.5 to 4.5 Mg C ha⁻¹ in the top 30 cm (Table 4), and was about 19
372 Mg C ha⁻¹ in the top 20 cm for the oldest silvoarable system (SJ). At the RE and VE silvoarable
373 sites, the delta SOC stock was significantly positive below 30 cm depth. At the TH silvopastoral
374 site, the delta SOC stock was not significantly different in the top 30 cm (-0.16 ± 0.25 Mg C
375 ha⁻¹) but was significantly positive for the whole soil profile (0.49 ± 0.27 Mg C ha⁻¹) down to
376 60 cm (Table 4).

377

378 3.4 Carbon stock in the tree biomass

379 The wood density of *Juglans regia* × *nigra* cv. NG23 was 0.62 g cm⁻³, that of *Juglans nigra*
380 was 0.59 g cm⁻³ and that of *Prunus avium* was 0.54 g cm⁻³. The C concentrations of the trunk
381 and branches of 18-year-old *Juglans regia* × *nigra* cv. NG23 were 445.71 ± 1.04 and $428.64 \pm$
382 1.70 mg C g⁻¹ DM, respectively. At the silvoarable sites, the organic carbon stocks in the
383 aboveground biomass of the trees ranged from 0.02 to 26.64 Mg C ha⁻¹ depending on the tree
384 density and age (Table 5). The aboveground tree C stock was the highest at the silvopastoral
385 site, reaching about 37 Mg C ha⁻¹. The estimated C stocks in the tree belowground biomass
386 ranged from 0.01 to 6.61 Mg C ha⁻¹ at the silvoarable sites and was more than 9 Mg C ha⁻¹ at
387 the TH silvopastoral site (Table 5).

388

389

390 **Table 4** Soil organic carbon stock (Mg C ha⁻¹) and SOC stock accumulation rate (Mg C ha⁻¹ yr⁻¹).

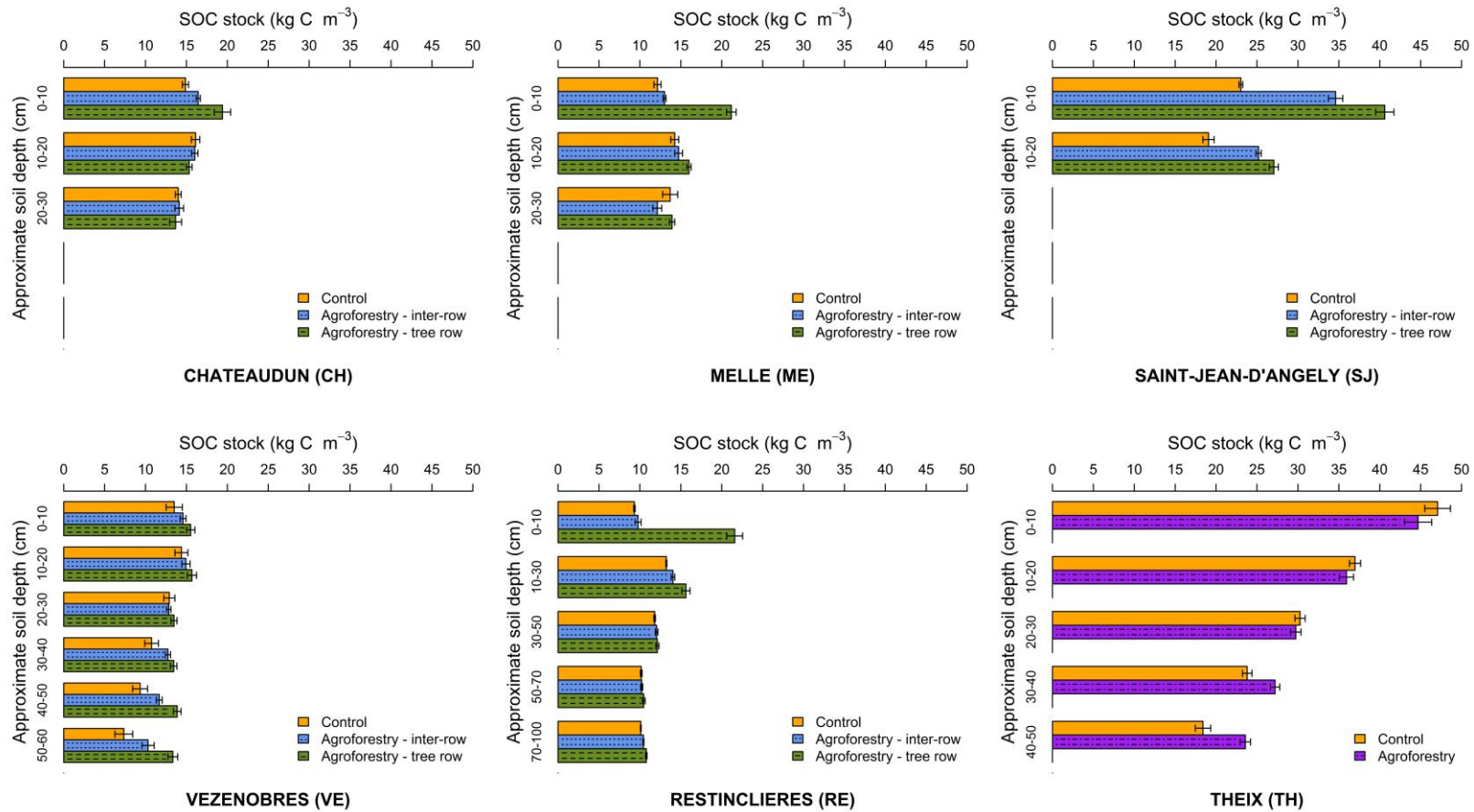
Site	Cumulative ESM (Mg ha ⁻¹)	Approximate soil depth (cm)	Cumulative SOC stock (Mg C ha ⁻¹)				$\Delta_{SOC\ stock}$ (Mg C ha ⁻¹)	SOC stock accumulation rate (Mg C ha ⁻¹ yr ⁻¹)		
			Tree row	Inter row	AF	Control		AF – Control	AF/Control	Tree row/Control
CH	1000	0-10	19.4 ± 1.0	16.4 ± 0.3	16.7 ± 0.3	14.9 ± 0.4	1.8 ± 0.5*	0.30 ± 0.08*	0.76 ± 0.18*	0.26 ± 0.08*
	2100	0-20	34.8 ± 1.2	32.5 ± 0.5	32.7 ± 0.5	31.0 ± 0.9	1.7 ± 1.0*	0.28 ± 0.17*	0.63 ± 0.25*	0.25 ± 0.17*
	3250	0-30	48.4 ± 1.7	46.6 ± 1.0	46.7 ± 1.0	45.0 ± 1.1	1.7 ± 1.4*	0.29 ± 0.24*	0.57 ± 0.33*	0.27 ± 0.25*
ME	1000	0-10	21.2 ± 0.6	13.0 ± 0.2	13.6 ± 0.2	12.2 ± 0.3	1.4 ± 0.4*	0.24 ± 0.07*	1.50 ± 0.11*	0.14 ± 0.07*
	2200	0-20	37.2 ± 0.6	27.7 ± 0.5	28.4 ± 0.5	26.4 ± 0.9	2.0 ± 1.1*	0.33 ± 0.18*	1.79 ± 0.19*	0.22 ± 0.18*
	3500	0-30	51.1 ± 0.8	39.9 ± 0.9	40.7 ± 0.9	40.1 ± 1.7	0.5 ± 2.0	0.09 ± 0.33	1.83 ± 0.32*	-0.04 ± 0.33
SJ	700	0-10	40.6 ± 1.1	34.6 ± 0.9	35.5 ± 0.8	23.0 ± 0.2	12.4 ± 0.8*	0.30 ± 0.02*	0.43 ± 0.03*	0.28 ± 0.02*
	1450	0-20	67.7 ± 1.1	59.8 ± 1.0	60.9 ± 0.9	42.1 ± 0.8	18.8 ± 1.2*	0.46 ± 0.03*	0.62 ± 0.03*	0.43 ± 0.03*
VE	900	0-10	15.5 ± 0.5	14.6 ± 0.4	14.8 ± 0.3	13.5 ± 1.0	1.3 ± 1.0*	0.07 ± 0.06*	0.11 ± 0.06*	0.06 ± 0.06*
	2000	0-20	31.2 ± 0.8	29.5 ± 0.8	29.8 ± 0.6	27.9 ± 1.5	1.9 ± 1.6*	0.11 ± 0.09*	0.18 ± 0.09*	0.09 ± 0.09*
	3150	0-30	44.7 ± 1.0	42.4 ± 0.9	42.8 ± 0.8	40.8 ± 2.0	2.0 ± 2.2	0.11 ± 0.12	0.21 ± 0.12*	0.09 ± 0.12
	4400	0-40	58.1 ± 1.2	55.1 ± 1.2	55.7 ± 1.0	51.8 ± 2.5	3.9 ± 2.7*	0.22 ± 0.15*	0.35 ± 0.16*	0.19 ± 0.16*
	5700	0-50	72.0 ± 1.5	66.8 ± 1.3	67.7 ± 1.1	61.2 ± 3.2	6.5 ± 3.4*	0.36 ± 0.19*	0.60 ± 0.20*	0.31 ± 0.19*
	7050	0-60	85.3 ± 1.9	77.1 ± 1.6	78.6 ± 1.4	68.6 ± 4.1	10.0 ± 4.3*	0.56 ± 0.24*	0.93 ± 0.25*	0.48 ± 0.25*
RE	1000	0-10	21.6 ± 1.0	9.8 ± 0.4	11.7 ± 0.3	9.3 ± 0.1	2.3 ± 0.4*	0.13 ± 0.02*	0.68 ± 0.05*	0.02 ± 0.02*
	4000	0-30	52.8 ± 1.4	37.9 ± 0.6	40.3 ± 0.5	35.8 ± 0.2	4.5 ± 0.6*	0.25 ± 0.03*	0.95 ± 0.08*	0.12 ± 0.03*
	7300	0-50	77.1 ± 1.5	62.0 ± 0.7	64.4 ± 0.6	59.4 ± 0.2	5.0 ± 0.6*	0.28 ± 0.04*	0.98 ± 0.08*	0.14 ± 0.04*
	10700	0-70	98.1 ± 1.5	82.4 ± 0.7	84.9 ± 0.6	79.7 ± 0.3	5.1 ± 0.7*	0.29 ± 0.04*	1.02 ± 0.08*	0.15 ± 0.04*
	15700	0-100	130.4 ± 1.5	113.7 ± 0.7	116.4 ± 0.7	110.1 ± 0.3	6.3 ± 0.7*	0.35 ± 0.04*	1.13 ± 0.09*	0.20 ± 0.05*
TH	700	0-10	-	-	44.2 ± 3.4	47.1 ± 1.6	-2.9 ± 3.8	-0.11 ± 0.14	-	-
	1450	0-20	-	-	80.4 ± 5.0	84.1 ± 1.9	-3.7 ± 5.3	-0.14 ± 0.20	-	-
	2200	0-30	-	-	110.2 ± 6.1	114.3 ± 2.3	-4.1 ± 6.5	-0.16 ± 0.25	-	-
	3000	0-40	-	-	137.6 ± 6.5	138.2 ± 2.3	-0.5 ± 6.9	-0.02 ± 0.26	-	-
	3800	0-50	-	-	169.3 ± 6.5	156.5 ± 2.7	12.8 ± 7.0*	0.49 ± 0.27*	-	-

391 Associated errors are standard errors. Approximate depths are presented here to give a better understanding of the ESM for a given site but do not
392 correspond to the precise mass of the profile, which may vary between tree rows, inter-rows and the control (Ellert and Bettany, 1995). At the TH
393 silvopastoral site, no distinction was made between tree rows and inter-rows (uniform cover). Significantly different (p-value < 0.05) delta SOC
394 stock ($\Delta_{SOC\ stock}$) and additional SOC storage rate are followed by *. ESM: Equivalent Soil Mass, AF: Agroforestry. CH: Châteaudun, ME: Melle,
395 SJ: Saint-Jean-d'Angély, VE: Vézénobres, RE: Restinclières, TH: Theix.

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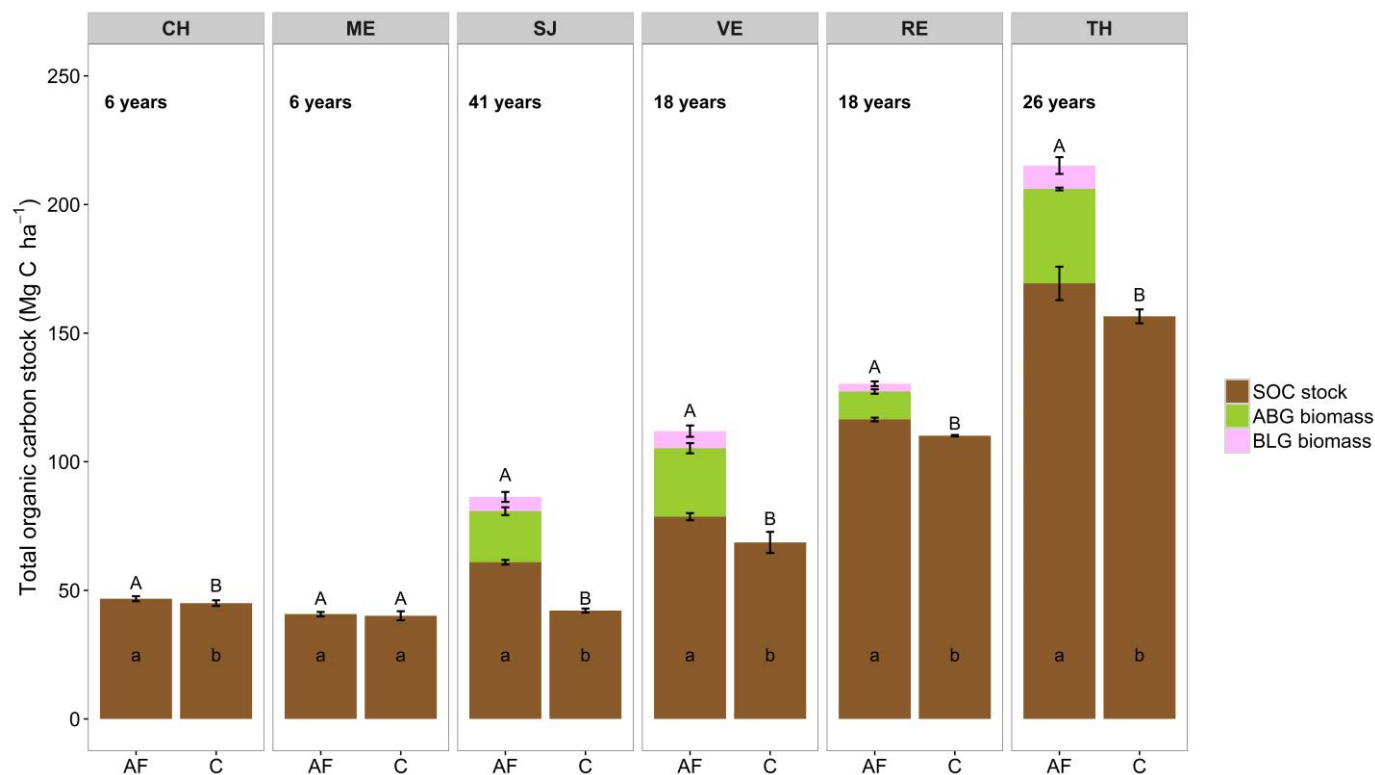
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400 **Figure 4.** Soil organic carbon stock (kg C m⁻³) at the different sites. Bars represent standard errors. Approximate depths are presented but refer to
 401 equivalent soil mass. At the TH silvopastoral site, no distinction was made between tree rows and inter-rows (uniform cover), values are
 402 for the whole agroforestry plot.



403

404 **Figure 5.** Total organic carbon stock (Mg C ha⁻¹) of the different sites. AF: agroforestry, C: agricultural control. SOC: Soil organic carbon, ABG:
 405 Aboveground, BLG: Belowground. CH: Châteaudun, ME: Melle, SJ: Saint-Jean-d'Angély, VE: Vézénobres, RE: Restinclières, TH:
 406 Theix. Studied depths vary between sites: 30 cm for CH, 30 cm for ME, 20 cm for SJ, 60 cm for VE, 100 cm for RE and 50 cm for TH.
 407 Different lowercase letters indicate a significant (p-value < 0.05) difference of SOC stock between AF and C plots per site, and different
 408 uppercase letters indicate a significant difference (p-value < 0.05) in the total organic carbon stock between AF and C plots per site.

409 *3.5 Total carbon stock of the different systems*

410 At the silvoarable sites, the total C stock (SOC + biomass) ranged from about 50 Mg C ha⁻¹ to
411 125 Mg C ha⁻¹, and reached 220 Mg C ha⁻¹ at the TH silvopastoral site (Fig. 5). The total C
412 stock was always higher in the agroforestry systems than in the control plots. In the young
413 plantations (CH and ME), the total C stock was mainly SOC, with tree C stock accounting for
414 less than 0.01% of the total C stock. At oldest sites, up to 75% of the difference between total
415 C stock in the agroforestry systems and control plots was explained by the tree biomass (Fig.
416 5).

417

418 *3.6 Organic carbon accumulation rate in soil and tree biomass*

419 The mean SOC stock accumulation rate in the top 30 cm in the silvoarable systems was 0.18
420 Mg C ha⁻¹ yr⁻¹ (0.09 to 0.29 Mg C ha⁻¹ yr⁻¹). This rate reached 0.24 Mg C ha⁻¹ yr⁻¹ when the SJ
421 silvoarable site and its shallow soil (20 cm) was taken into account. At the RE site, the SOC
422 stock accumulation rate was 0.25 Mg C ha⁻¹ yr⁻¹ in the top 30 cm, and 0.35 Mg C ha⁻¹ yr⁻¹ in the
423 top 100 cm, with a SOC stock accumulation rate of about 0.1 Mg C ha⁻¹ yr⁻¹ in the 30-100 cm
424 layer (Table 4). Tree rows contributed about 20% to 50% to the SOC stock accumulation rate
425 although they covered only 7% to 18% of the agroforestry surface area.

426 The C accumulation rate in the tree biomass in CH and ME young plantations was negligible
427 (0.004 and 0.02 Mg C ha⁻¹ yr⁻¹, respectively) (Table 5). In the older and denser silvoarable
428 sites, this rate ranged from 0.62 to 1.85 Mg C ha⁻¹ yr⁻¹, and was 1.76 Mg C ha⁻¹ yr⁻¹ at the TH
429 silvopastoral site (Table 5).

430

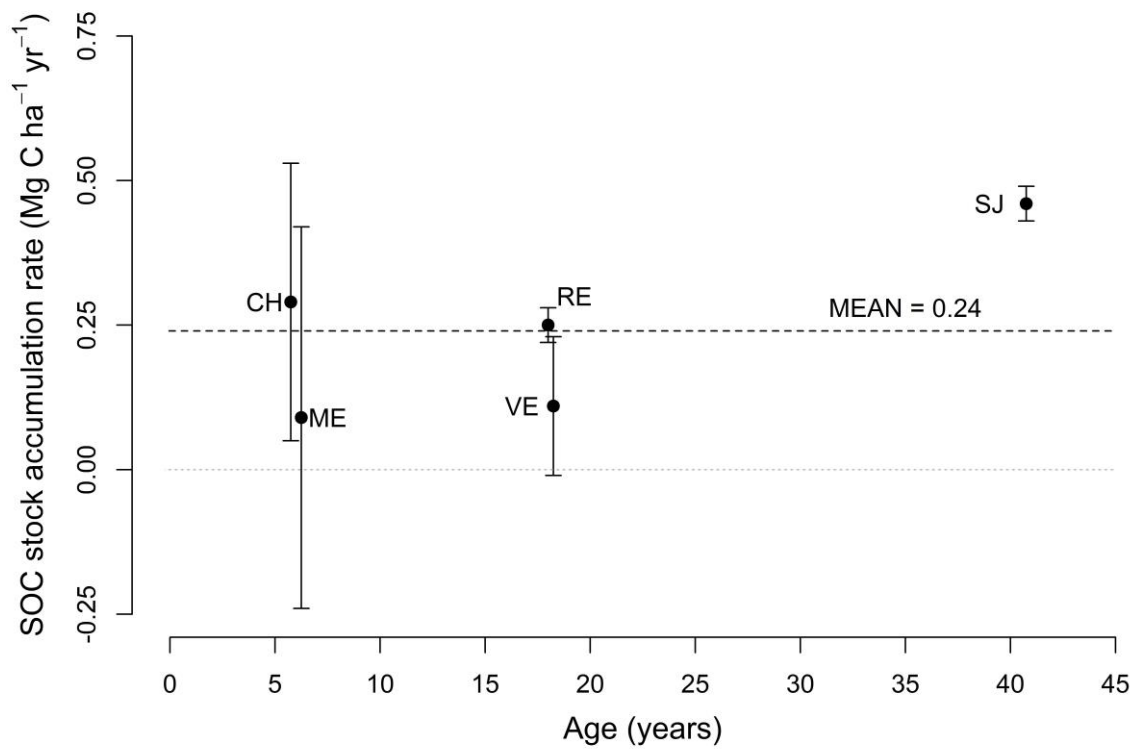
431

432 **Table 5** Tree characteristics, aboveground and belowground carbon stocks at the various sites.

Site	Age (yr)	DBH (cm)	Height of merchantable timber (m)	Total height (m)	C stock of merchantable timber (kg C tree ⁻¹)	ABG tree C stock (kg C tree ⁻¹)	ABG tree C stock (Mg C ha ⁻¹)	Estimated BEG tree C stock (Mg C ha ⁻¹)	Estimated total tree C stock accumulation rate (Mg C ha ⁻¹ yr ⁻¹)
CH	6	2.6 ± 0.2	1.45 ± 0.04	2.12 ± 0.11	0.44 ± 0.06	0.49 ± 0.07	0.017 ± 0.002	0.01 (0.01-0.01)	0.004 ± 0.0004
ME	6	5.5 ± 0.3	1.13 ± 0.03	3.18 ± 0.13	1.18 ± 0.12	2.07 ± 0.19	0.073 ± 0.007	0.03 (0.03-0.04)	0.02 ± 0.001
SJ	41	29.9 ± 1.3	3.11 ± 0.23	13.18 ± 0.10	41.44 ± 2.36	194.56 ± 14.94	19.85 ± 1.52	5.55 (3.28-9.38)	0.62 ± 0.10
VE	18	31.7 ± 1.5	4.17 ± 0.18	15.52 ± 0.36	56.85 ± 3.77	266.44 ± 19.90	26.64 ± 1.99	6.61 (4.00-10.95)	1.85 ± 0.27
RE	18	25.5 ± 1.4	4.49 ± 0.39	11.21 ± 0.65	46.23 ± 2.47	98.93 ± 7.80	10.88 ± 0.86	2.99 (1.89-4.72)	0.77 ± 0.11
TH	26	30.7 ± 1.4	4.10 ± 0.23	14.70 ± 0.32	53.80 ± 1.76	183.46 ± 2.66	36.69 ± 0.53	9.13 (5.34-15.63)	1.76 ± 0.25

433 Errors represent standard errors. Number of measured trees: CH=24, ME=20, SJ=10, VE=10, RE=9 except for biomass measurements where n=3,
 434 and TH=10. Values in brackets represent the 95% prediction interval for estimating the belowground biomass (Cairns et al., 1997). ABG:
 435 Aboveground, BEG: Belowground. CH: Châteaudun, ME: Melle, SJ: Saint-Jean-d'Angély, VE: Vézénobres, RE: Restinclières, TH: Theix.

436



437

438 **Figure 6.** SOC stock accumulation rates as a function of plantation age. Values are for the
 439 approximate top 30 cm, except for the SJ site (approximate top 20 cm, maximum soil
 440 depth).

441 **4. Discussion**

442 *4.1 Spatial variation of SOC stock in silvoarable systems*

443 The sampling protocol was designed to take account of the spatial distribution of SOC stocks
444 as a function of distance from the trees. Sampling in the inter-rows in front of a tree or between
445 two trees did not affect the estimation of SOC stocks. The protocol could, therefore, be
446 simplified for instance by sampling only in front of a tree or by sampling along the diagonal of
447 the sampling pattern, which was equivalent to a quarter of the Voronoi polygon (Levillain et
448 al., 2011). Field sampling would then be less costly and less time-consuming.

449 The distance from the trees had no effect on SOC stocks in the inter-rows, except at the oldest
450 SJ site. At this 41-year-old site, the width of the cropped alley had been reduced over the past
451 10 years owing to light competition, which might explain the gradient of SOC stocks observed.
452 At the RE site, Cardinael et al., (2015b) suggested that close to the trees, organic C input coming
453 from tree fine root senescence (Cardinael et al., 2015a; Germon et al., 2016), exudates and
454 leaves might be compensated by a decrease in organic C input from crop residues owing to
455 lower yields (Dufour et al., 2013). The same hypothesis might apply at the VE site, where no
456 SOC stock gradient was found in the inter-rows (same tree density, same tree species and tree
457 age as the RE site). Consequently, fewer soil samples could be taken to estimate SOC stock in
458 the inter-rows. However, these two 18-year-old sites had a high tree density, the distance
459 between two tree rows (11 m and 13 m) being almost the same as the mean tree height (15 m
460 and 11 m). It is possible that a SOC stock gradient may appear with time in the inter-rows in
461 low-density plantations with a large distance between two tree rows (> 30 m). This gradient
462 effect could also depend on the tree species. This hypothesis could be tested in the future at the
463 CH and ME sites.

464 At all the silvoarable sites, the SOC stock was higher in the tree rows than in the inter-rows and
465 in the control plot, especially in the topsoil layer (0-10 cm). Tree rows therefore had a
466 considerable effect on SOC storage, contributing up to 50% of the additional SOC storage at
467 silvoarable plot scale for only a small surface area. There were two main sources of organic
468 matter returned to the soil in the tree rows: carbon from the trees (litter, fine roots and exudates)
469 and carbon from the herbaceous vegetation. At the RE site, the aboveground and belowground
470 biomass of the herbaceous vegetation in the tree rows was 2.13 Mg C ha⁻¹ and 0.74 Mg C ha⁻¹,
471 respectively (unpublished data). The C input to the soil from this vegetation in the tree rows
472 could, therefore, be up to 2.9 Mg C ha⁻¹ yr⁻¹. The spaces between the trees along the tree rows
473 could be considered comparable to grass strips or natural grassland because of the herbaceous
474 cover and the lack of soil tillage. Converting annual crop cultivation to grassland was shown to
475 be very efficient in terms of SOC storage by Conant et al., (2001), Arrouays et al., (2002), and
476 Soussana et al., (2004) with SOC stock accumulation rates ranging from 0.49 Mg C ha⁻¹ yr⁻¹ to
477 1.01 Mg C ha⁻¹ yr⁻¹ in the top 30 cm. Based on their results and on the high SOC stocks also
478 measured in the topsoil in tree rows of young plantations with small tree biomass, we suggest
479 that a major part of the SOC storage in the tree rows is due to the herbaceous vegetation. There
480 was no clear difference between sown and natural herbaceous vegetation in the tree rows,
481 although the highest SOC stock accumulation rate was obtained for sown grass (ME site, 1.3
482 Mg C ha⁻¹ yr⁻¹). However, the management of these tree rows seems to be a key factor for
483 increasing the SOC storage capacity of silvoarable systems. Several studies showed that
484 including legumes in the composition of grasslands increased herbage productivity (Tilman et
485 al., 2001; Marquard et al., 2009; Prieto et al., 2015) and SOC storage (Steinbeiss et al., 2008;
486 Lange et al., 2015).

487

488

489 4.2 SOC stock accumulation rates in silvoarable systems

490 In the five silvoarable systems studied, the mean SOC stock accumulation rate in the top 30 cm
491 was 0.24 (0.09-0.46) Mg C ha⁻¹ yr⁻¹. This estimate for silvoarable plots with an average age of
492 17.8 -yr, is slightly lower than previously suggested for 20-yr-old agroforestry systems in
493 France (0.30 (0.03-0.41) Mg C ha⁻¹ yr⁻¹) by Pellerin et al. (2013) based on a literature review
494 but it is of the same order of magnitude. The SOC stock accumulation rate was also slightly
495 lower than those reported by Oelbermann et al. (2006) for a 13-yr-old Canadian alley cropping
496 system combining hybrid poplars and wheat, soybean and maize grown in rotation (0.30 Mg C
497 ha⁻¹ yr⁻¹ in the top 20 cm and 0.39 Mg C ha⁻¹ yr⁻¹ in the top 40 cm). As well as, Peichl et al.
498 (2006) reported a SOC stock accumulation rate of 1.04 Mg C ha⁻¹ yr⁻¹ in the top 20 cm for a
499 13-yr-old hybrid poplar and Norway spruce-barley agroforestry system. Overall, our estimated
500 SOC stock accumulation rate is slightly lower than most published results (Lorenz and Lal,
501 2014; Kim et al., 2016). However, as reported by Cardinael et al. (2015b), our study estimated
502 SOC storage in silvoarable systems using the equivalent soil mass, which gives more accurate
503 results when soil bulk density is modified by changes in land use (Ellert and Bettany, 1995;
504 Ellert et al., 2002), as was the case in these systems, especially in the tree rows. Furthermore,
505 most fields in our study were owned and managed by farmers. Although this fact may generate
506 some uncertainties, it has the advantage of taking account of a broad variety of practices that
507 are commonly used by farmers.

508 At the two 18-year-old silvoarable sites (RE and VE) there was a significant increase in deep
509 SOS stocks (below 30 cm). At the VE site this might be partially due to a slightly higher sand
510 content in the control plot than in the agroforestry plot below 30 cm. At the RE site, this increase
511 might result from a high density of deep tree fine roots (Mulia and Dupraz, 2006; Cardinael et
512 al., 2015a). Although the SOC stock accumulation rate was lower than in topsoil layers, deep
513 soil layers might then be able to store a large amount of SOC over a longer period owing to

514 better SOC stabilization conditions (Rasse et al., 2005). However, little is known about the
515 effect of fresh organic matter input on deep soil layers and some authors found that this might
516 stimulate the mineralization of old organic matter (Fontaine et al., 2004, 2007).

517 There was no change in the SOC stock accumulation rates with time in the silvoarable systems
518 (Fig. 6) but very old sites (> 40 year old) were under-represented in this study. It is therefore
519 difficult to assess the possible effect of tree age on the SOC accumulation rate. Tree growth
520 increases organic litter production with time but competition with the intercrop also increases,
521 potentially causing a decrease in crop yields such as cereals (Dufour et al., 2013). In a recent
522 meta-analysis, Kim et al., (2016) found a slight decrease in the SOC stock accumulation rates
523 in very old agroforestry systems, which was attributed to the soil reaching a new SOC stock
524 equilibrium. Based on technical limits (soil depth, water holding capacity, field size), Pellerin
525 et al., (2013) and Chenu et al., (2014) estimated that about 4 M ha of arable land could be
526 converted to silvoarable systems in France. Given the estimated SOC stock accumulation rate
527 in this study, this would mean that $3.6 \cdot 10^5$ to $1.84 \cdot 10^6$ Mg C could be stored annually in the soil.

528

529 *4.3 Carbon storage in silvopastoral systems*

530 The silvopastoral system set up on an andosol on permanent grassland (Tables 3 and 4) had no
531 more additional SOC in the top 30 cm than grassland without trees. This site had been under
532 pasture for decades before tree planting. It had a high SOC concentration (about 65 mg C g^{-1} at
533 0-10 cm) and the soil was possibly at a steady state so that it could not store additional SOC, at
534 least in fine soil fractions (Hassink, 1997). On a Patagonian andosol, Dube et al., (2012) also
535 found that there was no significant difference in the SOC stocks in the top 40 cm of a
536 silvopastoral system compared to a natural pasture. At our site, there was a significant effect of
537 the silvopastoral system on SOC concentration and stock in the 30-50 cm layer: the SOC

538 concentration in the silvopastoral system was about 29 mg C g⁻¹ while in the grassland control
539 it was only about 23 mg C g⁻¹. It is possible that these deep soil layers in grasslands might be
540 less SOC-saturated than topsoil layers and that roots from agroforestry trees could, therefore,
541 contribute to additional SOC storage at depth. Haile et al. (2010) also found that trees affected
542 deep SOC storage in silvopastoral systems. The biomass production of pastures in silvopastoral
543 systems is usually less sensitive to shade than that of annual crops such as cereals grown in
544 silvoarable systems (Moreno et al., 2007a, b; Moreno, 2008), except for N₂ fixing species
545 (Carranca et al., 2015). Furthermore, grass under the tree cover can have a longer growing
546 season (Puerto et al., 1990) and forage quality can be improved under tree canopies (Cubera et
547 al., 2009). Therefore, silvopastoral systems might support a higher tree density than silvoarable
548 systems (Benavides et al., 2009; Devkota et al., 2009), resulting in higher C stocks in the tree
549 biomass (> 35 Mg C ha⁻¹ in this case).

550

551 *4.4 Carbon storage in the tree biomass*

552 The C stock in the tree biomass in the young plantations was negligible but, in the old
553 plantations, C storage was greater in the tree biomass than in the soil (Fig. 5). The C
554 accumulation rate in the tree biomass was higher in the old plantations than in young
555 plantations. This is explained by the much higher total leaf area of old trees compared to very
556 young trees and, therefore, by a higher photosynthesis capacity (Stephenson et al., 2014).
557 However, estimates of the tree root biomass may be underestimated by the forest allometrics
558 used. The architecture of agroforestry trees is different from forest trees owing to a lower
559 intraspecific competition and to pruning. Moreover, agroforestry trees have been shown to be
560 very deep rooted owing to soil tillage and to competition with intercrops (Mulia and Dupraz,
561 2006; Cardinael et al., 2015a).

562 Carbon stock in the tree biomass is not usually considered as a long-term C sink in the same
563 way as the SOC stock but the residence time of C in the harvested biomass depends on the fate
564 of wood products and can be as long as many decades for timber wood (Profft et al., 2009;
565 Bauhus et al., 2010), which was the case for the trees grown at the sites studied. Branches could
566 be used as a substitute for fossil fuel to produce energy (Kürsten, 2000; Cardinael et al., 2012)
567 or be returned to the soil as ramial chipped wood amendments (Barthès et al., 2010).

568

569 **5. Conclusion**

570 This study showed the potential of agroforestry systems to increase carbon stock in both the
571 soil and tree biomass under different pedo-climatic conditions in France. The sampling protocol
572 evaluated the spatial distribution of SOC stock and the results showed that it could be simplified
573 for future studies. SOC stocks accumulated mainly in the tree rows and mainly in the top 30 cm
574 of soil, but at deeper soil layers in two silvoarable sites, as well. Further studies are required to
575 gain a better assessment of the effect of agroforestry on deep SOC stock. Allometric equations
576 should be developed for trees grown in temperate agroforestry systems to reduce the uncertainty
577 of tree root biomass estimates. Very old sites (> 40 years old) were under-represented in our
578 dataset and long-term experimental agroforestry sites are required to assess the effect of trees
579 on soil carbon over long periods.

580

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591

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801 **Table S1** ANOVA on the linear mixed-effects (LME) model for SOC content, bulk density and SOC stock in the agroforestry plots as a function
 802 of depth, location (inter-row or tree row), distance to the closest tree, and interactions between these.

Site		Soil organic carbon content		Bulk density		Soil organic carbon stock	
		F-value	Pr(>F)	F-value	Pr(>F)	F-value	Pr(>F)
CH	Depth	64.982	<0.0001	10.956	0.0001	22.341	<0.0001
	Location	2.246	0.137	3.153	0.079	1.890	0.173
	Distance	0.394	0.532	0.266	0.607	0.379	0.540
	Depth×Location	8.078	0.0006	0.672	0.513	6.908	0.002
	Depth×Distance	0.576	0.564	0.296	0.744	0.570	0.568
	Location×Distance	0.227	0.635	0.226	0.636	0.472	0.494
ME	Depth	140.956	<0.0001	20.473	<0.0001	24.004	<0.0001
	Location	130.363	<0.0001	78.246	<0.0001	116.989	<0.0001
	Distance	0.012	0.911	7.257	0.008	0.016	0.900
	Depth×Location	51.699	<0.0001	15.888	<0.0001	45.731	<0.0001
	Depth×Distance	1.627	0.202	1.910	0.154	2.895	0.063
	Location×Distance	0.004	0.949	0.162	0.688	0.144	0.705
SJ	Depth	370.623	<0.0001	7.285	0.0104	284.905	<0.0001
	Location	35.543	<0.0001	0.356	0.554	33.719	<0.0001
	Distance	15.183	0.0004	0.691	0.411	8.827	0.005
	Depth×Location	6.719	0.014	6.305	0.017	9.250	0.004
	Depth×Distance	4.101	0.0501	7.985	0.008	10.264	0.002
	Location×Distance	0.987	0.327	1.534	0.223	0.728	0.399
VE	Depth	110.547	<0.0001	39.920	<0.0001	19.071	<0.0001
	Location	24.017	<0.0001	5.956	0.016	23.272	<0.0001
	Distance	0.001	0.980	0.674	0.413	0.083	0.773
	Depth×Location	2.801	0.019	1.998	0.082	2.243	0.053
	Depth×Distance	0.086	0.994	0.917	0.472	0.151	0.980
	Location×Distance	0.278	0.599	0.095	0.758	0.075	0.785
RE	Depth	703.719	<0.0001	391.32	<0.0001	723.666	<0.0001
	Location	223.367	<0.0001	23.90	<0.0001	66.935	<0.0001
	Distance	2.229	0.1387	2.12	0.1491	2.353	0.1283
	Depth×Location	272.736	<0.0001	10.04	<0.0001	68.377	<0.0001
	Depth×Distance	2.338	0.0173	0.68	0.7137	1.775	0.0784
	Location×Distance	4.425	0.0380	1.25	0.2666	3.285	0.0731

	Depth	89.206	<0.0001	2.739	0.033	59.624	<0.0001
	Location	0.040	0.842	0.577	0.449	0.032	0.859
	Distance	1.511	0.222	6.966	0.010	0.446	0.506
TH	Depth×Location	0.673	0.612	0.817	0.517	0.622	0.648
	Depth×Distance	0.225	0.924	0.750	0.560	0.341	0.850
	Location×Distance	0.235	0.629	1.663	0.200	0.001	0.975

803 CH: Châteaudun, ME: Melle, SJ: Saint-Jean-d'Angély, VE: Vézénobres, RE: Restinclières, TH: Theix.

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