Drivers of soil carbon stabilization in oil palm plantations

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26 **ABSTRACT**

27 Increasing soil organic carbon (SOC) in agroecosystems is necessary to mitigate climate

28 change and soil degradation. Management practices designed to reach this goal call for a

29 deeper understanding of the processes and drivers of soil carbon input stabilization. We

30 identified main drivers of SOC stabilization in oil palm plantations using the well-defined

31 spatial patterns of nutrients and litter application resulting from the usual management

32 scheme. The stabilization of oil palm-derived SOC (OP-SOC) was quantified by $\delta^{13}C$ from a

33 shift of C4 (savanna) to C3 (oil palm) vegetations. Soil organic carbon stocks under frond

34 piles were 20 and 22 % higher compared to harvest paths and interzones, respectively.

35 Fertilization and frond stacking did not influence the decomposition of savanna-derived SOC.

36 Depending on management zones, net OP-SOC stabilization equalled 16-27% of the fine root

37 biomass accumulated for 9 years. This fraction was similar between frond piles and litter-free

38 interzones, where mineral NPK fertilization is identical, indicating that carbon inputs from

39 dead fronds did not stabilize in SOC. A path analysis confirmed that the OP-SOC distribution

40 was largely explained by the distribution of oil palm fine roots, which itself depended on

41 management practices. SOC mineralization was proportional to SOC content and was

42 independent on phosphorus availability. We conclude that SOC stabilization was driven by C

43 inputs from fine roots and was independent of alteration of SOC mineralization due to

44 management. Practices favouring root growth of oil palms would increase carbon

45 sequestration in soils without necessarily relying on the limited supply of organic residues.

46

47 **KEYWORDS:** carbon isotopes - fertilization - fine roots - microbial activity - structural

48 equation modelling - savanna - Colombia

49

1. INTRODUCTION

Soil organic carbon (SOC) depletion in agroecosystems is a major source of greenhouse gas emissions, resulting in losses of soil fertility and ecosystem stability (Amundson et al., 2015). Policymakers have recently acknowledged the promotion of soil C sequestration in agroecosystems as a promising strategy to simultaneously mitigate climate change and enhance food security (Lal, 2016). Nonetheless, management practices favouring soil C sequestration lead to highly variable outcomes, calling for a deeper understanding of processes and factors controlling C stabilization, especially after land-use changes (Ghimire, Lamichhane, Acharya, Bista, & Sainju, 2017; Haddaway et al., 2017). This is particularly needed in regions that are undergoing rapid and substantial land degradation following conversion from largely forested landscapes to intensive agricultural systems, as has been the case in tropical landscapes dominated by oil palm (*Elaeis guineensis*) plantations. In Sumatra, a region with a long history of oil palm cultivation, a significant proportion of oil palm plantations has already reached a critical low level of SOC content (< 1%) in the topsoil (Guillaume, Holtkamp, Damris, Brümmer, & Kuzyakov, 2016).

Stocks of SOC depend on the balance between soil C inputs from vegetation and outputs from SOC mineralization, erosion and leaching (Lorenz & Lal, 2018). This balance is strongly affected by the conversion of natural ecosystems to intensive agricultural land (Guillaume et al., 2018). Predicting impacts of land-use change and management on SOC dynamics and its stabilization faces major difficulties as many factors affect both litter input and mineralization processes that determine the fraction of C input stabilized in SOC. While higher plant biomass inputs might lead to higher SOC accumulation, an increase of fresh organic matter inputs may enhance the mineralization of more recalcitrant SOC that ultimately reduces the gain in SOC, a process known as priming (Kuzyakov, Friedel, & Stahr, 2000). Nutrient application modifies the stoichiometry of organic matter inputs and of soil organic matter, which in turn

3

75   affects microbial processes controlling SOC stabilization (Qiao et al., 2016; Zang, Wang, &

76   Kuzyakov, 2016). For instance, altered microbial carbon use efficiency (i.e. the ratio of C

77   incorporated into microbial biomass to the added C) or mining for nutrients from recalcitrant

78   SOC result in either SOC gains or losses (Finn et al., 2016; Kirkby et al., 2014). Quantifying

79   soil C inputs remains a methodological challenge and few data are available, for instance, on

80   root turnover, rhizodeposition, and the fraction of aboveground litter C stabilized in SOC

81   (Pausch & Kuzyakov, 2018). Experimental data are especially limited for perennial plants in

82   tropics and subtropics.

83   The fast SOC turnover in the tropics makes soils particularly sensitive to land-use

84   change (Guillaume, Damris, & Kuzyakov, 2015; Pabst, Gerschlauer, Kiese, & Kuzyakov,

85   2016; Zech et al., 1997). For example, soil C inputs decrease up to 90% when rainforests are

86   converted to oil palm plantations, resulting in a rapid drop of SOC (Guillaume et al., 2018).

87   Soil organic C losses are not, however, uniform within plantations, and specific management

88   zones within the plantation may even exhibit a gain in SOC (Khasanah, van Noordwijk,

89   Ningsih, & Rahayu, 2015; Rahman et al., 2018). Soil C inputs in mature oil palm plantations

90   without cover crops (the most common practice) occurs mostly belowground through

91   rhizodeposition because the understorey is frequently cleared. Significant aboveground C

92   inputs occur only under frond piles, i.e. zones where dead fronds are stacked. A gradient of

93   fertilizer application is superimposed on the gradient of soil C input: most fertilizers are

94   applied around the trunks and, in some cases, additionally to the whole surface area at lower

95   rate, including the frond piles but excluding the harvest path. These management practises

96   lead to characteristic management zones with specific factors affecting SOC dynamics (Fig

97   1a). With plantation ageing, the heterogeneity of SOC distribution increases, depending on

98   the distance to the tree, the presence of frond piles and fertilizer applications (Frazão,

99   Paustian, Pellegrino Cerri, & Cerri, 2013; Goodrick et al., 2015). Carbon and nutrients cycling

are, thus, highly heterogeneous leading to a variable SOC equilibrium depending on management practices. This highlights the possibility to promote the increase of overall SOC stocks by redesigning management practices to reach this goal.

In Colombia, oil palm plantations are often established on native savanna grasslands dominated by grasses with a C4 photosynthesis pathway. The shift from C4 (grasses) to C3 vegetation (oil palm) allows source determination in soil organic matter using its δ^{13}C signature (Balesdent & Mariotti, 1987). The aim of the present study is to disentangle the effects of soil C and nutrient inputs on newly accumulated SOC (oil palm-derived) and the decomposition of old SOC (savanna-derived), taking advantage of the specific patterns of fertilization and soil C inputs in the four management zones. We hypothesized that soil C inputs and consequent SOC accumulation increase with fine root density, which itself depends on plantation age and distance to trees, as well as on the presence of frond piles. Fertilizer application is, however, expected to decrease SOC stabilization rates where soil C inputs are low. Hence, the specific aims of the study are to i) quantify the new oil palm-derived (C3 signature) and the old savanna-derived SOC stocks (C4) in a mature oil palm plantation established on native savanna grassland, ii) assess oil palm root development and its impact on SOC accumulation with plantation age, iii) determine the impacts of management practices on root development and soil microbial activity and iv) identify the main factors (root density, nutrient availability, microbial activity) driving SOC stabilization.

2. MATERIALS AND METHODS

2.1. Study area

The study was conducted in the Eastern Plains (*Llanos Orientales*), Department Meta, Colombia (4°05'7.0"N, 71°53'59.0"W). The region experiences a tropical climate (mean

125 annual temperature of 26 °C and yearly precipitation of 2200 mm yr^{-1}) with a distinct dry

126 season from December to March and 95% of the yearly rain falling between April and

127 November (Lavelle et al., 2014; Rippstein, Amézquita, Escobar, & Grollier, 2001). The study

128 site lies in the slightly undulating well-drained high plains (Altillanura plana) dominated by

129 Plinthosols and Ferralsols (IUSS Working Group WRB, 2014). These soils have a low

130 fertility, high acidity and high aluminium saturation limiting agricultural production (Lavelle

131 et al., 2014; Rippstein et al., 2001). The natural vegetation is an herbaceous savanna with

132 scarce bushes, which is drained by many small rivers. Gallery forests (morichales) grow in

133 the depressions along these rivers (Rippstein et al., 2001).

134 Two unmanaged native savanna sites and three oil palm plantations with increasing age

135 (2-, 4-, and 9-year old) were selected within an area of approximately 8 × 8 km and sampled

136 in July and August 2016 (Fig. S1). Sites were carefully chosen with the help of plantation

137 agronomists to ensure that the investigated plantations had been established on unmanaged

138 native savannas, i.e. no cattle grazing in the past. Soils in the five selected sites were classified

139 as sandy-loam Ferralsols (clay content and pH ranging from 11 to 16% and from 4.5 to 5.3 in

140 the top 30 cm, respectively) with compacted top soil (bulk density ranging from 1.31 to 1.46

141 g cm^{-3} in the top 10 cm). Drivers of SOC stabilization were assessed in the 9-year old

142 plantation. The 2- and 4-year old plantations were selected to assess the development of oil

143 palm rooting system and its relationship with SOC accumulation.

144

145 *2.2. Plantation management*

146 Oil palm plantations had been established on native savannas whose soils were first loosened

147 with a chisel plough (to a depth of 40 cm) and tilled with an overturning plough (10 cm).

148 Liming and phosphate rocks were applied before planting palms. Oil palm trees had been

149 planted in a triangular grid pattern with a distance of 9 m between trees, leading to 143 palms

150 ha^{-1} (Fig. 1b). In the young plantations (2- and 4-year old), a mixture of Kudzu (*Pueraria*

151 *phaseoloides*) and Desmodium (*Desmodium heterocarpon* subsp. *ovalifolium*) cover crops

152 (C3 vegetation) have been implemented after planting. Cover crops were never used in the

153 mature plantation (9 years), and in this case the soil was always kept bare after planting with

154 oil palms. Accordingly, C3-derived SOC in the 9-year old plantation are attributed solely to

155 oil palm-derived SOC.

156 Oil palm management leads to four well-defined management zones in productive

157 plantations (about 4 years after establishment). In the study region, the weeded circle (WC)

158 around the oil palm trunk is always kept free of vegetation (Fig. 1). At young ages (2- and 4-

159 year old), all fertilizers are applied in WC. Associated with the beginning of harvest after 4

160 years, pruning starts and fronds are piled up in between palm trees (frond pile, FP). Each

161 second avenue between palm lines becomes a harvest path (HP), where machines circulate.

162 In productive plantations (after 4 years), fertilizers are evenly spread from the harvest path by

163 machines, i.e. all management zone receive the same amount of fertilizers except the harvest

164 path that receive none. The remaining area, especially the alternating avenue, represents the

165 fourth zone, where the soil is kept bare and fertilization starts after 4 years (interzone, IZ).

166 The relative surface area of the four management zones were 60% (IZ), 18% (HP), 12% (WC)

167 and 10% (FP). Fertilization depends on oil palm stand age. The 9-year old plantation received

168 per hectare during the first year about 240 kg of NPK, 60 kg of kieserite (MgSO$_4$), and 25 kg

169 of KCl, of zinc and of boron. The amount of NPK increased over time while the use of other

170 types of fertilizer varied from year to year. The year before sampling, 600 kg of NPK, 200 kg

171 of phosphate rocks and 160 kg of KCl-MgO per hectare were spread in the plantation.

172

173 *2.3. Soil and roots sampling*

174   Plots of 1 ha were established in all plantations and savannas in areas with homogeneous soil,

175   far from the influence of roads, rivers or groundwater, free of laterite formations (arecife) and

176   without former amendment of compost or residues from processing oil mills. Five trees as

177   replicates for management zones were selected randomly in each plantation. For each of the

178   five replicate of trees, the adjacent management zones (FP, HP, IZ, and WC) were sampled

179   on a systematic grid (Fig. 1). Frond piles, harvest paths and interzones were sampled at the

180   same distance from trees (4.5 m) to assess the effects of management starting 4 years after

181   establishment. Two additional points in the interzone were sampled at 2 and 3 m away from

182   the trunk to assess the horizontal expansion of oil palm roots (IZ2, IZ3, Fig. 1). In the 2- and

183   4-year old plantations, only the weeded circles and interzones were sampled because of the

184   absence of frond piles and harvest path in young plantations. In the 2-year old plantation, the

185   point IZ3 was not sampled, as root densities were already low in IZ2 (Fig. S2). In the savanna

186   plots, five sampling points were selected at regular distances along a 100 m transect.

187   Roots and soils were sampled with a cylindrical corer of 5 cm diameter at three depth

188   intervals (0-10, 10-20 and 20-30 cm). Roots were separated from soil by sieving at 2 mm and

189   rinsed to remove attached mineral particles. Fine roots that passed through the sieve were

190   manually picked. For the 2- and 4-year old plantations outside of weeded circles, cover crop

191   roots were removed from oil palm roots. Oil palm roots were divided into coarse roots (> 2

192   mm, corresponding to primary and secondary roots of oil palms) and fine roots (< 2 mm,

193   corresponding to tertiary and quaternary roots of oil palms). Dry root biomass was determined

194   after drying at 60 °C for 48 h. Soil samples were air-dried and sieved at 2 mm directly after

195   collection and further oven dried at 40 °C for 48 h prior to laboratory analyses.

196

197   *2.4. Soil analysis*

198   Total C and nitrogen (N) contents in soil, as well as $\delta^{13}C$ signature were determined at the

199   University of Göttingen with an isotope ratio mass spectrometer (Delta Plus, Finnigan MAT,

200   Bremen, Germany). Because of the absence of carbonates in acidic soils, total C represents

201   organic C. Residual water content was assessed by drying soil samples at 105 °C for 24 h.

202   Bulk density was measured by inserting horizontally two cylinders of 100 cm^3 per depth at 0-

203   5, 5-10, 10-20 and 20-30 cm depth in a soil pit located at the centre of each sampling plot.

204   Bulk density in each cylinder was determined after drying at 105 °C and averaged between

205   four cylinders for 0-10 cm depth interval and 2 cylinders for 10-20 and 20-30 cm depth

206   intervals. Carbon stocks were calculated multiplying C contents with bulk density and the

207   layer thickness and the respective fractions of C4 (savanna-derived C) and C3 (oil palm-

208   derived) SOC. Soil available phosphorous (P) was determined using Bray II extraction

209   method (Bray & Kurtz, 1945). Three grams of soil were extracted by shaking for 15 min with

210   20 ml of 0.03 N NH_4F and 0.025 N HCl. Filtered extracts were mixed with a colorimetric

211   reagent ((NH_4)$_6Mo_7O_{24}$ – $SnCl_2$) and absorbance was measured with a UV/VIS spectrometer

212   at 660 nm (Lambda 35, Perkin Elmer, Buckinghamshire, United Kingdom).

213

214   ***2.5. C3 and C4 derived carbon***

215   Relative portion of oil palm- and savanna-derived C in SOC were calculated based on the

216   differences in $\delta^{13}C$ signature of biomass between savanna grassland, dominated by C4

217   photosynthetic pathway, and oil palms, C3 photosynthetic pathway, using two sources linear

218   isotopic mixing model (Balesdent & Mariotti, 1987):

219
$$f_{OP\_d} = \frac{\delta^{13}C_{S\_d} - \delta^{13}C_{NS\_d}}{\delta^{13}C_{OP\_b} - \delta^{13}C_{NS\_b}}$$

220   where f_{OP_d} is the fraction of oil palm (C3)-derived SOC, $\delta^{13}C_{S\_d}$ is the isotopic signature

221   measured in a soil sample at depth d, $\delta^{13}C_{NS\_d}$ is the average isotopic signature at the

222 corresponding depth in natural savanna reference sites, $\delta^{13}C_{OP\_b}$ is the averaged signature of

223 oil palm fine roots in the mature oil palm plantation (mean = -28.2‰, standard deviation (SD)

224 = 0.18, n = 9) and $\delta^{13}C_{NS\_b}$ is the average isotopic signature of the aboveground and

225 belowground savanna biomass determined on representative subsamples of aboveground

226 biomass collected on 1 m² and fine roots collected with soil cores at each sampling point

227 (mean = -13. 6 ‰, SD = 1.1, n = 19). This approach assumes that the ^{13}C fractionation

228 occurring during the integration of biomass into SOC at each soil depth is the same for

229 savanna and oil palm biomass (Pausch & Kuzyakov, 2012). No ^{13}C fractionation was

230 observed between savanna plant biomass and savanna SOC in 0-10 cm layer (-13.7 ‰, SD =

231 0.5, n = 10).

232

233 *2.6. Carbon stabilization per cumulative standing root biomass*

234 Fine root stocks served as a proxy for the C input from oil palm roots. To account for

235 differences in root stocks between management zones and root development time depending

236 on the distance to the palm tree, cumulative standing fine root biomass in each management

237 zone was estimated by fitting a linear model on root biomass measured in various plantation

238 ages. The model was integrated starting from plantation establishment for WC, but only

239 starting from 4 years for IZ, FP and HP, i.e. when oil palm rooting system reached 4.5 m away

240 from the tree (Fig. S2). Assuming constant belowground C input per unit of fine roots (Pausch,

241 Tian, Riederer, & Kuzyakov, 2013), oil palm-derived SOC stocks were normalized per unit

242 of cumulated fine root biomass to assess the effect of management zones on net C3

243 stabilization efficiency.

244

245 *2.7. Soil incubation*

246   Microbial biomass was analysed after incubation of topsoils (0-10 cm) from the 9-year old

247   plantation (zones FP, HP, IZ and WC). Twenty grams of dry soil were rewetted to 60% WHC

248   and incubated at 25 °C for 31 days. Jars were ventilated and weighed every week and rewetted

249   once to compensate for the evaporated water. Carbon and nitrogen (N) in microbial biomass

250   were measured at the end of the incubation by the fumigation-extraction method (Vance et

251   al., 1987). For C and N contents, 5 g of incubated soil were fumigated for 24 h with ethanol-

252   free $CHCl_3$ in a desiccator. Soils were extracted by shaking 1 h in 25 ml solution of 0.5 M

253   K_2SO_4 and then filtered. Non-fumigated samples were processed in parallel. Total extractable

254   organic C and N were analysed with a TOC-N analyser (Shimadzu, Kyoto, Japan). Extractable

255   C in the non-fumigated samples was assumed to represent dissolved organic carbon (DOC).

256   Microbial biomass C and N were calculated as the difference between fumigated and non-

257   fumigated samples, which were used also to calculate microbial C:N ratio. Microbial biomass

258   C was corrected by dividing extractable C with a factor of 0.45 (Beck et al., 1997), N with a

259   factor of 0.54 (Brookes, Landman, Pruden, & Jenkinson, 1985).

260

261   ***2.8. Basal respiration***

262   Basal respiration of the rewetted samples was measured with the MicroResp[TM] kit (Campbell,

263   Chapman, Cameron, Davidson, & Potts, 2003). Three analytical replicates of 0.5 g for each

264   field replicate were taken from the incubation jars after rewetting and incubated in 96 deep-

265   well plate in parallel to the incubation in jars. Soil was kept moist by a moist paper towel

266   fixed on the plate. Respiration was measured 1, 2, 4, 8, 15, 18, 24 and 31 days after rewetting

267   using a MicroResp[TM] kit (Campbell et al., 2003). To remove residual CO_2 in the wells, the

268   plate was aerated with a fan before incubating for 6 h with the indicator plate on top (at 27

269   °C). The indicator plate was read before and after incubation with a spectrophotometer

270   (Microplate reader BioTek SynergyMX) at 570 nm. Absorption calibration was done by

271 dissolving a known amount of $NaCO_3$ with 1 M HCl in excess in closed jars with eight

272 microwells of the indicator plate for 6 h (Campbell et al., 2003).

273   Soil respiration was partitioned using a two-pool mixed-model to describe SOC

274 mineralization kinetics (Bonde & Lindberg, 1988). The first pool follows a first-order

275 decomposition kinetics, while the second follows a zero-order kinetics, corresponding to the

276 stabilized basal respiration:

277 $$Cmin = C_l(1 - e^{-tk_l}) + BR\ t$$

278 where t is the time, *Cmin* is the cumulative CO_2 mineralized to time t, C_l is the labile C pool

279 released from sample preparation and re-wetting, k_l is the decomposition constant of the labile

280 pool and *BR* is the basal respiration. The basal respiration of each field replicate was

281 determined by fitting the model on the three analytical replicates. The metabolic quotient is

282 the ratio of basal respiration over microbial biomass C (Cmic).

283

284 ***2.9. Statistical analyses***

285 All statistical analyses were performed using the open source software R version 3.2.1 (R

286 Core Team, 2016). One sampling point in WC and one in IZ were removed from all analyses

287 due to very low $\delta^{13}C$ signatures, probably resulting from the former presence of C3 bush at

288 these exact sampling locations. We used a linear mixed-effects model approach ("lme4"

289 package), followed by Tukey HSD tests for post hoc pairwise comparisons, to test for the

290 effects of management zones (FP, HP, IZ and WC) on soil parameters (bulk, C3 and C4

291 stocks, fine root biomass, net C3 stabilization, basal respiration, microbial biomass C and C:N

292 ratio, and metabolic quotient) at each soil depth (0-10, 10-20 and 20-30 cm) in the mature

293 plantation (9-year old) with palm trees as random factor. Normal distribution of residuals and

294 homogeneity of variance were tested by Shapiro and Levene tests, respectively, and data was

295 log-transformed if necessary. Causal relationships between parameters (C stocks *vs.* age, C3

296   stocks *vs.* fine roots) were assessed by linear regressions. Average C stocks at plot scale down

297   to 30 cm depth were calculated using the relative surface area of each management zone.

298   Associations among parameters were calculated using Pearson correlation. *P-values* were

299   determined using the function *cor.test*.

300   A path analysis was performed to disentangle the direct and indirect effects of fine roots,

301   soil microorganisms and nutrient application on the accumulation of oil palm-derived SOC

302   by using the "lavaan" package (Rosseel, 2012). Based on the priori knowledge, we developed

303   an initial conceptual model that was both consistent with our data and which made biological

304   sense (Fig. S3). We first created five conceptual groups of measured variables, which

305   represented i) nutrient application (measure of available P), ii) fine roots C inputs (measure

306   of fine roots biomass), iii) SOM quality (measure of C:N ratio of SOM), iv) SOC

307   accumulation (measure of oil palm-derived SOC) and v) soil microorganism effects. As a

308   proxy for the microbial effect, we used the score of each sample on the first axis (PC1 = 68

309   %) of a principal component analysis (PCA) including all microbial related variables (soil

310   basal respiration, metabolic quotient, Nmic, Cmic, microbial C:N ratio) (Fig. S4). The

311   conceptual model hypothesized that fine roots biomass and microbial activity have a direct

312   impact on oil-palm SOC accumulation. Both might be affected by nutrient application.

313   Additionally, microbial activity would be directly affected by root density through the amount

314   of rhizodeposition and indirectly by changing organic matter quality. Finally, P availability

315   could have a direct effect on microorganisms and SOM quality by changing the resources'

316   stoichiometry in the soil. Pedoclimatic factors affecting SOC stabilization (e.g. soil

317   mineralogy) were not specified in the model because they are identical between zones and

318   cannot be modified by management. The adequacy of the model was determined by non-

319   significant differences between the predicted and observed covariance matrices ($\chi 2$ tests, *p* >

320   0.05), low root mean squared error of approximation index (RMSEA < 0.1), high Tucker-

321 Lewis index (TLI > 0.90) and high comparative fit index (CFI > 0.90) (Grace, 2006; Rosseel,

322 2012).

323

324 **3. RESULTS**

325

326 *3.1. Soil organic carbon stocks and origin*

327 Observations done on the 9-year old plantation showed lower soil C stocks compared to the

328 native savanna grasslands (Fig. 2). On average, 1.0 ± 0.2 kg C m^{-2} was lost down to 30 cm

329 depth, considering the relative area of each management zone. However, spatial SOC

330 distribution in the mature oil palm plantation depended on management zones. Soil C losses

331 during that period of time in the top 10 cm under frond piles and, to a lesser extent, under

332 weeded circles were lower than C losses in harvest paths and interzones (Fig. 2). This trend

333 was similar down to 30 cm depth but the differences were not significant below 10 cm depth.

334 Differences in SOC stocks between management zones arose mainly from a higher

335 accumulation of oil palm-derived SOC (C3-derived) under frond piles and weeded circles

336 (Fig. 2). Oil palm-derived SOC after 9 years already accounted for between 27% (IZ) and

337 45% (FP and WC) of the total SOC stock in the top 10 cm, where differences between zones

338 were highest. Below 20 cm depth, the contribution of oil palm-derived SOC dropped,

339 accounting for 2% (IZ) and maximum 12% (WC) of the total SOC stocks. The amount of

340 savanna-derived SOC (C4-derived) remaining after 9 years was lower in the top 10 cm than

341 between 10-20 cm depth, indicating a faster decomposition of this C pool in the top soil

342 compared to deeper soil layers. Nonetheless, management zones had little influence on the

343 decomposition rates of savanna-derived SOC, except in 10-20 cm depth under weeded circles

344 where more C lost than under frond piles. A similar trend was observed in the top 10 cm

345 that explains why total SOC under weeded circles was intermediate as compared to frond

14

piles and harvest paths, despite the high amount of oil palm-derived SOC stabilized under

weeded circles.

3.2. Root development and C inputs

Oil palm fine roots were first observed at 4.5 m away from palm trees in two out of the five

investigated palms in the 4-year old plantations (Fig. S2). This indicates that oil palm rooting

systems from adjacent palms started to overlap at that age, but root biomass at 4.5 m was still

very low. Fine root biomass under weeded circles increased constantly during 9 years (Fig.

3a). At the age of 9 years, roots were observed in all management zones but root growth was

strongly enhanced under frond piles, reaching the same fine root biomass as under weeded

circles in only 5 years, well above fine root biomass in the interzones and harvest paths (Fig.

3a).

Oil palm-derived SOC under weeded circles was highly correlated with fine root

biomass (Fig. 3b). Oil palm-derived SOC stocks corresponded to 70 ± 5 % of fine root

biomass stocks (slope = 0.70, R^2 = 0.80) at the time of measurement, independently of soil

depth and plantation age. This percentage was relatively constant between the three soil

depths; from $62 \pm 10\%$ in the top 10 cm to $50 \pm 11\%$ between 20-30 cm depth (Table 1). Oil

palm-derived SOC accumulation per year was 3 to 4 times faster in the top soil 10 cm than in

the underlying layers (Table 1).

While oil palm-derived SOC in the weeded circle was accumulating from the beginning

of the plantation, root biomass was measured at fixed time points. Oil palm fine root biomass

was integrated over the whole duration of the plantation to calculate the cumulative fine roots

biomass for each year and soil depth under weeded circles. Accordingly, oil palm-derived

SOC accumulation corresponded to $14 \pm 2\%$, $11 \pm 2\%$ and $11 \pm 1\%$ of the cumulated fine roots

biomass stocks under weeded circles at 0-10, 10-20 and 20-30 cm depth, respectively (Table

1). Since soil depth had little impact on the relationship between oil palm-derived SOC and fine root biomass, differences in oil palm-derived SOC stabilization rates between depths were mainly related to differences in fine root biomass. The linear relationship across age showed that the proportion of oil-palm derived SOC stabilizing per amount of fine roots present in the plantation remains constant at least during 9 years (Fig. 3b).

Oil palm derived-SOC and fine root biomass were similar under frond piles and weeded circles in the top 10 cm in the 9-year old plantation (Fig. 3a). However, fine roots appeared at 4.5 m away from palms 4 years later than under weeded circles. To remove the effects of root density and duration of C inputs between zones, oil palm-derived SOC stocks were also divided by the cumulative roots biomass stocks and compared between management zones (Fig. 4).

After this normalization to the amount of fine root biomass, the stabilization of oil palm-derived SOC was similar between frond piles and interzones, two zones receiving the same amount of mineral fertilizers and sampled at the same distance to the tree. Consequently, only little C from the large amount of C present in dead fronds is eventually stabilized in SOC. The stabilization of oil palm-derived SOC was lower under weeded circles, the zone receiving the largest amount of mineral fertilizer, than under harvest paths, the only zone experiencing no direct application of mineral fertilizers.

3.3. Soil microorganisms and fertility

Microbial activity (basal respiration and metabolic quotient) and biomass (microbial biomass C and microbial C:N ratio) parameters were similar under frond piles and weeded circles (Fig. 5). In these two zones, the same amount of microbial biomass respired more C compared to harvest paths and interzones. Consequently, the metabolic quotient was highest under frond piles and weeded circles.

396   Available P (Bray II) was an order of magnitude higher in weeded circles compared to

397   the other zones, as expected by the higher fertilization application in that zone. Weeded circles

398   also had the lowest amount of K_2SO_4-extractable C (DOC) despite high SOC content. (Table

399   S1). Between the three zones (HP, IZ and FP) located at the same distance to the palm trees

400   but varying in their management, P availability was two times lower in harvest paths (11.1 ±

401   0.3 µg g^{-1}) as compared to frond piles, but well above the P availability in native savanna sites

402   (2.2 ± 0.3 µg g^{-1}), despite the absence of direct fertilization. The DOC amount was similar

403   between the three zones and the C:N ratio was 1 unit higher under frond piles, indicating that

404   only small change in SOC quality occurred between management zones.

405

406   *3.4. Drivers of the accumulation of oil palm-derived SOC*

407   In the three zones located at the same distance to the palm trees (HP, IZ and FP), oil palm-

408   derived SOC stocks (C3) were highly correlated with fine root biomass (r = 0.82), as well as

409   to most microbial parameters, the amount of soil organic matter (C and N contents) and

410   available P (Fig. 6). The basal respiration, the metabolic quotient and the microbial biomass

411   N increased with higher oil palm-derived SOC but not with total C content, underlying the

412   role of fresh organic C to maintain microbial activity. By contrast, higher C:N ratio in

413   microbial biomass and, to a lesser extent, higher microbial biomass were associated to less

414   oil palm-derived SOC and less fine roots biomass but with more savanna-derived SOC

415   remaining after conversion to oil palm.

416   A path analysis was performed to disentangle the direct and indirect effects of fine roots,

417   soil microorganisms and nutrient availability on the accumulation of oil palm-derived SOC

418   at 4.5 m away from palm trees in the 9-year old plantation. Because of the high association

419   among all microbial parameters (Fig. 6), the scores of each sample on the first axis (PC1 = 68

420   %) of a principal component analysis (PCA) including all microbial related parameters were

17

421 used as a proxy for soil microorganisms in the path analysis (Fig. S4). The fitting parameters

422 of the model were good ($P\chi^2 = 0.33$, RMSEA = 0.09, TLI = 0.97, CFI = 0.99), and the model

423 explained 71% of the variance in oil palm-derived SOC (Fig. 7). Fine root biomass was

424 strongly influenced by nutrient availability (available P) and was an important driver of

425 microbial properties (i.e. increase in microbial biomass N, basal respiration, specific

426 respiration and metabolic quotient and, in the opposite, decrease of microbial biomass C and

427 C:N ratio – see also Fig. 6). By contrast, nutrient availability had only a marginal ($p = 0.09$)

428 and opposite effect on soil microorganisms. While fine root biomass influenced SOM quality

429 (C:N ratio), microorganisms were not affected by SOM quality. The direct effect of fine roots

430 on oil palm-derived SOC stabilization was 2.8 times stronger than the marginal effect ($p =$

431 0.06) of soil microorganisms. Accordingly, nutrient availability had an important indirect

432 impact on the accumulation of oil palm-derived SOC by favouring root development and

433 thereby C inputs without enhancing SOC mineralization.

434

435 **4. DISCUSSION**

436

437 *4.1. Drivers of SOC stabilization*

438 Soil organic C stocks strongly varied depending on the management zones of the plantation.

439 Specific management impacted the amount of new oil palm C input and its stabilization into

440 SOC but had little effect on the decomposition rate of old savanna-derived SOC (Fig. 2).

441 Carbon stabilization was mainly driven by C inputs from fine roots rather than by changes in

442 C outputs from microbial mineralization (Fig. 7). The relationship between fine roots and oil

443 palm derived SOC remained weakly affected by soil depth, plantation age and management

444 zones (Table 1, Fig. 3 and 4). Fine root biomass was a good proxy for soil belowground C

445 inputs. Oil palm fine roots absorb nutrient and water, and therefore have definite growth and

18

short-term self-pruning. In contrast, coarse roots, which have the function of conduction, have

indefinite growth and long term self-pruning (Jourdan, Michaux-Ferrière, & Perbal, 2000; Jourdan & Rey, 1997). The relationship between cumulated fine root biomass and oil-palm derived SOC stocks would not remain constant once stocks reach equilibrium. The relationship, however, was linear (Fig. 3), indicating that SOC stocks were still far from equilibrium after 9 years of cultivation and that oil palm-derived SOC will continue to increase.

Microbial metabolism and biomass were strongly affected by fine roots. Higher organic C availability in terms of oil palm-derived SOC and C inputs under frond piles and in the weeded circle were associated with microbial communities characterized by a high mineralization activity but of low efficiency – the so termed r strategy (Loeppmann, Blagodatskaya, Pausch, & Kuzyakov, 2016). The high metabolic quotient results from either a low C use efficiency or a high microbial biomass turnover. By contrast, zones with low C availability such as the harvest path and the interzones were associated with microbial communities more efficient to maintain their biomass despite lower mineralization rates. Their lower metabolic quotients and their higher C:N ratios suggest that the scarcity of C increased the proportion of K strategists and fungi within microbial communities (Mouginot et al., 2014; Six, Frey, Thiet, & Batten, 2006). While the main effect of nutrient availability on microbial communities was indirect by increasing roots C inputs, it tended to have also a minor direct but contrasting effect on microbial communities. Lower C to nutrients ratio favours high C use efficiency of microorganisms, which would explain the larger microbial biomass in interzones despite the low microbial activity and root density (Sinsabaugh, Manzoni, Moorhead, & Richter, 2013). Nonetheless, management impacts on microbial communities and their resource consumption strategies levelled-off resulting in similar fraction of SOC mineralized in all management zones. Weeded circles were the only area of

471   the plantation showing slightly lower net SOC stabilization and savanna-derived SOC stocks

472   (Fig. 2 and 4). The very high amount of fertilizer applied already in the early stage of the

473   plantation might have slightly fastened SOC turnover. Nonetheless, management effects were

474   small in regards to the 10-fold increase of P availability in this zone as compared to the rest

475   of the plantation. The fact that nutrient availability had little impact on the SOC mineralization

476   and stabilization indicates that microorganisms were mostly C-limited. Indeed, soils were

477   depleted in SOC and the whole surface area of the plantations, even areas not directly

478   fertilized, experienced an increase in P availability as compared to native savannas.

479   In summary, management and its impact on soil belowground C inputs and nutrient

480   availability did not lead to priming of recalcitrant SOC nor to faster turnover of fresh organic

481   SOC, except around palms in the weeded circles. Hence, SOC distribution was not driven by

482   an altered decomposition of SOC pools but by different rates of fine root growth and the

483   resulting soil C inputs depending on management.

484

485   *4.2. Drivers of soil C inputs*

486   Oil palm rooting system follows a relatively rigid and genetically determined development

487   (Jourdan et al., 2000; Jourdan & Rey, 1997). Primary lateral roots start to grow one year after

488   germination at a rate of 3 mm d^{-1}, confirming that roots of palms, which are planted a year

489   after germination, reach 4.5 m in the fourth year of a plantation (Jourdan & Rey, 1997).

490   Nevertheless, root development showed plasticity, reacting to management as shown by the

491   fast development of fine roots under frond piles. Root development is generally enhanced in

492   nutrients-rich zones (Hodge, 2004). Phosphorous availability was an important driver of root

493   development, favoring soil C inputs from fine roots, and consequently the accumulation of

494   new SOC (Fig. 7). Its distribution did not exactly reflect the pattern of fertilizer application

495   (Table S1). Despite no direct fertilization applications, harvest paths were enriched in

496   available P as compared to the reference savanna sites and only frond piles exhibited a

497   significantly higher P availability. This discrepancy may result from the initial soil

498   preparation with dolomite and phosphate rocks and seems to be maintained over time by the

499   recycling of organic P inputs from rhizodeposition, root turnover, and frond mineralization.

500   The positive impact of frond piles on root development is likely not limited to P availability.

501   Fronds piles increase the availability of major cations (Law, Husni, Ahmed, & Haniff Harun,

502   2009). Similarly, it was shown that the application of empty fruit bunches on the surface

503   increases soil moisture (Tao, Slade, Willis, Caliman, & Snaddon, 2016) and roots

504   development (Kheong, Rahman, Musa, & Hussein, 2010). The positive impact of frond piles

505   on SOC stocks has been previously reported (Haron, Brookes, Anderson, & Zakaria, 1998;

506   Law et al., 2009) but authors have already highlighted the small increase of SOC stocks given

507   the huge amount of frond's biomass C concentrated on a small surface area (2-3 kg C m^{-2} yr^{-1}

508   in frond piles). It was suggested that fronds were mineralized mostly aboveground with little

509   contribution to SOC (Haron et al., 1998). Our findings confirm this hypothesis and indicate

510   that the positive impacts of frond piles arise more from the improvement of soil conditions

511   (likely nutrient availability, humidity, protection from erosion) that favours root growth than

512   from their role as a C source.

513

514   *4.3. Increasing SOC stocks*

515   Soil organic C stabilization depends on belowground C inputs and not on the management

516   induced variation of SOC mineralization rates (Fig. 7). This field evidence-based finding is

517   similar to the conclusion of a modelling study on arable cropping system in temperate zones

518   (Autret et al., 2016). Soil C inputs should be enhanced to increase soil C sequestration in oil

519   palm plantations. The current management practice that consist in piling dead fronds,

520   however, is not efficient to integrate the fronds' organic matter into the soil. This can be

521 explained by several mechanisms. First, organic matter quality in fronds is low due to high C

522 to nutrient ratios (Yusuyin et al., 2015). This decreases the C use efficiency of

523 microorganisms. Second, bioturbation from soil fauna is limited as indicated by a sharp

524 transition between decomposing fronds and the soil surface observed in the field. Soil fauna

525 abundance, especially of earthworms, and biogenic macroaggregates are lower in oil palm

526 plantations as compared to native savanna and in improved pastures (Lavelle et al., 2014).

527 Consequently, fronds' organic matter does not benefit from the protection mechanisms that

528 minerals would provide if it was integrated into the soils by fauna activity (Schmidt et al.,

529 2011). Application of composted mill residues would be a solution to decrease C to nutrient

530 ratios of litter and improve the integration of organic matter into the soil by favouring soil

531 fauna activity, humification and mineral protection.

532 The availability of organic residues from the palm oil production chain that could be

533 applied in plantations, however, is limited. Leguminous cover crops, as already implemented

534 in the younger plantations, are an alternative to increase aboveground and belowground C and

535 N inputs. Enhancing root growth by mimicking the effects of frond piles is a promising

536 solution to increase SOC if palms have plasticity to allocate more C to their rooting system

537 when soil conditions are favourable or if palm varieties are developed for that purpose. Oil

538 palm fronds could be spread on larger surface area or mixed with other residues, such as

539 empty fruit bunched or fibers, to make a mulch. Even solutions not based on organic matter

540 that would limit soil evaporation, retain nutrients, limit run-offs and erosion might improve

541 root development. Future research should address whether SOC stocks eventually recover to

542 initial SOC levels. Ensuring long-term soil fertility in oil palm plantations is fundamental to

543 avoid a conversion of natural ecosystem constrained by soil degradation in older plantation.

544 The benefits from increasing SOC in terms of climate change mitigation would cascade far

545 beyond the amount of C sequestrated in the soil because of the gain in soil fertility.

22

553

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

556

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TABLES

Table 1. Oil palm-derived SOC stabilization under weeded circles at each depth depending

on time, fine root biomass in the plantation and fine root biomass cumulated since plantation

establishment (mean $\pm$ SE). All linear regressions were significant at $p < 0.001$.

Weeded circles Depths *cm*	OP-derived SOC per year $g\ SOC\ m^{-2}\ yr^{-1}$	R^2	OP-derived SOC per fine roots $g\ SOC\ g^{-1}\ roots$	R^2	OP-derived SOC per cumulative fine roots $g\ SOC\ g^{-1}\ roots$	R^2
0-10 (n=14)	54 ± 6	0.85	0.62 ± 0.10	0.76	0.14 ± 0.02	0.86
10-20 (n=15)	18 ± 6	0.55	0.53 ± 0.11	0.60	0.11 ± 0.02	0.59
20-30 (n=15)	12 ± 2	0.75	0.50 ± 0.11	0.57	0.11 ± 0.01	0.80

730

731 **Fig. 1**. Management zones in a mature oil palm plantation. **(a)** Four management zones

732 varying in terms of fertilization and aboveground C inputs. **(b)** Sampling points (red dots) in

733 the 9-year old plantation. Frond piles and harvest paths are absent in the 2- and 4-year old

734 plantations but two additional points (empty red dots) were sampled to assess palm root lateral

735 extension

736

737 **Fig. 2.** Soil organic C stocks separated between oil palm-derived soil organic carbon (C3-

738 derived SOC) and savanna-derived SOC (C4-derived C) depending on management zones

739 and soil depths after 9 years of oil palm cultivation on savanna grasslands. Mean values ± SE

740 are represented (n = 5 for FP and HP, n = 4 for IZ and WC). FP, frond pile; HP, harvest path;

741 IZ, interzone; WC, weeded circle. Letters indicate significant differences between

742 management zones in total SOC (upper-case) and oil palm-derived SOC (black lower-case)

743 and savanna-derived SOC (white lower-case). The red continuous line shows the original

744 SOC level (±SE) in savanna grasslands (n = 10). The difference between red line and the top

745 of the stacked bars show the C losses over 9 years of oil palm cultivation

746

747 **Fig. 3.** Oil palm fine root development and oil palm-derived soil organic carbon (SOC) stocks.

748 **(a)** Oil palm fine root development with plantation age in the top 10 cm under frond piles

749 (FP), weeded circles (WC), harvest paths (HP), and interzones (IZ). Mean values ± SE are

750 represented (n = 5 for FP and HP, n = 4 for IZ and WC). Letters indicate significant differences

751 between management zones in the 9-year old plantation; **(b)** relationship between oil palm-

752 derived SOC (C3-SOC) and fine root biomass under weeded circles. Overall linear regression

753 is indicated by the dashed line. Negative C3-SOC values result from the natural variation

31

754   standard of reference sites around the mean 13C value when C3-SOC accumulation is very

755   low or absent. Negative data were not set to zero to avoid increasing artificially the mean of

756   the respective depth and age and thus decreasing the overall slope of the relationship. The two

757   large arrows show the opposite effects of the plantation time and soil depth on the amount of

758   new C (C3) stabilized in soil

759

760   **Fig. 4.** Net oil-palm derived SOC (C3) stabilized per amount of cumulated fine root biomass

761   in each management zone after 9 years. Different letters indicate significant differences

762   between harvest paths (HP), interzones (IZ), frond piles (FP), and weeded circles (WC). Mean

763   values ± SE are represented (n = 5 for FP and HP, n = 4 for IZ and WC)
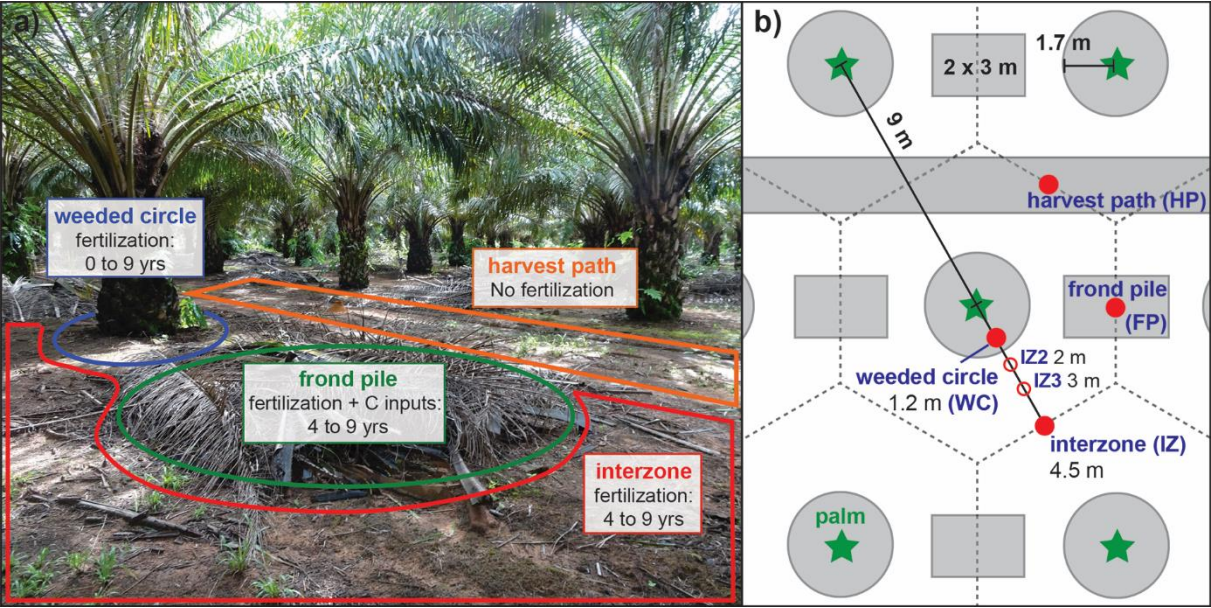
764

765   **Fig. 5.** Relative effects of management zones on soil microorganisms in the 9-year old

766   plantation: basal respiration, metabolic quotient, microbial biomass C, and C:N ratio of

767   microbial biomass. Microbial variables in interzones (IZ), frond piles (FP), and weeded

768   circles (WC) were normalized with their respective mean value in the harvest paths (HP), that

769   is, the zone receiving neither C inputs nor nutrient applications. Specific respiration (basal

770   respiration divided by C content) is not represented because the effect of management zone

771   was not significant. Error bars represent SE (n = 5 for FP and HP, n = 4 for IZ and WC).

772   Letters indicate significant differences between management zones for each parameter

773

774   **Fig. 6.** Pearson correlation matrix among soil variables in the top 10 cm. Correlation

775   performed on samples collected in the three management zones located at 4.5 m away from

776   palm trees (harvest paths, interzones, and frond piles). Variables are: basal respiration,

777   specific respiration, metabolic quotient, oil palm-derived (C3), and savanna-derived (C4)

778   SOC stocks, soil C and N contents (C, N), microbial biomass C and N (Cmic and Nmic), C:N
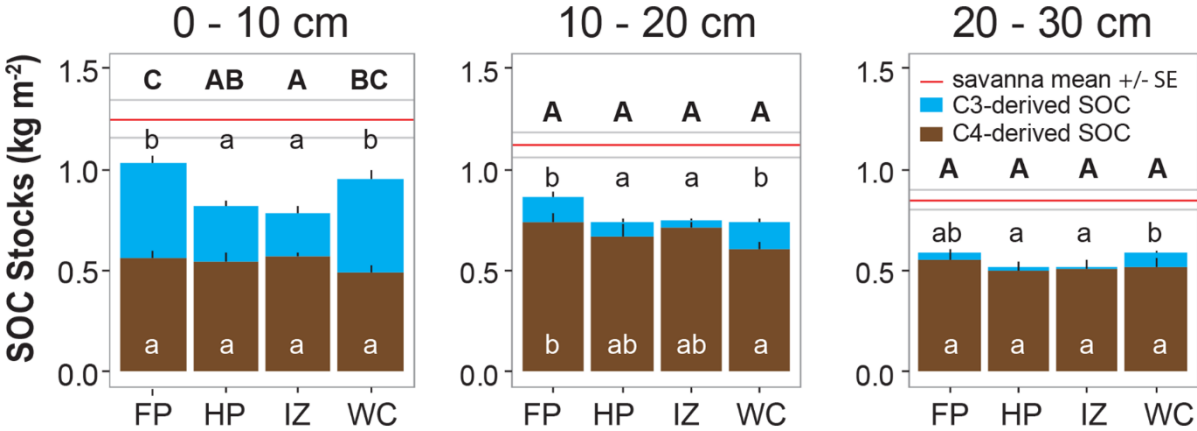
779   ratios of SOM (CN), K2SO4-extractable C (DOC), soil available P (P), and fine root biomass

780   stocks (Fine roots). Only significant correlations are represented (p < .05, n = 14)

781

782   **Fig. 7.** Drivers of oil palm-derived soil organic carbon (SOC) accumulation in the top 10 cm

783   of the three management zones located at 4.5 m away from palm trees (harvest paths,

784   interzones, and frond piles). Phosphorus availability was used as proxy for nutrient

785   availability. Fine roots correspond to fine root biomass stocks. Scores of samples on the first

786   axis (68%) of a principal component analysis (PCA) of all microbially related variables were

787   used as proxy for microbial effects. The C:N ratio of SOM was used as proxy for soil organic

788   matter quality. Solid arrows represent significant effects (*p < .05, ***p < .001, n = 14) and

789   widths are proportional to the effect. Dashed arrows represent marginally effects (p < .10).

790   Non-significant relationships (p > .10) are not represented (nutrient availability to SOM
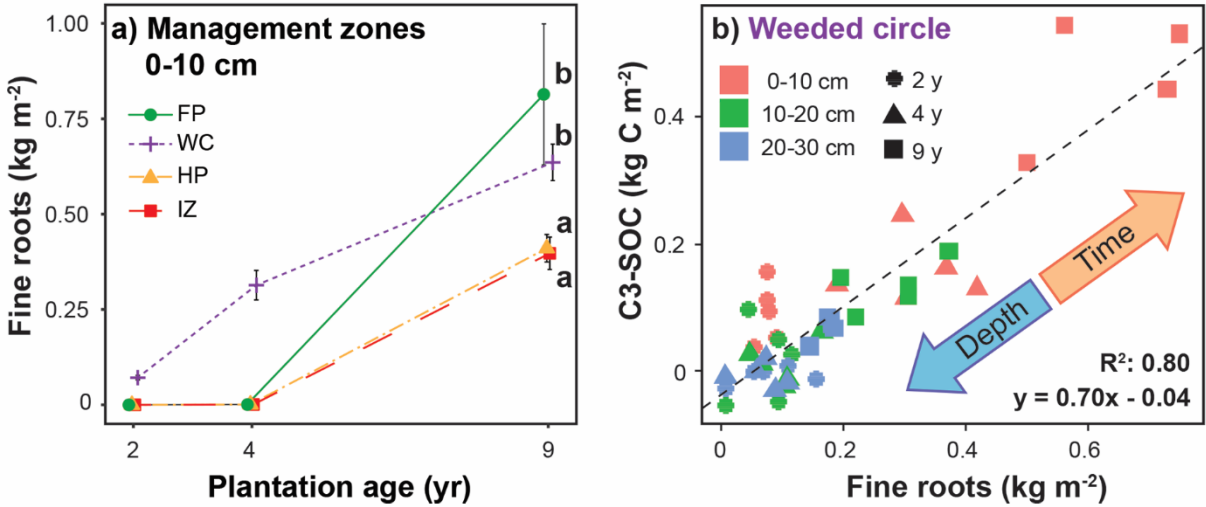
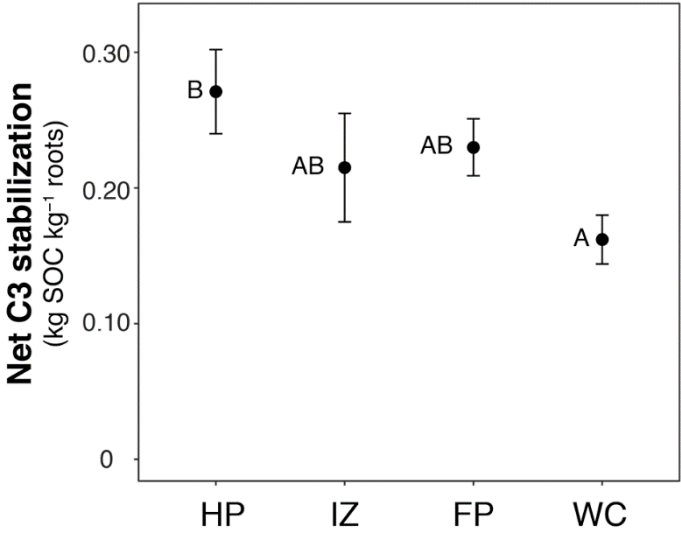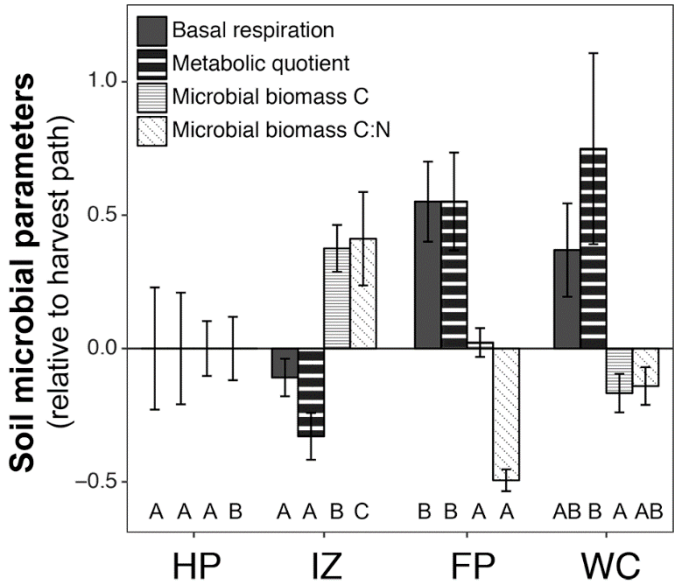791   quality and SOM quality to soil microorganisms)

792

793 **Fig. 1.**

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Fig. 2.

801   **Fig. 3.**

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805 **Fig. 4.**

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Fig. 5.

Fig. 6.

Fig. 7.