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## Logging residues promote rapid restoration of soil health after clear-cutting of rubber plantations at two sites with contrasting soils in Africa

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1 **Logging residues promote rapid restoration of soil health after clear-cutting of rubber**  
2 **plantations at two sites with contrasting soils in Africa**

3

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## 21 **Abstract**

22 Soil health is defined as the soil's capacity to deliver ecosystem functions within  
23 environmental constraints. On tree plantations, clear-cutting and land preparation between  
24 two crop cycles cause severe physical disturbance to the soil and seriously deplete soil  
25 organic carbon and biodiversity. Rubber, one of the main tropical perennial crops worldwide,  
26 has a plantation life cycle of 25 to 40 years, with successive replanting cycles on the same  
27 plot. The aim of this study was to assess the effects of clear-cutting disturbance on three soil  
28 functions (carbon transformation, nutrient cycling and structure maintenance) and their  
29 restoration after the planting of the new rubber crop, in two contrasting soil situations  
30 (Arenosol and Ferralsol) in Côte d'Ivoire. In this 18-month diachronic study, we intensively  
31 measured soil functions under different scenarios as regards the management of logging  
32 residues and the use or not of a legume cover crop. We investigated the relationship between  
33 soil macrofauna diversity and soil health. At both sites, clear-cutting and land preparation  
34 disturbed carbon transformation and nutrient cycling significantly and, to a lesser extent,  
35 structure maintenance function. When logging residues were applied, carbon transformation  
36 and structure maintenance functions were fully restored within 12 to 18 months after  
37 disturbance. By contrast, no restoration of nutrient cycling was observed over the study  
38 period. A legume cover crop mainly improved the restoration of carbon transformation. We  
39 found a strong relationship ( $P \leq 0.001$ ;  $R^2 = 0.62-0.66$ ) between soil macrofauna diversity and  
40 soil health. Our overall results were very similar at the two sites, despite their contrasting soil  
41 conditions. Keeping logging residues in the plots and sowing a legume in the inter-row at  
42 replanting accelerated the restoration of soil functions after major disturbance caused by  
43 clear-cutting and land preparation. Our results confirm the necessity of taking soil macrofauna  
44 diversity into account in the management of tropical perennial crops.

45 *Keywords:* rubber tree, soil health, soil biodiversity, logging residue, disturbance, restoration,  
46 legume.

## 47 1. Introduction

48

49 Soils perform a wide range of essential functions such as nutrient cycling and organic matter  
50 decomposition; in this way they provide provisioning, regulating and supporting ecosystem  
51 services (Leemans and de Groot, 2003). Soil health is defined as "the capacity of soils to  
52 deliver multiple functional traits that are required to maintain ecosystem stability" (Pawlett et  
53 al., 2021). These functions emerge from complex interactions between the physical, chemical  
54 and biological parameters of the soil (Kibblewhite et al., 2008). In the tropics, soil organic  
55 matter contents and nutrient availabilities are commonly low, which make these soils  
56 particularly sensitive to disturbance. Human activities, and particularly agricultural practices  
57 such as tillage and crop residue removal, are likely to undermine the soil's capacity to deliver  
58 numerous functions over the long term (Pawlett et al., 2021).

59 Rubber tree (*Hevea brasiliensis*) plantations, the main source of natural rubber, are a  
60 relevant model for studying the effects of crop management on soil functions in the tropics. In  
61 2018, rubber plantations covered 12.5 million ha worldwide, mostly in South-East Asia,  
62 followed by Africa (FAO, 2020). A rubber stand lasts 25 to 40 years and the same plot is used  
63 for successive replanting cycles. Management practices in the period from planting to clear-  
64 cutting do not greatly disturb soil functioning. Many recent studies have reported an increase  
65 in soil health throughout the life of the stand (Gao et al., 2019; Peerawat et al., 2018;  
66 Thoumazeau et al., 2019a; Tondoh et al., 2019). By contrast, clear-cutting and land  
67 preparation (mainly windrowing and subsoiling) between two crop cycles involve the passage  
68 of heavy machinery on industrial plantations, as well as drastic changes in soil temperature,  
69 light conditions and soil cover which might greatly disturb soil functioning (Watson, 1964).

70 Degradation of soil physical properties caused by the passage of machinery has been  
71 extensively reported in various crop systems worldwide, especially as regards increased bulk

72 density (Ampoorter et al., 2010) and decreases in pore volume, hydraulic conductivity and air  
73 permeability (Hartmann et al., 2014). Researchers have also demonstrated the negative  
74 impacts of clear-cutting on nutrient and carbon cycles (Christophel et al., 2015; Siebers et al.,  
75 2018; Mayer et al., 2020) and on faunal and microbial communities (Bottinelli et al., 2014;  
76 Frey et al., 2009; Hasegawa et al., 2014) in planted forests in various pedoclimatic conditions.  
77 Soil texture may significantly affect the way soil functions respond to disturbance. Hartmann  
78 et al. (2014) report that soil compaction had a stronger effect on the abundance and diversity  
79 of soil microorganisms in fine-textured soils than in coarse-textured soils in temperate forests.  
80 To maintain the crucial functions provided by soils, it is necessary to know how these  
81 functions respond to disturbance. Not enough is known about the disturbances caused by  
82 clear-cutting and land preparation in rubber tree plantations and other tropical perennial crops.

83 In the recent past, logging residues in rubber plantations (i.e. the trunks, branches, leaves  
84 and roots of the old stand) were burnt after clear-cutting (Simorangkir, 2006). This method  
85 has been discontinued in many countries to avoid air pollution. Nowadays, the most common  
86 practice in commercial rubber plantations is to export some logging residues, mainly trunks  
87 and branches, for economic use (Hytönen et al., 2019). Given the large amounts of carbon and  
88 nutrients that accumulate in the tree throughout the plantation cycle, removing the residues  
89 might lead to a decrease in soil health over successive cycles (Perron et al., 2021; Vrignon-  
90 Brenas et al., 2019). There is therefore a need for research to assess the sustainability of  
91 logging residue management practices in terms of soil function maintenance.

92 Soil organic carbon (SOC) is a recognized yardstick for assessing soil functioning in  
93 agricultural or forestry systems (Reeves, 1997). Retaining logging residues significantly  
94 increases both carbon stocks and nutrient availability in the soil (see Achat et al., 2015; Mayer  
95 et al., 2020 for complete reviews). In rubber plantations, the carbon stocks in the above- and  
96 belowground tree biomass at clear-cutting range from 78 to 154 t ha<sup>-1</sup> (Brahma et al., 2018;

97 Hytönen et al., 2019). The time required for logging residues to decompose completely  
98 depends on the type of residue; with rubber trees in Malaysia, it ranges from about 6 months  
99 for leaves to 2.5 years for trunks (Yew, 2001). Such a fast release of carbon after clear-cutting  
100 is likely to promote soil biological activity and increase overall soil functioning in the first  
101 years after replanting. Soil health is therefore expected to recover quickly. Soil texture is  
102 known to have a strong impact on the restoration process, with faster restoration of soil  
103 microbial activity reported in fine-textured soils in both temperate and tropical conditions  
104 (Bach et al., 2010; Schimann et al., 2007). Although diachronic studies are the most  
105 appropriate way to clearly reveal the soil restoration process, they have been little used in  
106 field experiments. As a result, there is a considerable knowledge gap regarding the restoration  
107 of soil functions after clear-cutting and land preparation in tropical perennial crops. Yet  
108 information on the capacity of logging residues to restore soil functions could provide key  
109 management recommendations.

110 Ways to monitor soil health are still keenly debated in the scientific community  
111 (Bunnemann et al., 2018; Lehmann et al., 2021; Janzen et al., 2021). Since the original  
112 definition of soil health is based on soil functions related to the soil's biological assemblages  
113 (Kibblewhite et al., 2008), we used Biofunctool<sup>®</sup>, a new tool for assessing soil health by  
114 evaluating three soil functions: nutrient cycling, carbon transformation and structure  
115 maintenance (Thoumazeau et al., 2019b). Biofunctool<sup>®</sup> has been already used in rubber  
116 plantations to assess the effect of rubber plantations ageing on soil functioning (Thoumazeau  
117 et al., 2019a), and in annual tropical crops to distinguish conservation agriculture from  
118 conventional practices (Pheap et al., 2019). Biofunctool<sup>®</sup> contributes to an integrated approach  
119 to soil assessment that takes into consideration the complex interactions between soil  
120 physical-chemical properties and living organisms. Among these organisms, soil macrofauna  
121 play a major role in the direct provision of numerous soil functions (Barrios et al., 2018;



122 Lavelle et al., 2006). A recent study showed that soil macrofauna diversity is particularly  
123 important for supporting these functions: the greater the diversity, the greater the provision of  
124 functions (Delgado-Baquerizo et al., 2020). That study showed that the relationship between  
125 soil macrofauna diversity and ecosystem functions followed a similar pattern to that between  
126 overall soil biodiversity (including 12 groups of soil organisms) and ecosystem functioning.  
127 Soil macrofauna diversity is therefore a relevant indicator of total soil biodiversity.

128 Our objectives were: (1) to quantify the effects of the disturbances resulting from clear-  
129 cutting and land preparation; (2) to assess the effects on soil restoration of different  
130 management practices regarding logging residues and the use or not of a legume cover crop;  
131 (3) to explore the relationships between soil macrofauna diversity and soil health during the  
132 restoration process. We conducted a diachronic study in two large-scale field experiments in  
133 Côte d'Ivoire, measuring soil functions just before plantation clear-cutting and then, 6, 12 and  
134 18 months later, in two rubber plantations.

135

## 136 2. Material and methods

137

### 138 2.1. Study sites

139

140 The study ran from October 2017 to April 2019 in two commercial rubber plantations in  
141 Côte d'Ivoire (Fig. 1). The Bongo plantation belongs to the *Société Africaine des Plantations*  
142 *d'Hévéas* (SAPH) and is located in the southeast of the country (latitude 5°30'32.364"N,  
143 longitude 3°32'51.755"W, altitude 96 m). The *Société de Caoutchouc de Grand-Béréby*  
144 plantation (SOGB) is located in the southwest of the country (latitude 4°43'9.696"N,  
145 longitude 7°6'41.795"W, altitude 34 m). Both plantations lie within the rainforest ecological  
146 zone, where a sub-equatorial climate favourable to rubber tree cultivation prevails. Rainfall in

147 southern Côte d'Ivoire is divided between two rainy seasons, a major one from May to July  
148 and a minor one from October to November, with two dry seasons from December to April  
149 and from August to September. Average annual rainfall (2003 to 2018) was 1640 mm at  
150 SAPH and 1674 mm at SOGB. Monthly rainfall throughout the study period is presented in  
151 Supplementary Fig. 1.

152 The SAPH site is characterized by slight slopes ( $< 5\%$ ). Its soil is classified as a yellow  
153 ferralic Arenosol in the FAO soil classification. The SOGB site features hilly areas (slopes of  
154 10-25%), and its soil is classified as a red Ferralsol in the FAO classification. Soil texture is  
155 loamy sand at SAPH (10% clay in the topsoil) and sandy loam at SOGB (23% clay in the  
156 topsoil) (Table 1). The soils at both sites are acidic, with a  $\text{pH}_{\text{H}_2\text{O}}$  of 4.3 and 4.7 in the 0-10 cm  
157 horizon at SAPH and SOGB respectively. While total carbon and nitrogen are higher at  
158 SOGB, the concentration of available phosphorus in the 0-10 cm soil layer is higher at SAPH.

159

## 160 2.1. Experiment design and crop management

161

162 Measurements began on the old rubber stands, just before clear-cutting. The old rubber  
163 trees were felled by bulldozer in November 2017 (Supplementary Fig. 2). The stand at SAPH  
164 was 40 years old with 253 living trees  $\text{ha}^{-1}$ , and the one at SOGB was 38 years old with 233  
165 living trees  $\text{ha}^{-1}$ . At both sites, the previous land use was tropical rainforest.

166 Experimental plots were set up from December 2017 to January 2018. The experimental  
167 design was the same at SAPH and SOGB. It consisted of four treatments replicated four times  
168 in randomized blocks, giving 16 plots per site. Each plot covered an area of 0.14 ha at SAPH  
169 and 0.16 ha at SOGB, with 80 trees at each site. The treatments were as follows (Fig. 2):

170 - R0L0: control treatment. All logging residues (R) removed from the plot. No legume (L)  
171 sown after clear-cutting.

- 172 - R0L1: all logging residues removed from the plot. The legume *Pueraria phaseoloides*  
173 sown after clear-cutting.
- 174 - R1L1: trunk removed from the plot. Twigs, leaves and stumps retained. The legume  
175 *Pueraria phaseoloides* sown after clear-cutting. This treatment is representative of the  
176 practice on most commercial rubber plantations in Africa.
- 177 - R2L1: no logging residue removed. Trunks, twigs, leaves and stumps left on-site. The  
178 legume *Pueraria phaseoloides* sown after clear-cutting.

179 The legume was sown broadcast in the R0L1, R1L1 and R2L1 treatments (10 kg ha<sup>-1</sup> of  
180 moistened seeds) in February 2018. Sowing *Pueraria phaseoloides* is a common practice on  
181 industrial rubber plantations while the trees are immature, especially to control soil erosion.  
182 Subsoiling to a depth of 80 cm, followed by an application of dolomite at 200 kg ha<sup>-1</sup> in the  
183 planting row, was carried out in early March 2018 in all treatments. At SOGB, young rubber  
184 trees were planted in May 2018 with the IRCA230 clone spaced at 8 x 2.5 m (i.e. 500 trees ha<sup>-1</sup>  
185 <sup>1</sup>). At SAPH, planting took place in July 2018 with the IRCA41 clone spaced at 6 x 3 m (i.e.  
186 555 trees ha<sup>-1</sup>). At planting, 40 g tree<sup>-1</sup> of N, P, K and Mg slow-release fertilizer (formulation:  
187 15-8-9-3) was applied in the planting hole in all treatments.

188

## 189 2.2. Biofunctool indicators

190

191 Biofunctool<sup>®</sup> consists in a core set of ten selected expert-based function indicators  
192 assessing three main soil functions: carbon transformation, nutrient cycling and soil structure  
193 maintenance (Thoumazeau et al., 2019b). Of the 10 Biofunctool<sup>®</sup> indicators (Table 2), three  
194 assess factors linked to carbon transformation. These are permanganate oxidizable carbon  
195 (Weil et al., 2003), basal soil respiration using the SituResp<sup>®</sup> method (Thoumazeau et al.,  
196 2017), and soil meso-fauna activity using the bait-lamina method (van Gestel et al., 2003).

197 Three indicators assess nutrient cycling: available ammonium and nitrate from soil extraction  
198 with 1M KCl, and nitrate adsorption on ion exchange membranes (Qian and Schoenau, 2002).  
199 The last four indicators assess soil structure maintenance. These are aggregate stability at 0–2  
200 cm depth, aggregate stability at 2–10 cm depth (Herrick et al., 2001), water infiltration using  
201 the Beerkan method (Lassabatère et al., 2006), and visual evaluation of soil structure (VESS  
202 method) at 0–25 cm depth (Guimarães et al., 2011).

203 Soil samples were collected from the 0-10 cm soil layer, except for the VESS samples,  
204 which were taken from the 0-25 cm soil layer. Only the 0-10 cm layer was sampled because  
205 the soil functioning indicators in this study were selected from soil zones where treatment  
206 effects are expected to be highest. Logging residues are left on the soil surface during land  
207 preparation and their effect on soil functioning the first months after clear-cutting occur  
208 mainly in the 0-10 cm layer, as shown by successive measurements of soil properties down to  
209 a depth of 30 cm in the same plots (data not shown).

210

### 211 2.3. Assessment of soil biodiversity

212

213 Soil macrofauna were sampled using the standard Tropical Soil Biology and Fertility  
214 method (Anderson et al., 1993). This consists in hand-sorting macroinvertebrates visible to  
215 the naked eye from a soil monolith 25 x 25 cm in area and 10 cm deep. In the field, animals  
216 were placed in ethanol (96%). In the laboratory, invertebrates were identified as belonging to  
217 20 taxonomic groups: Annelida, Anoplura, Arachnida, Chilopoda, Coleoptera, Dermaptera,  
218 Dictyoptera, Diplopoda, Embioptera, Heteroptera, Homoptera, Hymenoptera, Isopoda,  
219 Isoptera, Lepidoptera, Mecoptera, Neuroptera, Orthoptera, Thysanoptera and Thysanoura. A  
220 "group" could be family, class or order, the purpose being to comprise a set of individuals of  
221 similar body plan. We used richness (i.e., the number of taxonomic groups) to assess

222 macrofauna diversity, as it is the simplest and most widely used metric for biodiversity. At  
223 both sites, the richness of the soil macrofauna was highly correlated with the Shannon index  
224 (Pearson  $r=0.83-0.90$ ;  $P<0.001$ ). This suggests that our simple soil biodiversity indicator was  
225 relevant for characterizing the effects of different management practices at replanting in  
226 rubber plantations.

227

#### 228 2.4. Diachronic assessment of soil health

229

230 Soil indicators were measured on 4 dates at both sites (Supplementary Fig. 2). The first  
231 sampling was performed in the old rubber stands, just before clear-cutting (October 2017,  
232 month 0). The others were performed at 6-month intervals, in April 2018 (month 6), October  
233 2018 (month 12) and April 2019 (month 18). Soil macrofauna were collected at months 6, 12  
234 and 18. This diachronic approach gave us an overview of soil disturbance and the progressive  
235 restoration of soil functions after clear-cutting and land preparation.

236 All samplings were undertaken in the middle of the inter-row (i.e. between two planting  
237 rows). This meant that the subsoiling carried out in March 2018 did not have a direct impact  
238 on our samplings. At month 0, the experimental plots had not yet been set up, so we collected  
239 one sample per block, i.e. 4 samples per site in total. At months 6, 12 and 18, the experimental  
240 plots having been set up, one sample per plot was taken for soil indicators (i.e. 4 samples per  
241 treatment, site and date). Macrofauna samples were taken close to the soil samples collected  
242 for soil indicators in three blocks.

243

#### 244 2.5. Disturbance rate

245

246 Since soil health improves continually as the rubber stand ages (Peerawat et al., 2018;  
247 Thoumazeau et al., 2019a), the mature stand before clear-cutting (i.e. month 0) was taken as  
248 the reference level. The sampling at month 6 was regarded as the disturbed level, as it was the  
249 closest to the clear-cutting and land preparation operations (windrowing and subsoiling). A  
250 disturbance rate (*Dr*) was calculated for each soil function using the following formula (Chaer  
251 et al., 2009):

$$252 \quad Dr (\%) = \frac{(F_{month\ 0} - F_{month\ 6})}{F_{month\ 0}} \times 100 \quad (1)$$

253 where *F* stands for a given soil function at month 0 or month 6. The higher the *Dr* the stronger  
254 the disturbance of a given function. For instance, a *Dr* of 50 % would mean a 50 % decrease  
255 in the soil function between month 0 and month 6.

256 The disturbance rates of a given soil function were averaged for each site, as the  
257 treatments showed no differences in their effects on soil functions at month 6, on either site  
258 ( $P > 0.05$ ). As a result, one disturbance rate per function and per site was computed.

259

## 260 2.6. Statistical analysis

261

### 262 2.6.1. Computation of soil indices

263

264 We calculated an index for each soil function (i.e. a nutrient cycle index, a carbon  
265 transformation index and a structure maintenance index), as per Obriot et al. (2016) and  
266 Thoumazeau et al. (2019b). Briefly, the 10 soil indicators were first normalized using a “more  
267 is better”, “less is better” or “optimum” response curve, depending on the indicator (Table 2).  
268 The “optimum” response curve was chosen for soil indicators related to nutrient availability  
269 (i.e. NO<sub>3</sub>, NH<sub>4</sub> and AMNO<sub>3</sub>). The concentration of available nutrient at month 0 was chosen  
270 as the optimum value since mature rubber stands are often considered to be self-sustainable as

271 regards nutrient cycling (Jessy et al., 2009; Sivanadyan et al., 1995). The “optimum” response  
272 curve for available soil nutrients has already been used to reflect the risk of environmental  
273 hazards, especially leaching, that high concentrations of available nutrients may entail (Obriot  
274 et al., 2016). Then, a weighted principal component analysis (PCA) based on correlation  
275 matrix was run to provide the same weight to each soil function. The indices were calculated  
276 from the relative contributions of the soil indicators to the principal components with  
277 eigenvalues  $> 1$ . A soil health index (SHI) was computed from the sum of the three indices, to  
278 reflect the multiple functions delivered by soils. All indices were calculated for each site  
279 separately, to avoid co-effects linked to the two sites' contrasting edaphic conditions.

280

### 281 2.6.2. Modelling

282

283 All statistical analyses were carried out using R software (V. 3.6.2). Level of statistical  
284 significance for all analysis was set at  $P < 0.05$ .

285 Analysis of variance (ANOVA) was used to assess whether land preparation led to  
286 significant differences between the disturbance rates of different soil functions. Student's t-  
287 test (t-test) was used to compare the disturbance rate of a given soil function to a theoretical  
288 mean  $\mu=0$ . A t-test resulting in a  $P < 0.05$  for a given soil function indicated a significant  
289 disturbance of that function.

290 To calculate the degree of soil function restoration, we investigated the trend of each soil  
291 function's index over time using mixed linear models with the *lme4* R package (Bates et al.,  
292 2020). The time variable (*month*) was used as a fixed effect while the plot was used as a  
293 random effect to take into account the repeated measurements over time. The effect of logging  
294 residues management on SHI and soil functions at month 18 was also investigated using one-  
295 way ANOVA. Finally, mixed linear models were used (*lme4* package) to assess the effect of

296 soil biodiversity on SHI and soil functions after clear-cutting and land preparation. The  
297 models were fitted using the *treatment* variable as a random effect.

298 For the mixed linear models, the Akaike Information Criterion (AIC) was used to select  
299 the random effects resulting in the most parsimonious models. All models were fitted for each  
300 site separately, as inherent parameters (soil texture especially) could hide the variability of the  
301 explanatory variables of interest (*treatment* and *month*). The normality of the residuals and the  
302 homoscedasticity of the variance residuals were checked. Where there was a significant effect  
303 ( $P < 0.05$ ), Tukey HSD multiple comparison of means (post-hoc test) was implemented, using  
304 the *agricolae* package (de Mendiburu, 2020) for ANOVA and the *emmeans* R-package for the  
305 mixed linear models (Lenth et al., 2020).

306 In the PCA, Pearson coefficient of correlation was used to assess the correlation between  
307 each variable and each axis using *FactoMineR* R package (Lê and Husson, 2008). A p-value  
308 calculated from this coefficient makes it possible to tell whether a correlation was significant  
309 or not.

310

### 311 3. Results

312

313 3.1. Overview of the effects on soil indicators of time since clear-cutting and logging  
314 residue management

315

316 A principal component analysis incorporating the 10 soil indicators showed that soil  
317 health was strongly influenced by length of time since clear-cutting and by type of logging  
318 residue management and/or legume cover (Fig. 3). At both sites, 9 out of 10 indicators were  
319 positively and significantly correlated to axis 1, explaining 36.2% and 40.6% of the variability  
320 at SAPH and SOGB respectively (Fig. 3A; Fig. 3C). This pattern shows that axis 1 could be



321 considered a gradient of soil health: individuals located to the left of axis 1 will exhibit a low  
322 level of soil health, while individuals to the right of axis 1 will exhibit a high level of soil  
323 health. At both sites, the distribution of the sampling dates on axis 1 was as follows, from  
324 lowest soil health to highest: month 6 < month 12 ≤ month 18 < month 0 (Fig. 3B; Fig. 3E).  
325 As regards treatments, their distribution on axis 1 was similar at the two sites, with the  
326 following order from the left side to the right side of axis 1: R0L0 < R0L1 < R1L1 ≤ R2L1  
327 (Fig. 3C; Fig. 3F).

328 Axis 2 explained only 14.9% and 18.9% of the variability at SAPH and SOGB  
329 respectively. The soil indicators that contributed most to its construction were different  
330 between the two sites. The highest contributions were VESS and NH<sub>4</sub> at SAPH, but Beerkan  
331 and POXC at SOGB.

332

### 333 3.2. Level of disturbance of soil functions after clear-cutting and land preparation

334

335 Disturbance rates were calculated to assess the disturbance of each soil function between  
336 month 0 (before clear-cutting) and month 6 (after clear-cutting and land preparation). Clear-  
337 cutting and land preparation resulted in significant disturbance to all soil functions at both  
338 sites (t-test:  $P < 0.001$ ), except for structure maintenance at SOGB (t-test:  $P > 0.05$ ) (Fig. 4). At  
339 both sites, disturbance rates were highest for nutrient cycling and carbon transformation,  
340 while structure maintenance exhibited the lowest disturbance rate.

341

### 342 3.2. Restoration of soil functions from 6 to 18 months after clear-cutting

343

344 *Carbon transformation function.* In treatment R0L0 the carbon transformation index  
345 decreased significantly (SAPH) or was stable (SOGB) between month 6 and month 18 (Fig.

346 5A). In all others treatments, the carbon transformation index increased at both sites from  
347 month 6, although the differences were not always statistically significant. At SAPH, the  
348 index followed the same trend with treatments R0L1, R1L1 and R2L1. It ranged from 0.20 to  
349 0.23 at month 18, these values being intermediate between those of month 0 (reference level)  
350 and month 6 (disturbed level). The index increased more, and faster, at SOGB in treatments  
351 with logging residues (R1L1 and R2L1 treatments); at month 12 it was not statistically  
352 different to month 0 and it then remained stable until month 18.

353 *Nutrient cycling function.* From month 6, in almost all treatments and at both sites, the  
354 nutrient cycle index was fairly stable with no statistical differences at the end of the study  
355 (month 18) compared to month 6 (Fig. 5B). There were 2 exceptions: in control treatment  
356 R0L0 at SOGB, the index continued to decrease significantly from month 6 to month 18,  
357 while in the R2L1 treatment at SAPH, this index was significantly higher at month 18 than at  
358 month 6.

359 *Structure maintenance function.* The structure maintenance index after 18 month was not  
360 statistically different to month 0 in the R0L0, R1L1 and R2L1 treatments at SAPH and in the  
361 R0L1 and R2L1 treatments at SOGB, attesting a full restoration of this function (Fig. 5C). In  
362 R0L1 at SAPH and R0L0 at SOGB, the structure maintenance index kept decreasing after  
363 clear-cutting and the value at month 18 was statistically different to month 0, attesting a  
364 continuous decline of this soil function. Finally, in R1L1 at SOGB, no statistical difference of  
365 the structure maintenance index among months was found.

366

### 367 3.3. Effect of treatments on soil health index 18 months after clear-cutting

368

369 The SHI at month 18 differed significantly among treatments at both sites, with the  
370 highest values in the treatments with logging residues (R2L1 and R1L1) and the lowest in

371 R0L0 (Fig. 6). As with SHI, the carbon transformation, nutrient cycling and structure  
372 maintenance indices were significantly higher in the treatments with logging residues (R1L1  
373 and R2L1) than in the control treatment (R0L0) at both sites, except for the nutrient cycle  
374 index at SAPH where there were no statistical differences between treatments.

375

### 376 3.4. Relationships between soil functions and soil macrofauna diversity

377

378 The diversity of the soil macrofauna increased radically from month 6 to month 12 and  
379 then remained stable between months 12 and 18 in all treatments at both sites, except for  
380 R0L0 where there was no change in diversity over time (Supplementary Fig. 3). At month 18,  
381 the treatments with logging residue input (R2L1 and R1L1) exhibited significantly higher soil  
382 macrofauna diversity than treatments without logging residues (R0L1 and R0L1), at both  
383 sites.

384 The relationships between soil macrofauna diversity and the SHI, carbon transformation  
385 index and structure maintenance index were positive and significant at both sites (Fig. 7A, 7B,  
386 7D). The nutrient cycle index was an exception, showing a non-significant relationship at both  
387 sites (Fig. 7C). The model coefficients (intercept and slope) of the significant relationships  
388 were very similar between the two sites (Supplementary Table 1).

389

## 390 4. Discussion

391

### 392 4.1. How clear-cutting and land preparation impact soil functions

393

394 We have demonstrated that all the soil functions studied were significantly and negatively  
395 affected by clear-cutting and land preparation at both sites, except for structure maintenance

396 at SOGB. At both sites, nutrient cycling was the function most strongly affected. Nitrate and  
397 ammonium concentrations in the topsoil increased sharply over the 6 months following clear-  
398 cutting (Supplementary Table 2). The nutrient cycle index was computed using the  
399 “optimum” response curve, with the concentration of mineral N at month 0 as optimum value.  
400 The increase in soil N concentration in month 6 resulted in a decrease in the nutrient cycling  
401 index. This confirms our choice of the “optimum” response curve for the computation of this  
402 index (Obriot et al., 2016), in that large amounts of ammonium and nitrate may be leached in  
403 the first years after replanting, when the rubber tree roots have not yet spread very far (Otoul,  
404 1960). Soil solution samples collected in ceramic cup lysimeters at the SAPH site showed  
405 very high concentrations of mineral N throughout the soil profile to a depth of 2 m in  
406 treatments R0L1 and R2L1 (data not shown) throughout the study period, which confirms the  
407 risk of nutrient leaching during this period. The sharp increase in soil mineral N after clear-  
408 cutting and land preparation could be due firstly to an increase in N mineralization linked to  
409 higher soil temperature after the clear-cut (Guntiñas, 2012). Secondly, it could be linked to a  
410 drop in N uptake by plants after the rubber trees were felled and the weeds removed during  
411 land preparation (Bergholm et al., 2015).

412 The significant disturbance to carbon transformation is consistent with previous studies  
413 dealing with the impact of plantation clear-cutting on soil indicators related to that function.  
414 Plantation clear-cutting has led to a reduction in microbial and fungal abundance after soil  
415 compaction during logging operations (Hartmann et al., 2014), a major decrease in soil  
416 organic carbon in the topsoil (Rab, 1994) and a decline in the abundance of macroarthropod  
417 communities (Blasi et al., 2013)

418 A drop in soil structure maintenance was expected after clear-cutting and land preparation  
419 since the use of heavy machinery is known to negatively influence soil physical properties.  
420 Surprisingly, structure maintenance was the least disturbed function at both sites. This cannot

421 be explained by the decompacting effect of subsoiling, since the soil was sampled in the inter-  
422 rows and the subsoiling was carried out in the planting rows. It might be explained by the fact  
423 that soil structure had already started to be restored by month 6. High functional redundancy  
424 among soil macrofauna in their soil structure maintenance role could enable soil structure to  
425 recover faster than the other soil functions (cf. section 4.3). The fact that this function was less  
426 disturbed at SOGB than at SAPH is not consistent with an earlier finding that fine-textured  
427 soils are more sensitive to vehicle-induced compaction than coarse-textured soils (Mariotti et  
428 al., 2020). We suggest, first, that higher rainfall at SAPH at the time when vehicles were  
429 passing (November 2017 for clear-cutting and March 2018 for subsoiling) may have caused  
430 greater disturbance to soil structure at that site, as high soil moisture increases the effects of  
431 vehicle-induced compaction (Shah et al., 2017). Secondly, the visibly faster growth of  
432 *Pueraria phaseoloides* after clear-cutting at SOGB could explain why soil structure  
433 disturbance was less at this site than at SAPH (data not shown), since legumes play a key role  
434 in enhancing soil physical properties in degraded systems (Salako et al., 2001). This  
435 highlights the importance of fast legume growth and of sowing as early as possible after  
436 plantation clear-cutting.

437

#### 438 4.2. Restoration of soil functions after disturbance: what is the best management 439 strategy?

440

441 The management of logging residues and legume sowing consistently influenced soil  
442 restoration processes at both sites, with different patterns over time for the different soil  
443 functions. The soil functions that recovered most quickly as a result of adding logging  
444 residues were carbon transformation and structure maintenance, while little effect was  
445 detected on the restoration of nutrient cycling.

446 Many studies show that logging residues have a strong impact on soil indicators related to  
447 carbon transformation. In eucalypt plantations, keeping logging residues on the soil surface  
448 after clear-cutting increased the microbial biomass in Brazil (Maillard et al., 2019; Oliveira et  
449 al., 2021) and greatly increased soil carbon respiration (Epron et al., 2015; Versini et al.,  
450 2013). Importantly, in our study the application of low (R1L1) or high (R2L1) amounts of  
451 logging residues on the soil surface did not significantly influence the restoration of carbon  
452 transformation function. This could be due to differences in decomposition rate between  
453 residue components (trunk, branch, leaves and stump). Trunks, which differentiated treatment  
454 R2L1 from R1L1, are slowest to decompose given their high carbon to nitrogen ratio. And  
455 trunks make up the largest proportion of the stand's total biomass at clear-cut, amounting to  
456 about 150 t ha<sup>-1</sup> (Perron et al., 2021). Trunks decompose completely in 29 months, while  
457 leaves and twigs decompose within 6 and 12 months respectively, according to the only  
458 reference that deals with the decomposition of logging residues in rubber plantations (Yew,  
459 2001). So our 18-month diachronic study was probably too short to detect the effects of trunk  
460 decomposition on soil functioning. We suggest that further samplings would be needed to  
461 detect a possible difference between treatments R1L1 and R2L1 with regard to carbon  
462 transformation and structure maintenance. Further research, addressing the decomposition  
463 dynamics of each type of logging residue, would be useful for gaining insight into SOC and  
464 nutrient releases.

465 When logging residues were exported from plots (in R0L0 and R0L1), the structure  
466 maintenance index was not restored within the first 18 months after clear-cutting at either site.  
467 By contrast, in treatments with logging residues (R1L1 and R2L1) full restoration of the index  
468 was observed over 18 months. This suggests that input of logging residues plays a major role  
469 in the improvement of this function, while legume cover has little effect. The addition of fresh  
470 organic matter (such as logging residues) is known to greatly enhance soil macrofauna

471 activity (Bengtsson et al., 1997), which directly influences soil structure by improving  
472 macroporosity (Bottinelli et al., 2015). Carbon transformation, however, was strongly  
473 influenced by the cover crop in the plots without logging residues. Partial restoration of this  
474 function within 18 months was observed in R0L1, while it was still significantly disturbed in  
475 R0L0 at both sites at month 18. Our results confirm the crucial role of legume cover crops on  
476 soil indicators linked to carbon transformation in rubber plantations, as highlighted in  
477 previous studies (Broughton, 1977; Watson, 1957).

478 Interestingly, at SAPH, restoration of the carbon transformation index over 18 months  
479 after clear-cutting was not affected by the amount of logging residues on the soil surface in  
480 plots with the legume cover crop (i.e. comparing treatments R0L1, R1L1 and R2L1).

481 *Pueraria phaseoloides* is characterized by high carbon accumulation in its aboveground  
482 biomass in the first year after replanting rubber trees ( $3.6 \text{ t ha}^{-1} \text{ year}^{-1}$ ), with 50% of the carbon  
483 in its litter released within 7 days (Clermont-Dauphin et al., 2016). So the considerable carbon  
484 input to the soil through legume litter could have been enough to mask the effect of logging  
485 residues on the carbon transformation index at SAPH.

486 The nutrient cycling function was not restored within our study period in any treatment at  
487 either site, except for treatment R2L1 at SAPH, where a significant increase was observed at  
488 month 18. After a peak at month 6, concentrations of mineral N in the topsoil decreased  
489 steadily (data not shown). The concentration of nitrate remained higher than the initial  
490 optimum value (month 0), while the concentration of ammonium decreased below the initial  
491 optimum value at both sites. This trend in mineral N concentration, characterized by a nitrate  
492 to ammonium ratio  $> 1$ , indicates large amounts of available N and an open N cycle, as  
493 reported in a post-agricultural succession (Xiao et al., 2018). The low nutrient cycling index 6  
494 months after clear-cutting and onward points to a risk of N losses through leaching and  
495 environmental issues, such as eutrophication. This hypothesis is corroborated by the high N

496 concentrations to a depth of 2 m, which we found in soil solutions collected over the study  
497 period using ceramic cup lysimeters in R2L1 and R0L1 plots at SAPH (data not shown). An  
498 increase in the nutrient cycling index is expected at a later date, through (1) a decrease in N  
499 mineralisation after logging residue decomposition (Mendham et al., 2004; O'Connell, 2004),  
500 and (2) a strong increase in the rubber trees' demand for N (Perron et al., 2021) with a  
501 concomitant exploration of the upper soil layers by rubber tree roots.

502 Finally, the similarity in restoration patterns between the two sites for nutrient cycling and  
503 structure maintenance with the different treatments suggests that moderate differences in soil  
504 texture have little effect on the restoration of these soil functions. On the other hand, the  
505 carbon transformation function was restored faster at SOGB (clay + silt content: 33 %) than at  
506 SAPH (clay + silt content: 12 %) with treatments R0L1, R1L1 and R2L1. Faster restoration of  
507 soil microbial functions in clay soils than in sandy soils has already been reported in the  
508 tropics (Schimann et al., 2007). Our result is consistent with this, given that higher clay  
509 content in a soil entails higher SOC, a key soil component closely linked to soil indicators  
510 related to carbon transformation (i.e. labile carbon, soil basal respiration and mesofauna  
511 activity) (Swift et al., 2004, 1991).

512

#### 513 4.3. What is the role of soil macrofauna diversity in providing soil functions?

514

515 While the key role of soil biodiversity in soil functioning is frequently pointed out (e.g.  
516 Bardgett and van der Putten, 2014), field studies showing relationships between soil  
517 biodiversity and soil functions are scarce. Most of the relationships highlighted through linear  
518 regressions in the literature suffer from low explanatory power (Delgado-Baquerizo et al.,  
519 2020; Li et al., 2020). Here, we demonstrate with highly significant models ( $P \leq 0.01$ ;  $R^2 = 0.37$ -  
520 0.71) at two experimental sites that soil macrofauna diversity is linked to soil health and soil



521 functions. We found positive relationships between soil macrofauna diversity and the indices  
522 of carbon transformation, at both study sites. The nutrient cycling index, however, was not  
523 significantly linked to soil macrofauna diversity. The indicator used in our study relates to N  
524 cycling, which mainly depends on soil microorganisms (Horz et al., 2004). In future studies  
525 the soil biodiversity index should include soil bacteria and archaea diversities to be more  
526 representative of soil biodiversity as a whole.

527 A steeper slope in the carbon transformation model than in the structure maintenance  
528 model indicates that the loss of one macrofauna taxonomic group would result in a greater  
529 loss of carbon transformation than of structure maintenance. This pattern suggests that the soil  
530 macrofauna has less functional redundancy for providing carbon transformation than for  
531 structure maintenance. High functional redundancy may act as buffer against the impact of  
532 biodiversity loss on soil functioning after disturbance (Griffiths and Philippot, 2012). Greater  
533 functional redundancy of the soil macrofauna with regard to structure maintenance would be  
534 consistent with the low level of disturbance of this function after land preparation at both sites  
535 in our study. High functional redundancy in the macrofauna with regard to soil structure has  
536 already been demonstrated in microcosm and field experiments (Davidson and Grieve, 2006).  
537 However, further investigation is needed to assess the distinct functional contributions of  
538 different soil organisms (bacteria, fungi, nematodes, etc.) to soil restoration after clear-cutting  
539 in rubber plantations, to identify key taxonomic groups that provide critical soil functions.

540 The model parameters for the relationship between SHI and macrofauna richness were  
541 similar at SAPH and SOGB. This suggests that environmental features and inherent soil  
542 conditions such as texture do not significantly affect the way soil biodiversity drives soil  
543 functions. A decrease in macrofauna species richness can therefore result in a loss of soil  
544 functions to the same degree in any rubber plantation. This is consistent with the finding in a

545 recent study exploring the role of soil biodiversity on ecosystem multifunctionality across 5  
546 continents and 83 locations (Delgado-Baquerizo et al., 2020).

547

#### 548 4.4. Consequences for plantation management

549

550 Currently, logging residues are seldom burnt in commercial rubber plantations, the trunks  
551 and branches being mainly exported commercially for timber or fuelwood. Even though this  
552 practice removes large amounts of carbon and nutrients from the plots (Perron et al., 2021), in  
553 our study soil function restoration was the same whether trunks were exported (R1L1) or not  
554 (R2L1). Thus far, and given the increasing worldwide demand for biomass energy (Krukanont  
555 and Prasertsan, 2004), this result suggests that trunks would be best used for power  
556 production rather than leaving them on the plot. However, the large amounts of carbon and  
557 nutrients stocked in the trunks (~400, 100 and 200 kg ha<sup>-1</sup> of N, P and K respectively) at the  
558 clear-cut stage are very likely to benefit both soil functioning and rubber tree nutrition once  
559 they have decomposed completely (Perron et al., 2021). Keeping all logging residues on-site  
560 could stimulate the biogeochemical cycling of nutrients, as already demonstrated in eucalypt  
561 plantations (Versini et al., 2014), and reduce the need for mineral fertilization at the start of  
562 the rotation (Vrignon-Brenas et al., 2019). Further studies in young rubber plantations rubber  
563 plantations are needed to confirm or refute this hypothesis.

564 The substantial disturbance of soil functions through clear-cutting and land preparation in  
565 our study calls for a change in management practices to reduce such disturbance. For the  
566 clear-cutting, bulldozers might be replaced by lighter machinery such as a combination of  
567 chainsaw to fell the tree and excavator to remove the stump. This is already the practice on  
568 some commercial plantations. Subsoiling, which also involves a bulldozer, may be  
569 unnecessary in light, sandy soil conditions such as at SAPH. The effect on soil functioning of

570 not removing the stumps could also be investigated, as stump removal is very likely to cause  
571 severe soil disturbance. In a such case, the development of root rot disease on the young  
572 rubber trees should be carefully monitored at the beginning of the plantation cycle (Nandris et  
573 al., 1987).

574 Finally, the land preparation phase when the ground is left bare should be as short as  
575 possible, as shown by the lack of soil function restoration in the R0L0 treatment. To this end,  
576 we suggest (1) reducing the gap between clear-cutting and replanting as much as possible, (2)  
577 sowing the legume as early as possible after clear-cutting and (3) spreading the logging  
578 residues over a larger area of the plot.

579

## 580 **5. Conclusion**

581

582 This study emphasizes the beneficial role of logging residues and a legume ground cover  
583 in restoring soil functions after severe disturbance caused by clear-cutting and land  
584 preparation in rubber plantations. The main results were similar at both study sites despite  
585 their contrasting soil properties: (1) clear-cutting severely disturbed the carbon transformation  
586 and nutrient cycling functions; (2) leaving logging residues on the ground improved the  
587 restoration of carbon transformation and structure maintenance, but showed no impact on  
588 nutrient cycling; (3) the relationship between soil macrofauna diversity and soil health is both  
589 strong and positive.

590 The severe disturbance of soil functions during clear-cutting and land preparation suggests  
591 that alternatives that cause less disturbance, such as not removing stumps or not subsoiling in  
592 light soil conditions, should be investigated. The similarities between the two sites in their  
593 patterns of soil function restoration suggest that adding large amounts of organic matter, by  
594 spreading logging residues and/or sowing a legume, is essential for supporting soil functions

595 and hence for the sustainability of rubber plantations. Our findings provide evidence that soil  
596 macrofauna diversity is crucial for maintaining soil health across different tropical soil  
597 conditions. In rubber plantations, more thorough knowledge of soil biodiversity and soil  
598 health is needed to help design more sustainable plantation management systems, especially  
599 as regards the clear-cutting and land preparation periods.

600

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610

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614

### 615 **Conflict of interests**

616 The authors declare that they have no conflict of interests.

617

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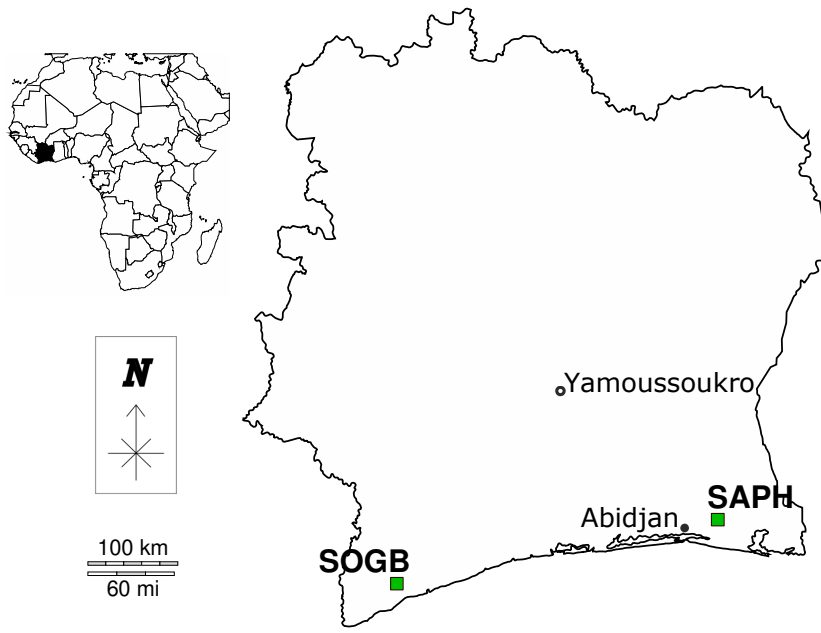


Figure 1: Geographical location of the study sites.

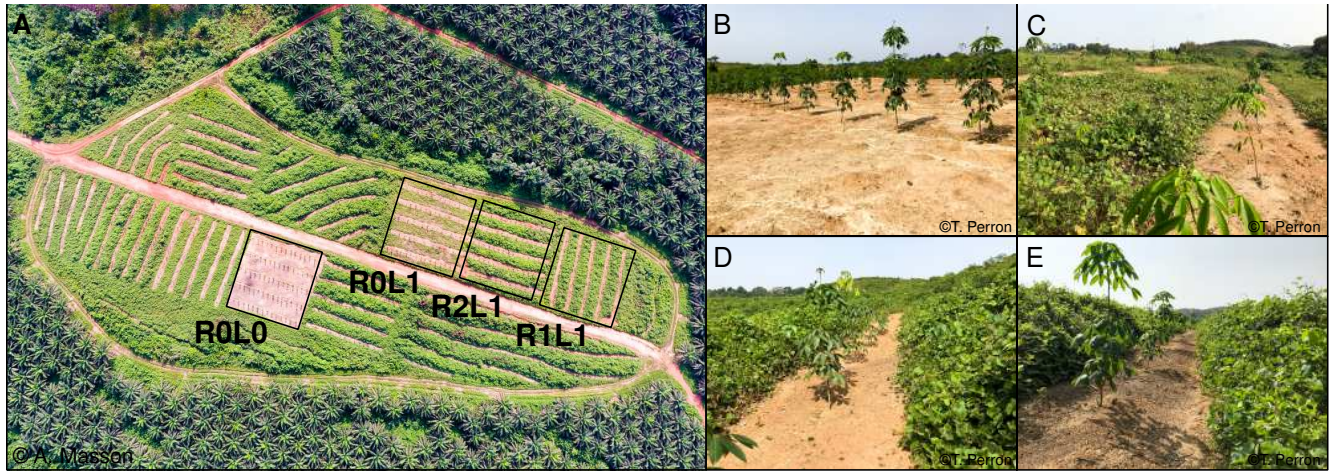


Figure 2: Photos of a block with the different treatments (A), treatment R0L0 (B), treatment R0L1 (C), treatment R1L1 (D) and treatment R2L1 (E) at SOGB. All photos were taken in February 2019.

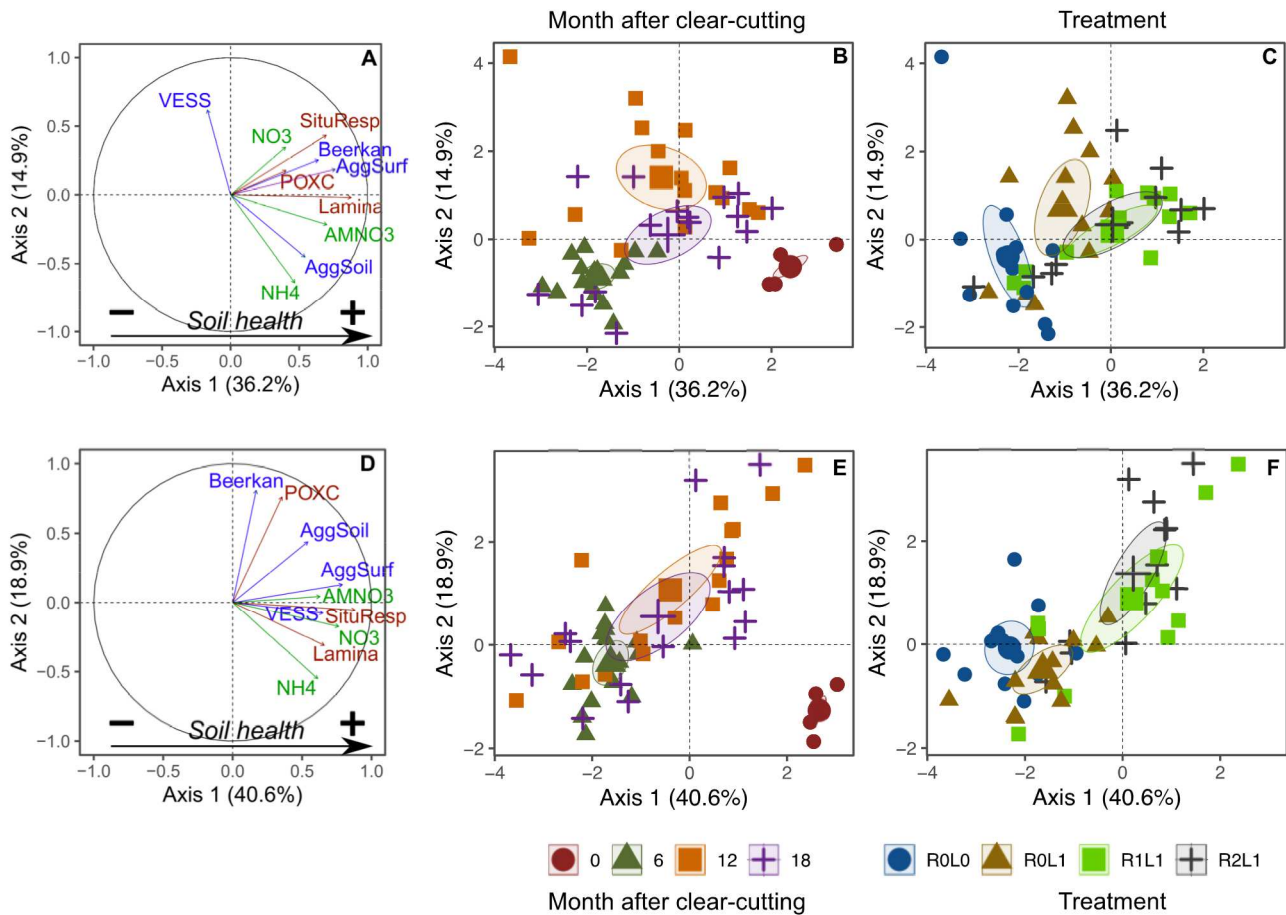


Figure 3: Principal component analysis assessing the effects of time since clear-cutting and type of treatment on soil indicators at SAPH and SOGB (n=52). A: correlation circle at SAPH; B: graph of individuals at SAPH with the effect of time since clear-cutting; C: graph of individuals at SAPH with the effect of treatment type; D: correlation circle at SOGB; E: graph of individuals at SOGB with the effect of time since clear-cutting; F: graph of individuals at SOGB with the effect of treatment type. See Table 2 for the description of the soil indicator codes. In B, C, E and F: large symbols represent barycentres while small ones stand for individual measurements; ovals represent confidence ellipses for each time after clear-cutting (B, E) or each treatment (C, F). R0L0: all logging residues removed from the plot, no legume; R0L1: all logging residues removed from the plot, legume; R1L1: trunk removed from the plot (twigs, leaves and stumps left on-site), legume; R2L1: no logging residues removed (trunks, twigs, leaves and stumps remaining left on-site), legume.

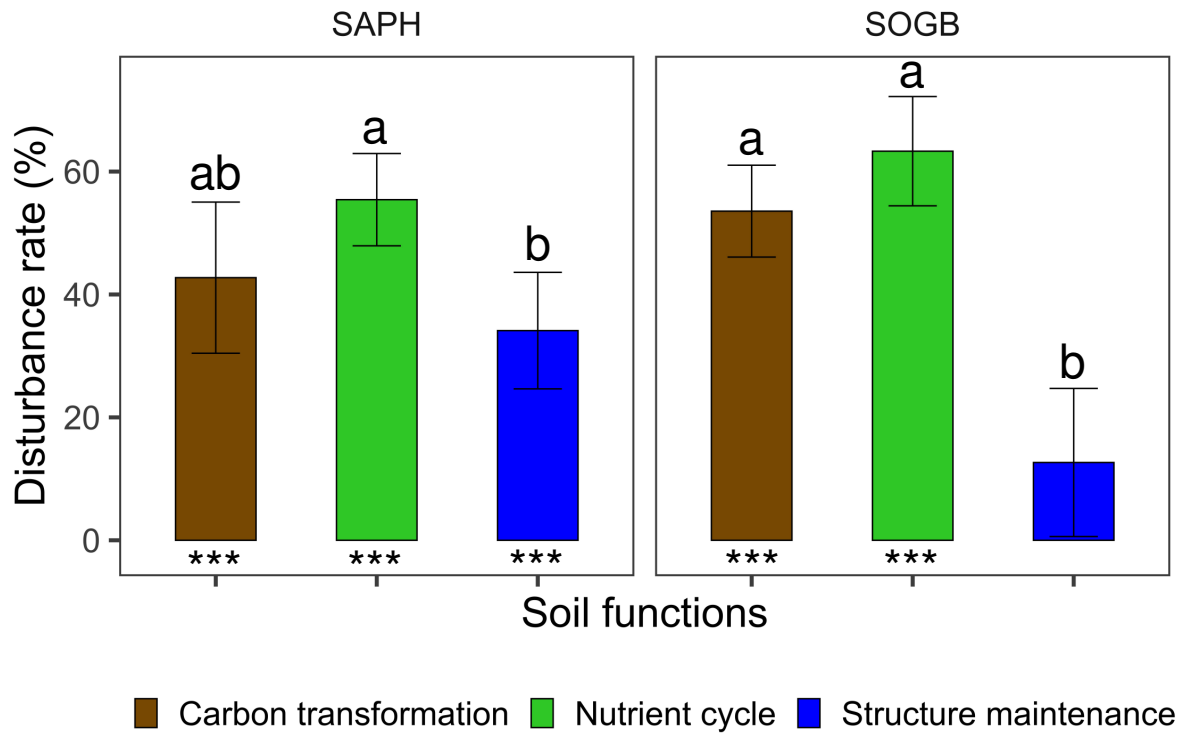


Figure 4: Disturbance rates (%) of soil functions at SAPH and SOGB (n=4) between month 0 and month 6. Different letters indicate significant differences between soil functions at a given site after the Tukey post-hoc test with  $P < 0.05$ . Vertical bars correspond to standard deviation. Asterisks indicate the  $P$  values of the t-test comparing the mean of a given soil function to the theoretical value  $\mu = 0$ . \*\*\* $P < 0.001$ .

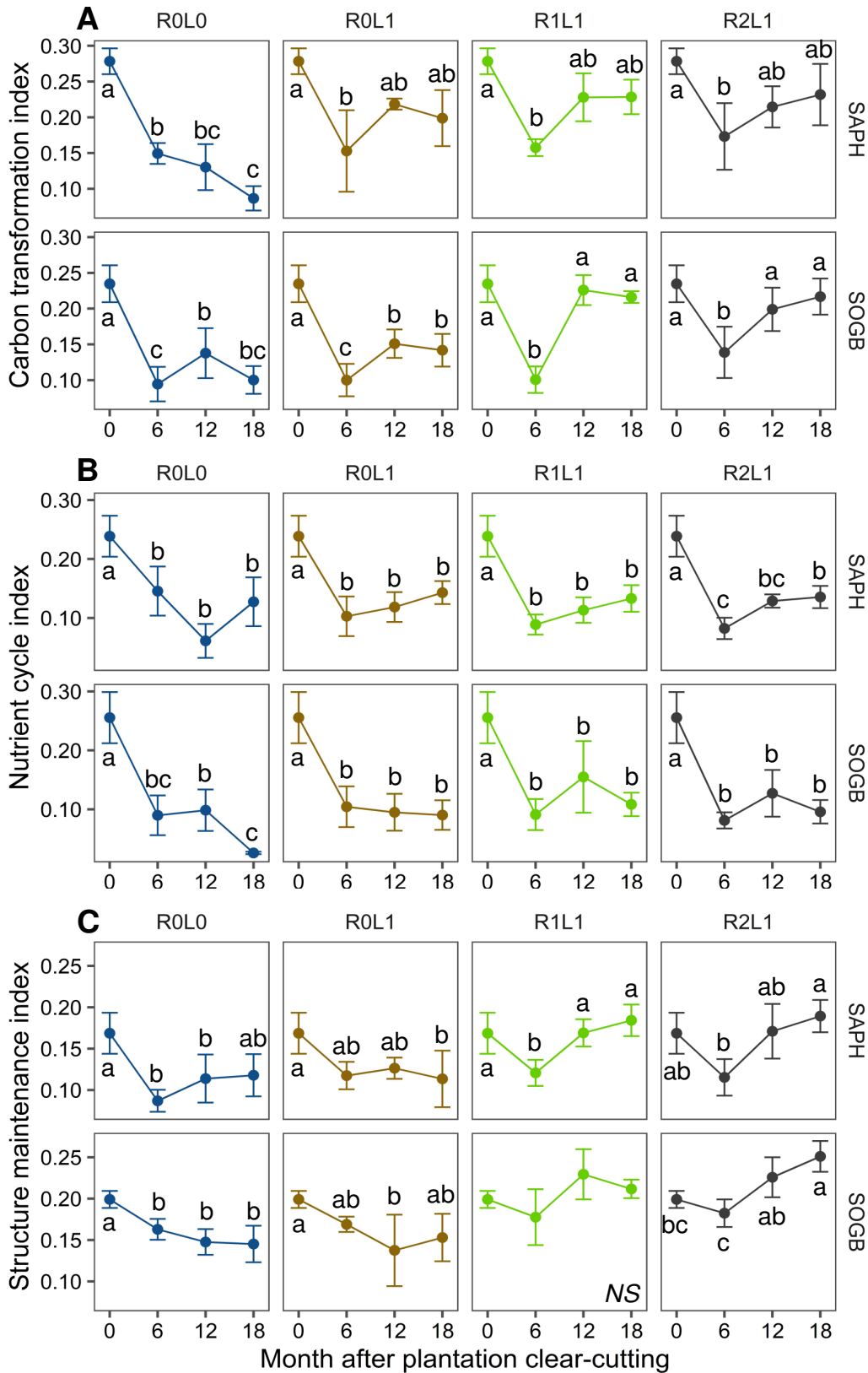


Figure 5: Changes in the carbon transformation (A), nutrient cycling (B) and structure maintenance (C) functions over time at SAPH and SOGB with the four treatments (n=4). Vertical bars correspond to standard deviation. Different letters indicate significant differences between months for a given site and treatment after the Tukey post-hoc test with  $P < 0.05$ . NS: non-significant differences among months at  $P < 0.05$ .

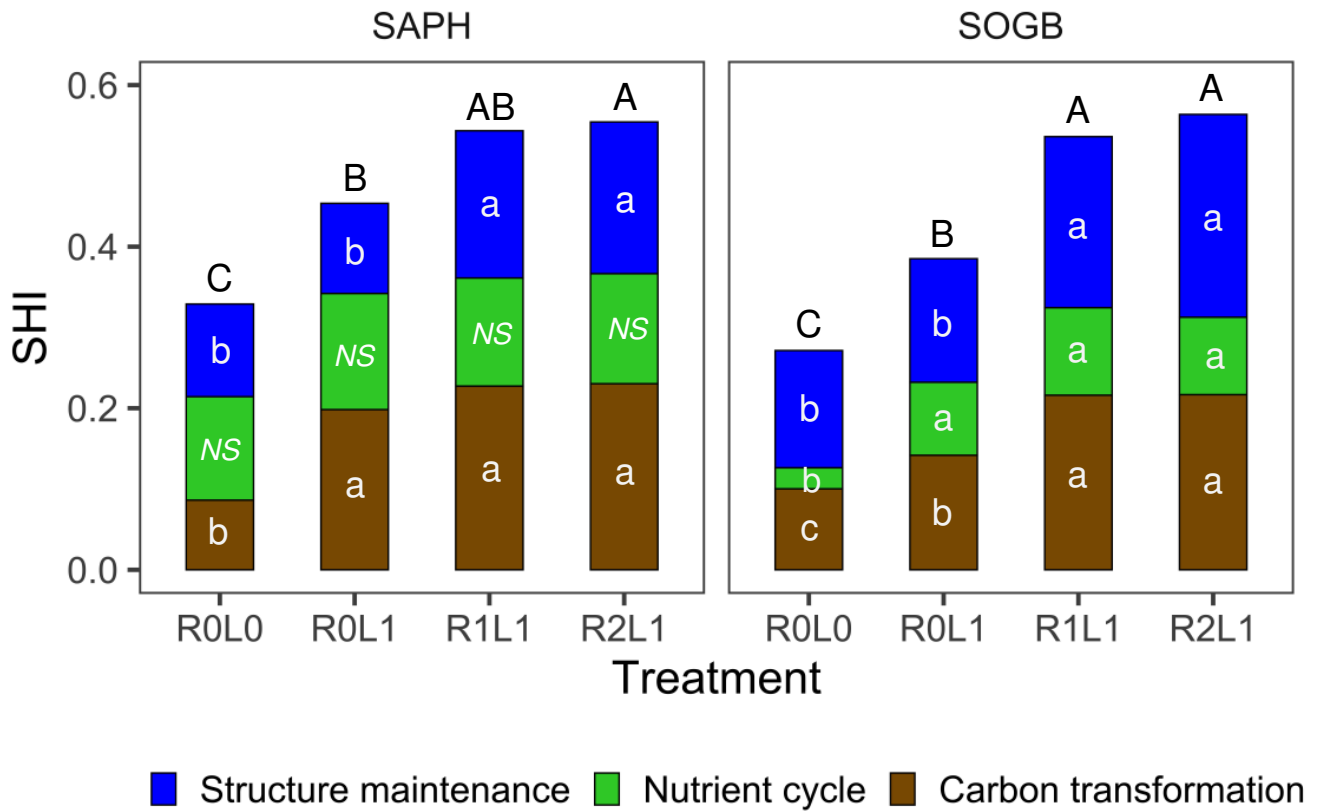


Figure 6: Soil health index (SHI) in the different treatments at month 18 at SAPH and SOGB (n=4). Different capital letters indicate significant differences of SHI between treatments at a given site after the Tukey post-hoc test ( $P < 0.05$ ). Different lower-case letters mean significant differences in soil functions between treatments at a given site after the Tukey post-hoc test ( $P < 0.05$ ). NS: non-significant difference among treatments at  $P < 0.05$ .

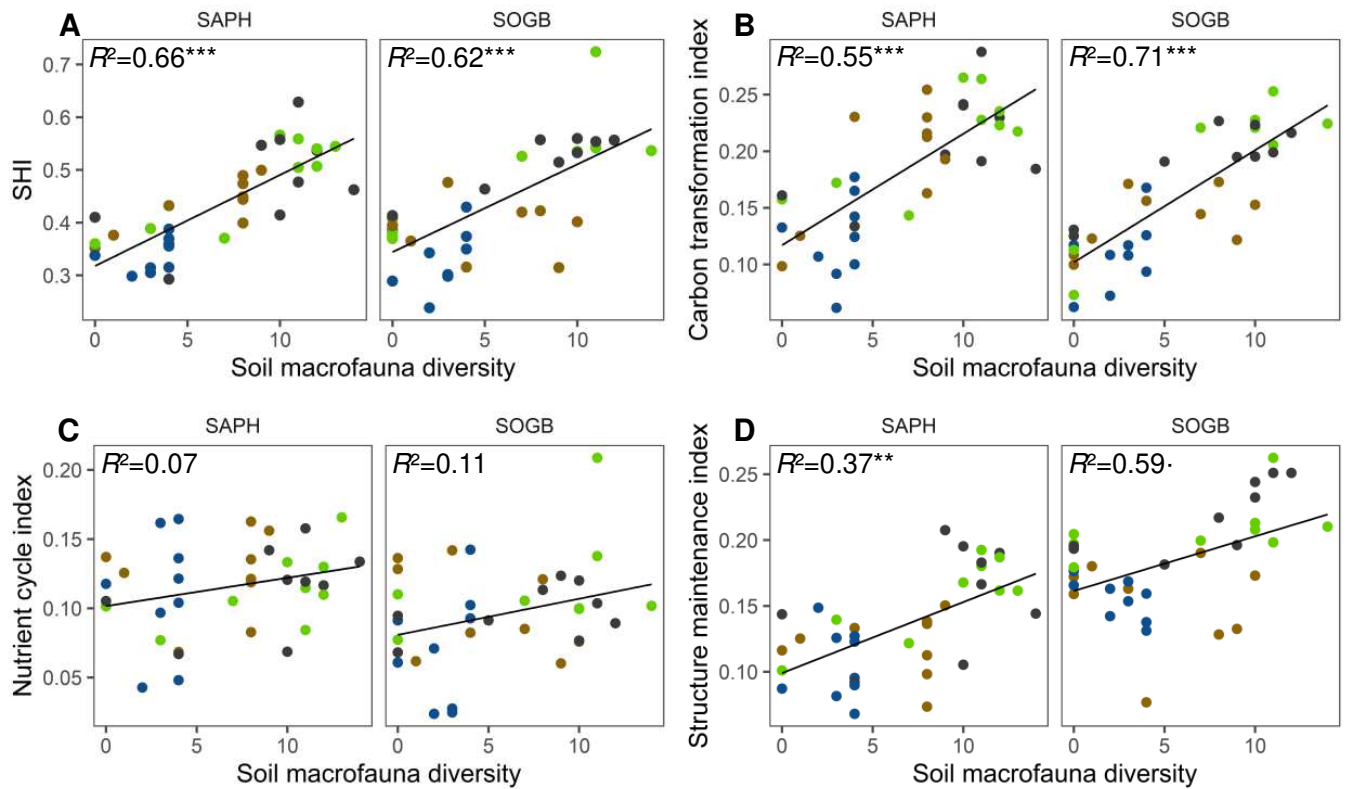


Figure 7: Relationships between soil macrofauna diversity (richness in taxonomic groups) and soil health index (A), carbon transformation (B), nutrient cycling (C) and structure maintenance (D) functions at SAPH and SOGB ( $n=36$ ). Blue dots stand for treatment R0L0, orange dots for treatment R0L1, green dots for treatment R1L1 and grey dots for treatment R2L1.  $R^2$  values correspond to conditional  $R^2$ , taking into consideration both fixed and random effects.  $P \leq 0.10$ ,  $P < 0.05$ ,  $P < 0.01$ , and  $P < 0.001$  are indicated by ·, \*, \*\*, \*\*\*, respectively.



Table 1: Soil properties at SAPH and SOGB in the 0-10 cm layer. Data in brackets are standard deviations (n=4).

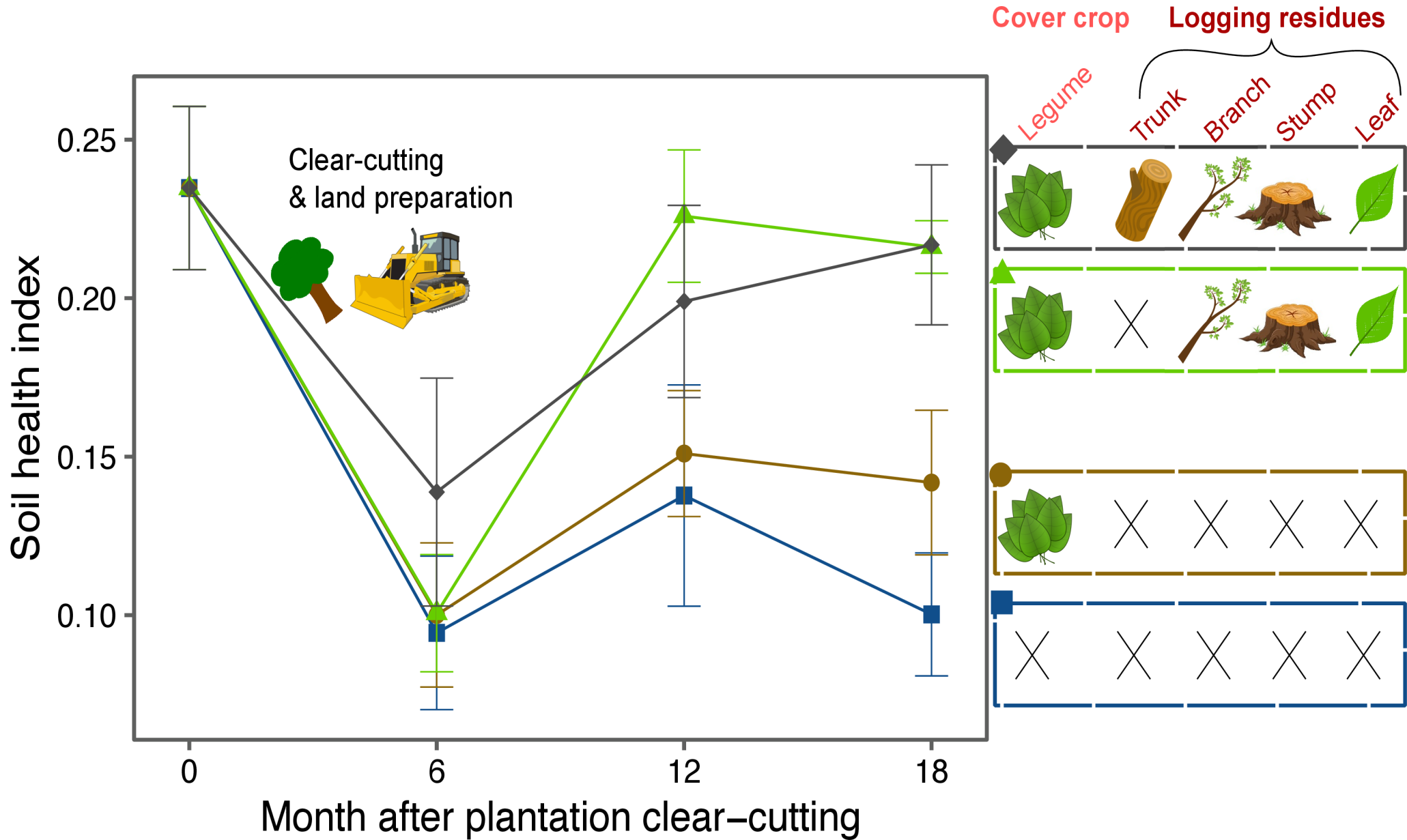
Site	pH <sub>H2O</sub>	Total C <sup>a</sup> (%)	Total N <sup>a</sup> (ppm)	Available P <sup>b</sup> (ppm)	Clay (%)	Silt (%)	Sand (%)
SAPH	4.3 (0.2)	0.85 (0.22)	707 (155)	7.2 (1.6)	10 (1)	2 (1)	87 (5)
SOGB	4.7 (0.2)	1.28 (0.32)	974 (184)	5.2 (2.0)	23 (4)	10 (2)	67 (6)

<sup>a</sup> By elemental analyser (FlashSmart™, ThermoFisher).

<sup>b</sup> Extraction and determination with vanado-molybdate (Bray II method).

Table 2: Soil indicators of each soil function in the 0-10 cm layer and the response curve used for data normalization. A detailed description of Biofunctool indicators is given in Thoumazeau et al. (2019b).

Soil function	Indicator description (unit)	Code	Response curve
Nutrient cycle	Concentration of NO <sub>3</sub> <sup>-</sup> (mg kg <sup>-1</sup> )	NO3	Optimum
	Concentration of NH <sub>4</sub> <sup>+</sup> (mg kg <sup>-1</sup> )	NH4	Optimum
	Adsorption rate of nitrate on ion exchange membranes (µg cm <sup>-2</sup> day <sup>-1</sup> )	AMNO3	Optimum
Carbon transformation	Labile organic carbon, Permanganate oxidizable carbon method (mg kg <sup>-1</sup> )	POXC	More is better
	Soil basal respiration, SituResp <sup>®</sup> method (absorbance difference)	SituResp	More is better
	Decomposition of organic matter, bait-lamina method (% of degradation day <sup>-1</sup> )	Lamina	More is better
Structure maintenance	Visual evaluation of soil structure (score)	VESS	Less is better
	Soil aggregate stability at 0-2 cm depth (score)	AggSurf	More is better
	Soil aggregate stability at 2-10 cm depth (score)	AggSoil	More is better
	Water infiltration capacity, Beerkan method (ml min <sup>-1</sup> )	Beerkan	More is better



 Clear-cutting & land preparation: **strong disturbance** of soil health.

◆▲ **Full restoration** of soil health 18 months after clear-cutting.

● **Partial restoration** of soil health over 18 months.

■ **No restoration** of soil health over 18 months.