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Abstract

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

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

1. **Introduction**

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

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

Degradation of soil physical properties caused by the passage of machinery has been extensively reported in various crop systems worldwide, especially as regards increased bulk density (Ampoorter et al., 2010) and decreases in pore volume, hydraulic conductivity and air permeability (Hartmann et al., 2014). Researchers have also demonstrated the negative impacts of clear-cutting on nutrient and carbon cycles (Christophel et al., 2015; Siebers et al., 2018; Mayer et al., 2020) and on faunal and microbial communities (Bottinelli et al., 2014; Frey et al., 2009; Hasegawa et al., 2014) in planted forests in various pedoclimatic conditions. Soil texture may significantly affect the way soil functions respond to disturbance. Hartmann et al. (2014) report that soil compaction had a stronger effect on the abundance and diversity of soil microorganisms in fine-textured soils than in coarse-textured soils in temperate forests. To maintain the crucial functions provided by soils, it is necessary to know how these functions respond to disturbance. Not enough is known about the disturbances caused by clear-cutting and land preparation in rubber tree plantations and other tropical perennial crops.

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

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

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

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

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

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

2. Material and methods

2.1. Study sites

The study ran from October 2017 to April 2019 in two commercial rubber plantations in Côte d'Ivoire (Fig. 1). The Bongo plantation belongs to the *Société Africaine des Plantations d'Hévéas* (SAPH) and is located in the southeast of the country (latitude 5°30'32.364"N, longitude 3°32'51.755"W, altitude 96 m). The *Société de Caoutchouc de Grand-Béréby* plantation (SOGB) is located in the southwest of the country (latitude 4°43'9.696"N, longitude 7°6'41.795"W, altitude 34 m). Both plantations lie within the rainforest ecological zone, where a sub-equatorial climate favourable to rubber tree cultivation prevails. Rainfall in southern Côte d'Ivoire is divided between two rainy seasons, a major one from May to July and a minor one from October to November, with two dry seasons from December to April and from August to September. Average annual rainfall (2003 to 2018) was 1640 mm at SAPH and 1674 mm at SOGB. Monthly rainfall throughout the study period is presented in Supplementary Fig. 1.

The SAPH site is characterized by slight slopes (< 5 %). Its soil is classified as a yellow ferralic Arenosol in the FAO soil classification. The SOGB site features hilly areas (slopes of 10-25 %), and its soil is classified as a red Ferralsol in the FAO classification. Soil texture is loamy sand at SAPH (10 % clay in the topsoil) and sandy loam at SOGB (23 % clay in the topsoil) (Table 1). The soils at both sites are acidic, with a pH_{H20} of 4.3 and 4.7 in the 0-10 cm horizon at SAPH and SOGB respectively. While total carbon and nitrogen are higher at SOGB, the concentration of available phosphorus in the 0-10 cm soil layer is higher at SAPH.

2.1. Experiment design and crop management

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

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

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

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

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

2.2. Biofunctool indicators

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

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

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

2.3. Assessment of soil biodiversity

Soil macrofauna were sampled using the standard Tropical Soil Biology and Fertility method (Anderson et al., 1993). This consists in hand-sorting macroinvertebrates visible to the naked eye from a soil monolith 25 x 25 cm in area and 10 cm deep. In the field, animals were placed in ethanol (96%). In the laboratory, invertebrates were identified as belonging to 20 taxonomic groups: Annelida, Anoplura, Arachnida, Chilopoda, Coleoptera, Dermaptera, Dictyoptera, Diplopoda, Embioptera, Heteroptera, Homoptera, Hymenoptera, Isopoda, Isoptera, Lepidoptera, Mecopotera, Neuroptera, Orthoptera, Thysanoptera and Thysanoura. A "group" could be family, class or order, the purpose being to comprise a set of individuals of similar body plan. We used richness (i.e., the number of taxonomic groups) to assess macrofauna diversity, as it is the simplest and most widely used metric for biodiversity. At both sites, the richness of the soil macrofauna was highly correlated with the Shannon index (Pearson r=0.83-0.90; P<0.001). This suggests that our simple soil biodiversity indicator was relevant for characterizing the effects of different management practices at replanting in rubber plantations.

2.4. Diachronic assessment of soil health

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

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

2.5. Disturbance rate

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

$$Dr\ (\%) = \frac{(F_{month\ 0} - F_{month\ 6})}{F_{month\ 0}}\ x\ 100 \qquad (1)$$

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

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

2.6. Statistical analysis

2.6.1. Computation of soil indices

We calculated an index for each soil function (i.e. a nutrient cycle index, a carbon transformation index and a structure maintenance index), as per Obriot et al. (2016) and Thoumazeau et al. (2019b). Briefly, the 10 soil indicators were first normalized using a “more is better”, “less is better” or “optimum” response curve, depending on the indicator (Table 2). The “optimum” response curve was chosen for soil indicators related to nutrient availability (i.e. NO3, NH4 and AMNO3). The concentration of available nutrient at month 0 was chosen as the optimum value since mature rubber stands are often considered to be self-sustainable as regards nutrient cycling (Jessy et al., 2009; Sivanadyan et al., 1995). The “optimum” response curve for available soil nutrients has already been used to reflect the risk of environmental hazards, especially leaching, that high concentrations of available nutrients may entail (Obriot et al., 2016). Then, a weighted principal component analysis (PCA) based on correlation matrix was run to provide the same weight to each soil function. The indices were calculated from the relative contributions of the soil indicators to the principal components with eigenvalues > 1. A soil health index (SHI) was computed from the sum of the three indices, to reflect the multiple functions delivered by soils. All indices were calculated for each site separately, to avoid co-effects linked to the two sites' contrasting edaphic conditions.

2.6.2. Modelling

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

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

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

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

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

3. **Results**

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

A principal component analysis incorporating the 10 soil indicators showed that soil health was strongly influenced by length of time since clear-cutting and by type of logging residue management and/or legume cover (Fig. 3). At both sites, 9 out of 10 indicators were positively and significantly correlated to axis 1, explaining 36.2% and 40.6% of the variability at SAPH and SOGB respectively (Fig. 3A; Fig. 3C). This pattern shows that axis 1 could be considered a gradient of soil health: individuals located to the left of axis 1 will exhibit a low level of soil health, while individuals to the right of axis 1 will exhibit a high level of soil health. At both sites, the distribution of the sampling dates on axis 1 was as follows, from lowest soil health to highest: month 6 < month 12 ≤ month 18 < month 0 (Fig. 3B; Fig. 3E). As regards treatments, their distribution on axis 1 was similar at the two sites, with the following order from the left side to the right side of axis 1: R0L0 < R0L1 < R1L1 ≤ R2L1 (Fig. 3C; Fig. 3F).

Axis 2 explained only 14.9% and 18.9% of the variability at SAPH and SOGB respectively. The soil indicators that contributed most to its construction were different between the two sites. The highest contributions were VESS and NH4 at SAPH, but Beerkan and POXC at SOGB.

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

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

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

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

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

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

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

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

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

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

3.4. Relationships between soil functions and soil macrofauna diversity

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

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

4. Discussion

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

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

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

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

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

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

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

When logging residues were exported from plots (in R0L0 and R0L1), the structure maintenance index was not restored within the first 18 months after clear-cutting at either site. By contrast, in treatments with logging residues (R1L1 and R2L1) full restoration of the index was observed over 18 months. This suggests that input of logging residues plays a major role in the improvement of this function, while legume cover has little effect. The addition of fresh organic matter (such as logging residues) is known to greatly enhance soil macrofauna activity (Bengtsson et al., 1997), which directly influences soil structure by improving macroporosity (Bottinelli et al., 2015). Carbon transformation, however, was strongly influenced by the cover crop in the plots without logging residues. Partial restoration of this function within 18 months was observed in R0L1, while it was still significantly disturbed in R0L0 at both sites at month 18. Our results confirm the crucial role of legume cover crops on soil indicators linked to carbon transformation in rubber plantations, as highlighted in previous studies (Broughton, 1977; Watson, 1957).

Interestingly, at SAPH, restoration of the carbon transformation index over 18 months after clear-cutting was not affected by the amount of logging residues on the soil surface in plots with the legume cover crop (i.e. comparing treatments R0L1, R1L1 and R2L1). *Pueraria phaseoloides* is characterized by high carbon accumulation in its aboveground biomass in the first year after replanting rubber trees (3.6 t ha^{-1} year^{-1}), with 50% of the carbon in its litter released within 7 days (Clermont-Dauphin et al., 2016). So the considerable carbon input to the soil through legume litter could have been enough to mask the effect of logging residues on the carbon transformation index at SAPH.

The nutrient cycling function was not restored within our study period in any treatment at either site, except for treatment R2L1 at SAPH, where a significant increase was observed at month 18. After a peak at month 6, concentrations of mineral N in the topsoil decreased steadily (data not shown). The concentration of nitrate remained higher than the initial optimum value (month 0), while the concentration of ammonium decreased below the initial optimum value at both sites. This trend in mineral N concentration, characterized by a nitrate to ammonium ratio > 1, indicates large amounts of available N and an open N cycle, as reported in a post-agricultural succession (Xiao et al., 2018). The low nutrient cycling index 6 months after clear-cutting and onward points to a risk of N losses through leaching and environmental issues, such as eutrophication. This hypothesis is corroborated by the high N concentrations to a depth of 2 m, which we found in soil solutions collected over the study period using ceramic cup lysimeters in R2L1 and R0L1 plots at SAPH (data not shown). An increase in the nutrient cycling index is expected at a later date, through (1) a decrease in N mineralisation after logging residue decomposition (Mendham et al., 2004; O'Connell, 2004), and (2) a strong increase in the rubber trees' demand for N (Perron et al., 2021) with a concomitant exploration of the upper soil layers by rubber tree roots.

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

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

While the key role of soil biodiversity in soil functioning is frequently pointed out (e.g. Bardgett and van der Putten, 2014), field studies showing relationships between soil biodiversity and soil functions are scarce. Most of the relationships highlighted through linear regressions in the literature suffer from low explanatory power (Delgado-Baquerizo et al., 2020; Li et al., 2020). Here, we demonstrate with highly significant models ($P \leq 0.01$; $R^2=0.37$-0.71) at two experimental sites that soil macrofauna diversity is linked to soil health and soil functions. We found positive relationships between soil macrofauna diversity and the indices of carbon transformation, at both study sites. The nutrient cycling index, however, was not significantly linked to soil macrofauna diversity. The indicator used in our study relates to N cycling, which mainly depends on soil microorganisms (Horz et al., 2004). In future studies the soil biodiversity index should include soil bacteria and archaea diversities to be more representative of soil biodiversity as a whole.

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

The model parameters for the relationship between SHI and macrofauna richness were similar at SAPH and SOGB. This suggests that environmental features and inherent soil conditions such as texture do not significantly affect the way soil biodiversity drives soil functions. A decrease in macrofauna species richness can therefore result in a loss of soil functions to the same degree in any rubber plantation. This is consistent with the finding in a recent study exploring the role of soil biodiversity on ecosystem multifunctionality across 5 continents and 83 locations (Delgado-Baquerizo et al., 2020).

4.4. Consequences for plantation management

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

The substantial disturbance of soil functions through clear-cutting and land preparation in our study calls for a change in management practices to reduce such disturbance. For the clear-cutting, bulldozers might be replaced by lighter machinery such as a combination of chainsaw to fell the tree and excavator to remove the stump. This is already the practice on some commercial plantations. Subsoiling, which also involves a bulldozer, may be unnecessary in light, sandy soil conditions such as at SAPH. The effect on soil functioning of not removing the stumps could also be investigated, as stump removal is very likely to cause severe soil disturbance. In a such case, the development of root rot disease on the young rubber trees should be carefully monitored at the beginning of the plantation cycle (Nandris et al., 1987).

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

5. Conclusion

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

The severe disturbance of soil functions during clear-cutting and land preparation suggests that alternatives that cause less disturbance, such as not removing stumps or not subsoiling in light soil conditions, should be investigated. The similarities between the two sites in their patterns of soil function restoration suggest that adding large amounts of organic matter, by spreading logging residues and/or sowing a legume, is essential for supporting soil functions and hence for the sustainability of rubber plantations. Our findings provide evidence that soil macrofauna diversity is crucial for maintaining soil health across different tropical soil conditions. In rubber plantations, more thorough knowledge of soil biodiversity and soil health is needed to help design more sustainable plantation management systems, especially as regards the clear-cutting and land preparation periods.

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Conflict of interests

The authors declare that they have no conflict of interests.

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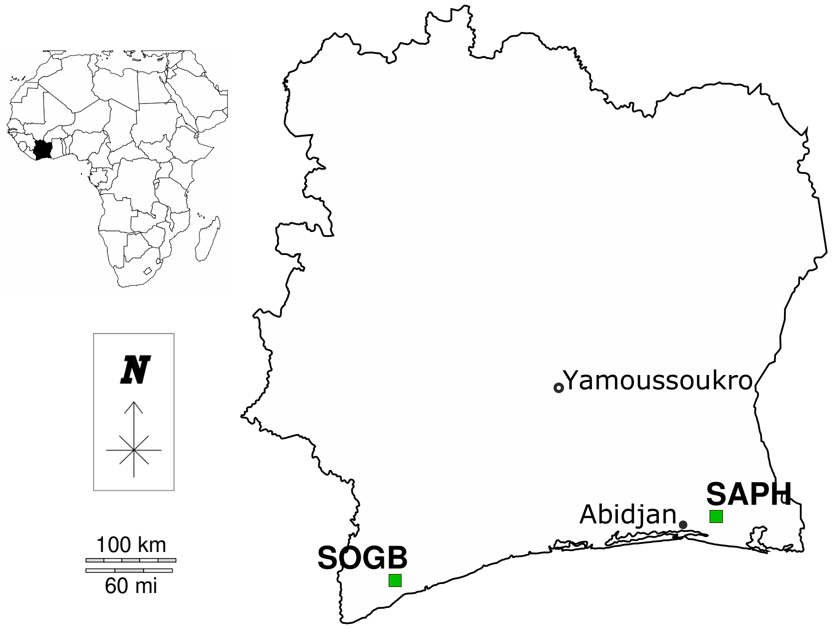


Figure 1: Geographical location of the study sites.

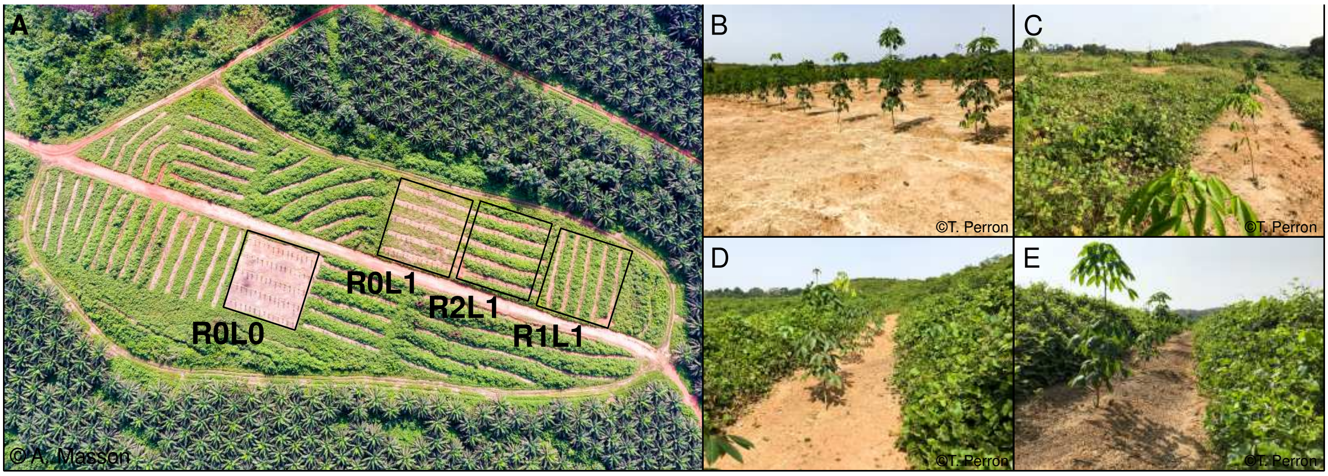


Figure 2: Photos of a block with the different treatments (A), treatment R0L0 (B), treatment R0L1 (C), treatment R1L1 (D) and treatment R2L1 (E) at SOGB. All photos were taken in February 2019.

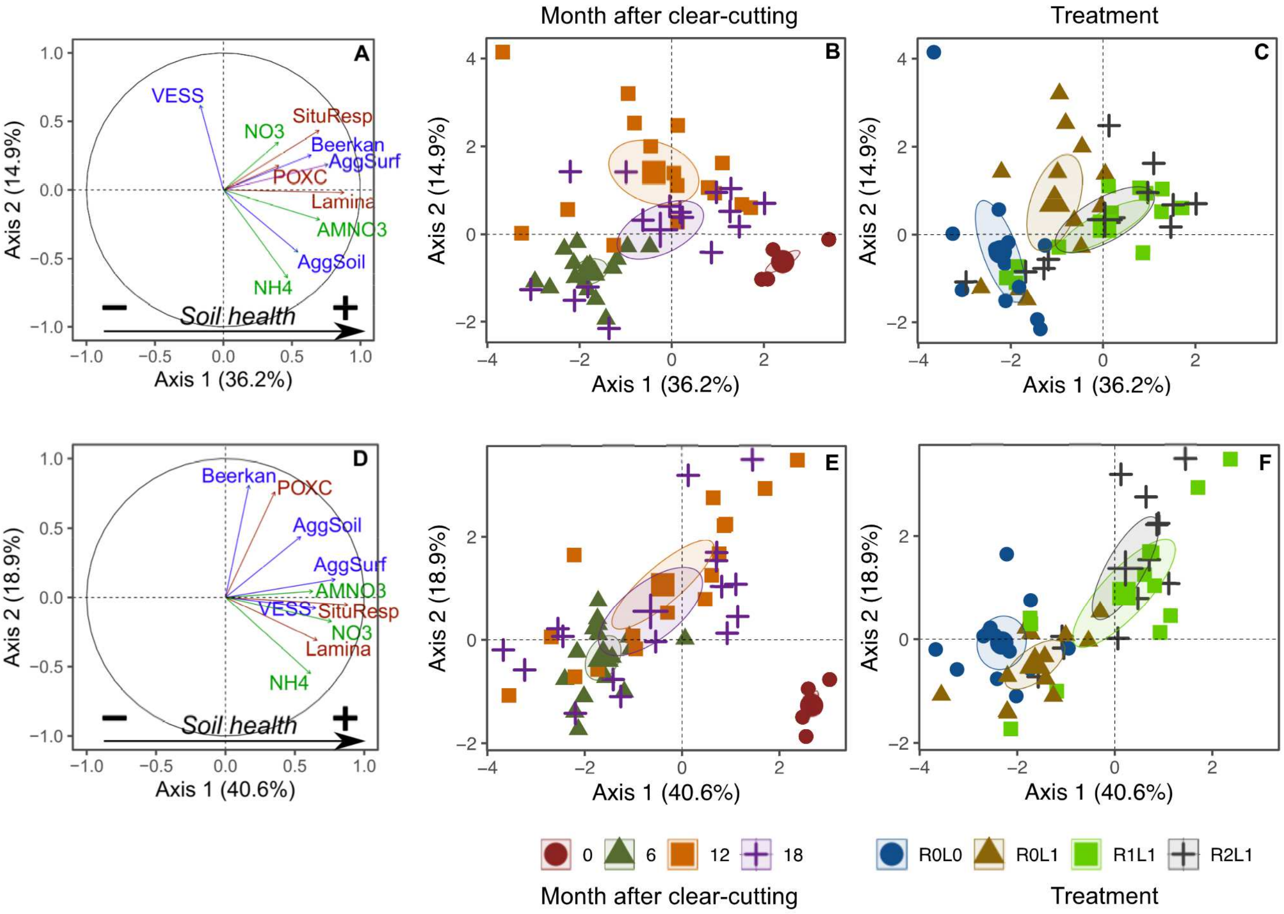


Figure 3: Principal component analysis assessing the effects of time since clear-cutting and type of treatment on soil indicators at SAPH and SOGB (n=52). A: correlation circle at SAPH; B: graph of individuals at SAPH with the effect of time since clear-cutting; C: graph of individuals at SAPH with the 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.

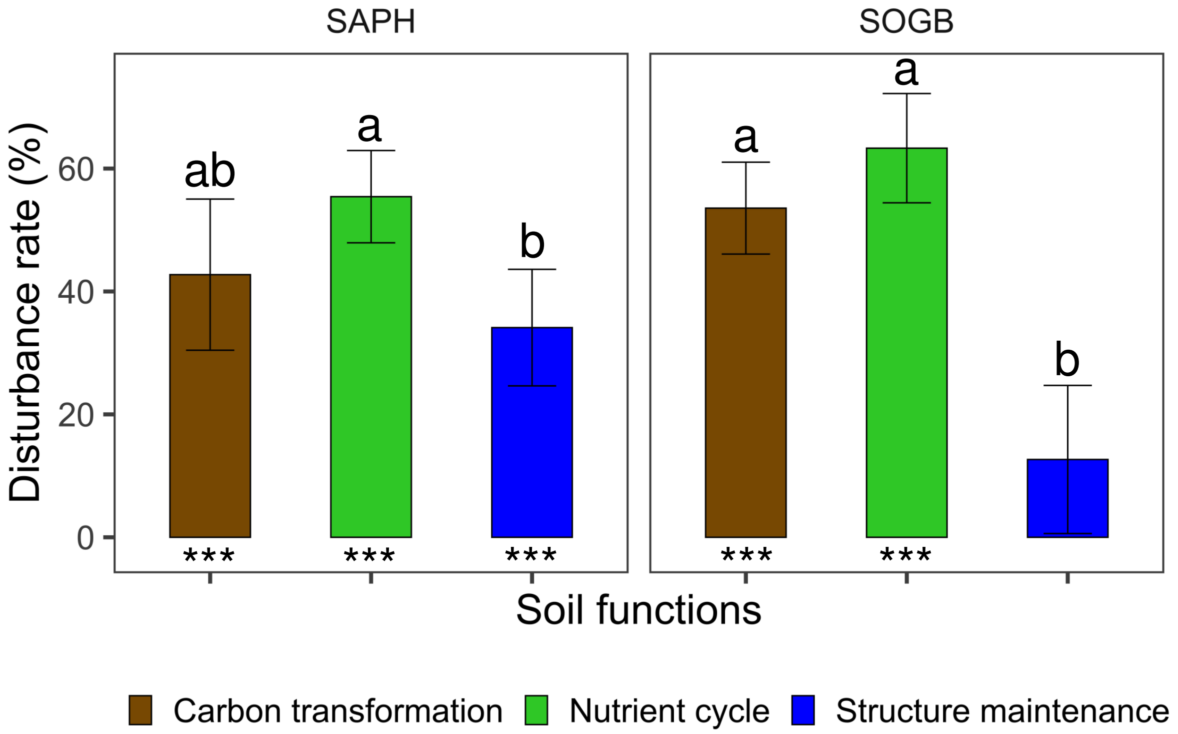


Figure 4: Disturbance rates (%) of soil functions at SAPH and SOGB (n=4) between month 0 and month 6. Different letters indicate significant differences between soil functions at a given site after the Tukey post-hoc test with $P<0.05$. Vertical bars correspond to standard deviation. Asterisks indicate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

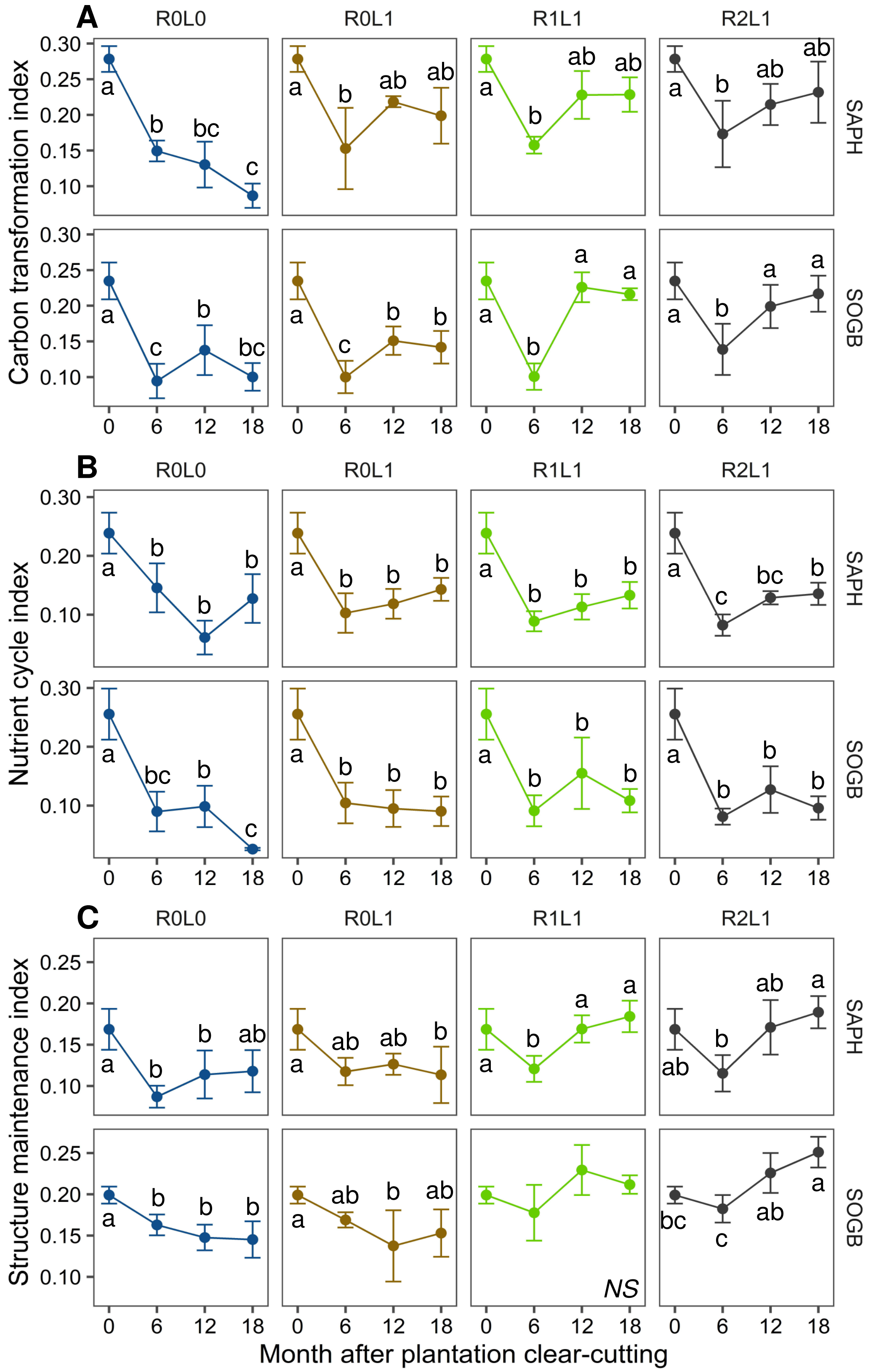


Figure 5: Changes in the carbon transformation (A), nutrient cycling (B) and structure maintenance (C) functions over time at SAPH and SOGB with the four treatments (n=4). Vertical bars correspond to standard deviation. Different letters indicate significant differences between months for a given site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

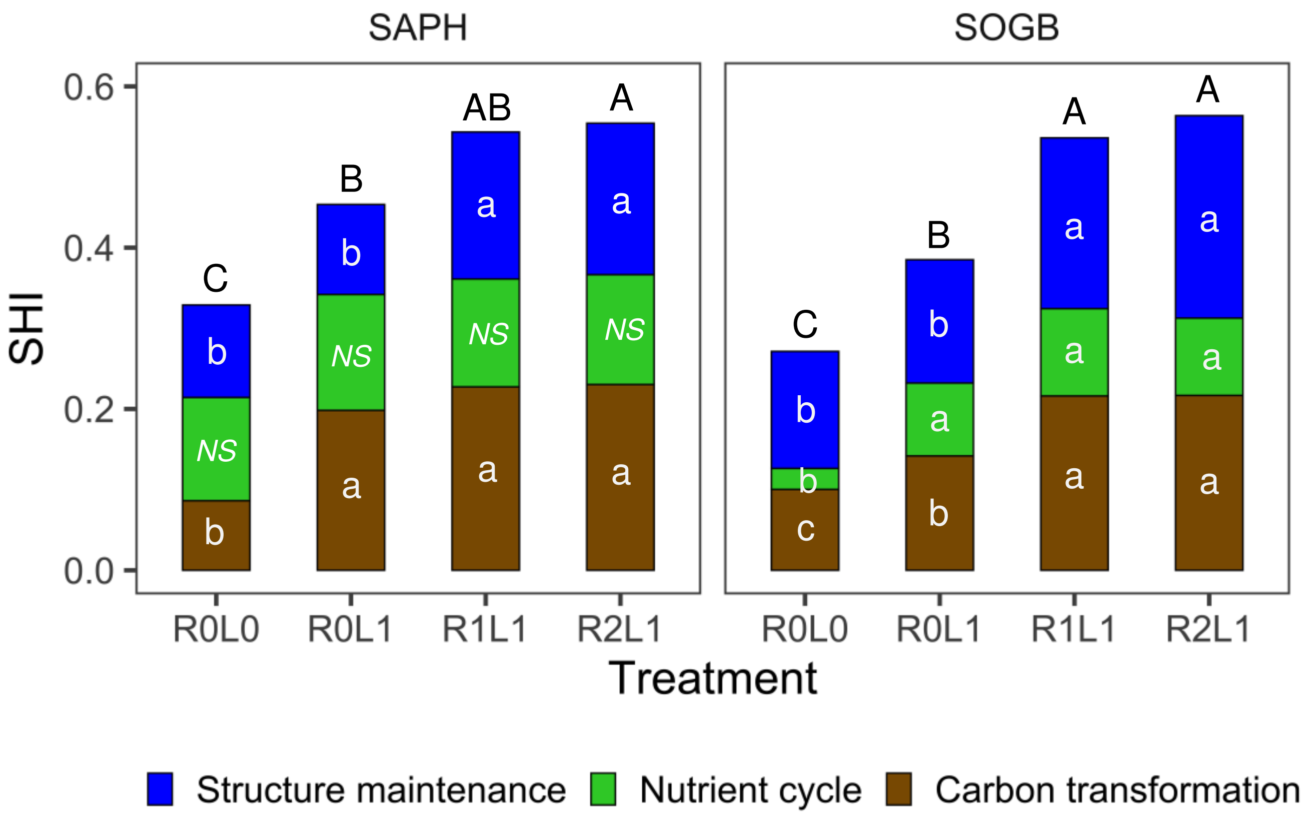


Figure 6: Soil health index (SHI) in the different treatments at month 18 at SAPH and SOGB (n=4). Different capital letters indicate significant differences of SHI between treatments at a given site after the Tukey post-hoc test ($P<0.05$). Different lower-case letters mean significant differences in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

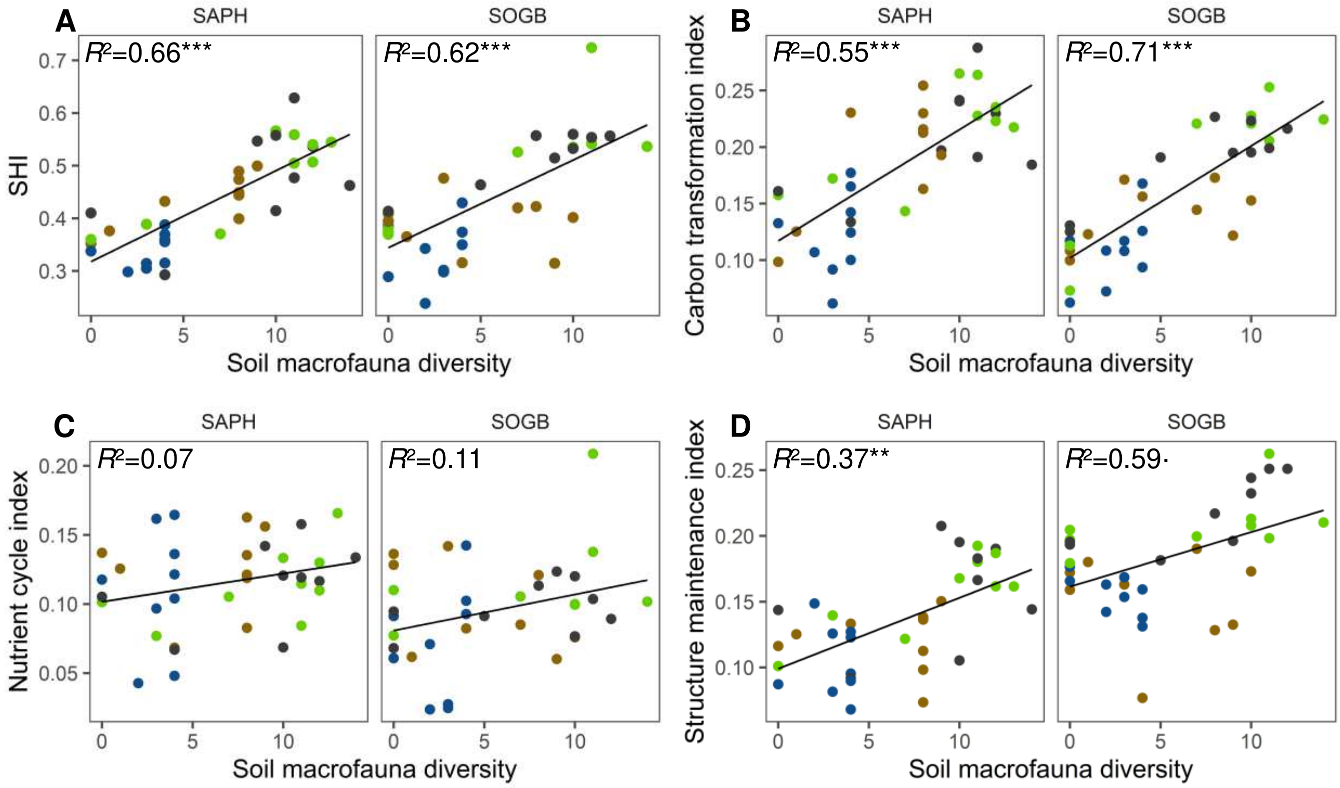


Figure 7: Relationships between soil macrofauna diversity (richness in taxonomic groups) and soil health index (A), carbon transformation (B), nutrient cycling (C) and structure maintenance (D) functions at SAPH and SOGB (n=36). Blue dots stand for treatment R0L0, orange dots for treatment R0L1, green 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).

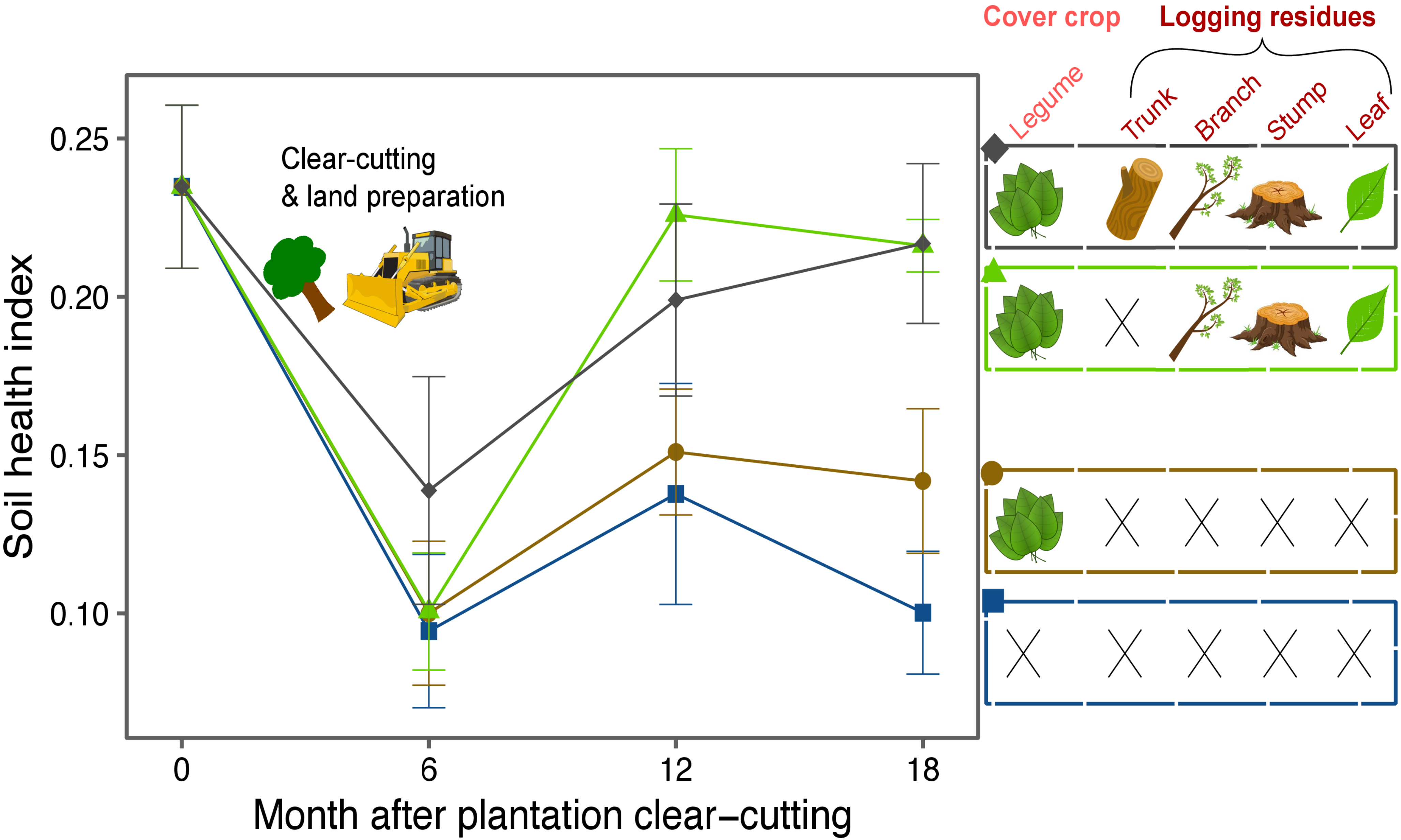
Site	pH_{H20}	Total C [a] (%)	Total N [a] (ppm)	Available P [b] (ppm)	Clay (%)	Silt (%)	Sand (%)
SAPH	4.3 (0.2)	0.85 (0.22)	707 (155)	7.2 (1.6)	10 (1)	2 (1)	87 (5)
SOGB	4.7 (0.2)	1.28 (0.32)	974 (184)	5.2 (2.0)	23 (4)	10 (2)	67 (6)

[a] By elemental analyser (FlashSmart™, ThermoFisher).

[b] 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_3^- (mg kg^{-1})	NO3	Optimum
	Concentration of NH_4^+ (mg kg^{-1})	NH4	Optimum
	Adsorption rate of nitrate on ion exchange membranes (µg cm^{-2} day^{-1})	AMNO3	Optimum
Carbon transformation	Labile organic carbon, Permanganate oxidizable carbon method (mg kg^{-1})	POXC	More is better
	Soil basal respiration, SituResp® method (absorbance difference)	SituResp	More is better
	Decomposition of organic matter, bait-lamina method (% of degradation day^{-1})	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^{-1})	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.