# Rubber, rubber and rubber: How 75 years of successive rubber plantation rotations affect topsoil quality?

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**Highlights**

- First study of long-term impacts of rubber plantations on topsoil quality
- Three successive rubber rotations negatively affected topsoil quality
- We observed significant degradation after the second rotation
- SOC thermal stability was more affected by successive rotations than SOC content
- Tree logging and land preparation are the main drivers of declining topsoil quality

**Abstract:**

Rubber tree plantations (*Hevea brasiliensis*) cover large areas in the tropics. In historical producing regions like South Thailand, rubber has been planted by smallholders for three successive rotations lasting a total of 75 years. Despite possible consequences on topsoil, the long-term impacts of repeated rubber plantations on soil quality remain unknown. This study aims to better understand how various factors linked to long-term rubber land use and land use change affect topsoil physico-chemical properties and soil organic carbon (SOC) thermal stability. We focus on the effects of three factors: i. deforestation (change from forest to first rubber plantation); ii. the age of the rubber stand (immature vs mature); and iii. long-term rubber cultivation (first, second or third successive rotation) over a chronosequence in farmers plots. Our results show that soil was deeply degraded after deforestation to a rubber plantation. Long-term rubber cultivation is also detrimental for the soil and has a more negative impact on soil physico-chemical properties and carbon dynamics, than the age of the rubber stand (e.g. on average, decrease of 50% of SOC content between forest and third rotation). At the third rotation, after 50 years of rubber cultivation, the quality of the 0-10 cm soil layer was very low, with an increase in SOC thermal stability. At this stage, logging practices upset the sustainability of the system. These impacts could be limited by less destructive practices during planting.

**Key words:** Rubber plantations; Successive rotation; Long term; Soil quality.

## 1. Introduction

Natural rubber (*Hevea Brasiliensis*) plays an important role in the world economy as it supplies about half the world demand for elastomer driven by industry (FAOSTAT, 2018). Southeast Asia (including parts of Southwest China) is the epicentre of rubber cultivation (Warren-Thomas et al., 2015) and accounts for nearly 80% of world production (FAOSTAT, 2018). This development originally occurred at the expense of natural forest and rubber is still considered as one of the main drivers of deforestation in Southeast Asia (Fox and Castella, 2013; Warren-Thomas et al., 2015). Thailand has the second largest area under rubber in the world, with more than 3.3 million ha of rubber plantations, and is the top rubber producing country (FAOSTAT, 2018), because the Thai rubber sector has been very efficiently organized with government incentives (Delarue and Chambon, 2012). In Southern Thailand, the country's historical rubber producing area, the first plantations were established in the first half of the 20$^{th}$ century (Chambon et al., 2016). This area is characterized by optimal soil and climatic conditions for successive rubber plantations. This encouraged smallholders to cultivate up to three successive rotations of rubber monoculture on the same plots.

In terms of land use, this considerably relieves the pressure on natural forest and a recent survey by Chambon et al. (2016) showed that less than 10% of the rubber expansion during the last 30 years in Thailand has taken place on forest land. However, repeated plantation of the same species on the same land may have detrimental effects on soil and calls the sustainability of the system into question. The long-term effect of tree plantations on productivity was first documented in the late 1950s. For example, Thomas (1957) observed a declining tree growth after the second successive rotation of *Pinus Radiata*. This declining trend after the second rotation was confirmed across several sites in Australia (Woods, 1990) and for other tree species such as Eucalyptus and Acacia (Hardiyanto and Sadanandan Nambiar, 2014; Huong et al., 2020). The decline in tree productivity was mainly linked to a decrease in soil quality. Indeed short rotations lead to a rapid degradation of soil organic matter, nutrient content, and soil biodiversity (Selvaraj et al., 2017; Zhu et al., 2019). The intensity of the depletion varies markedly depending on logging and replanting practices that may accelerate the loss of organic matter and nutrient reserves (Hardiyanto and Sadanandan Nambiar, 2014). Logging using heavy machinery including windrowing and subsoiling cause severe and substantial damage to soil physical properties, leading to soil compaction and reducing hydraulic conductivity, particularly during wet conditions (Ampoorter et al., 2010; Hartmann et al., 2014). Compaction can have detrimental effects in the long term, even 20 years after logging in *Pinus Radiata* plantations (Murphy et al. 2004). However, most such studies concerned tree plantations systems with short rotations (< 10 years) such as for Acacia and Eucalyptus (Chen et al., 2013; Hardiyanto and Sadanandan Nambiar, 2014; Huong et al., 2015; Xu et al., 2020; Zhu et al., 2019). Longer-term studies are scarce, particularly those that deal with trees with a longer lifespan such as rubber or oil palm. To our knowledge, this study is the first to explore the effect of successive rotations of rubber stands. In Thailand, the lifespan of a rubber plantation is around 25 years. This long period could be more favorable than shorter-rotation species for topsoil restoration following the initial disturbance caused by logging. Indeed, soil quality and soil biodiversity at 0-10 cm depth improves with age over one cycle of rubber plantation (Peerawat et al., 2018; Thoumazeau et al., 2019a; Tondoh et al., 2019; Zhou et al., 2017) especially due to the absence of physical perturbation, high litter input and improved soil moisture (N'Dri et al., 2018). Therefore, plantations were sometimes considered close to a restored forest ecosystem (Bremer and Farley, 2010). However, this restoration process has only been assessed for one first rubber tree cycle, leaving the effect of successive rubber rotations on soil quality an open question.

The concept of soil quality and the way to assess it is still the subject of debate in the scientific community (Bünemann et al., 2018) despite a certain consensus linked to the the definitions of soil quality given by Karlen et al. (1997). To assess soil quality in the present study, we focused on the following parameters (i) soil physico-chemical parameters, as they are particularly disturbed by tree logging (ii) soil organic carbon (SOC) content and thermal stability because they reflect the chemical, biological and physical status of the soils (Karlen and al., 1997), which could be affected by successive tree rotations. Topsoil (0-10cm) seems especially adapted to tackle land management effects, as it illustrate the interface between above ground inputs and deeper soil layer characteristics (Matteodo et al., 2018). Topsoil also harbor the main part of soil biota that drive soil processes and is at the spotlight of soil quality assessments (Bünemann et al., 2018).

The specific aim of the present study was to assess the impact of successive rubber rotations on topsoil quality. To evaluate the long-term impact and include the temporal dimension, we selected a 75-year chronosequence of rubber plantations including three full rotations, each with an average lifespan of about 25 years. We disentangled problems concerning land use and changes in land use in rubber plantations by highlighting the relative importance of forest-to-rubber conversion, rubber stand age and the long-term impacts of cultivation on soil quality. Our main hypothesis was that, following an initial disturbance caused by logging, topsoil quality would recover during each rubber cycle, and the extent of the recovery would determine the resilience of the system.

## 2. Materials and Methods

### 2.1. Site description and experimental design

The study site is located in Ban Nasan district, Surat Thani province, Thailand (8°54'-8°56'N; 99°24'-99°28'E). The site is characterized by a tropical monsoon climate with cumulative annual precipitation of 1,497 mm and an average temperature of 27 °C in 2015 (Thai Meteorological Department, 2015). The soils are Inceptisols (Thung Wa serie, Vijarnsorn and Fehrenbacher, 1973) with a sandy loam texture comprising around 11% clay, 12% silt and 77% sand in the 0-10 cm soil layer.

This area is the historical region for rubber plantations in Thailand, where rubber has been cultivated for more than 80 years (Chambon et al., 2016). This can be explained by favourable soil-climatic conditions and low pest pressure on rubber tree in the area. The experiment was implemented in smallholders' plots in a succession of three rubber plantation rotations (R1 for first rotation, R2 for second rotation, R3 for third rotation) using a space-for-time approach. One rubber rotation usually lasts around 25 years meaning that a total chronosequence of 75 years was studied. For each rotation, we investigated two different rubber stand ages with young (immature) rubber plantations 3-6 years old (y) and older (mature) rubber plantations 18-22 years old (o). A neighbouring natural forest (F) was studied as the baseline. All the rubber plots were originally cultivated after conversion from the undisturbed forest. The plot design was the same (6-7 m x 2-3 m) with around 550 trees/ha, and the same rubber clone was used throughout (RRIM 600). All the rubber plots were cultivated using standard practices. At immature stage, there were no intercrops and soil surface was covered with spontaneous vegetation controlled both chemically and mechanically. There was no tillage in the inter-rows. Understory vegetation was controlled and almost no weed was observed in mature plantations (see pictures in **Supplementary material 1**).

### 2.2. Soil sampling

Soil sampling was performed in September 2015, except for two measurements linked to nutrient cycling ($N_{av}$ and AEMNO3, see part 2.3) that were performed in the same plots (but not in R1y) in 2017. Soils were collected half way between the rows and inter-rows. For each type of land management, three plots representing three replications were studied. The study plots were located maximum 10 km apart and plot slope was generally low (**Supplementary material 2**). We focused on farmers plots and the design could not be perfectly randomized. We identified soil texture as a relevant proxy to highlight possible cofounded effect of soil inherent parameters with the land management tested. Soil texture was especially relevant for this study tackling changes of topsoil quality (0-10cm). Prior to analysis, the effects of soil inherent parameters (i.e. soil texture at 0-10cm) on the soil physico-chemical properties was checked using RDA methodology (**Supplementary material 3**, R vegan package; Oksanen et al., 2019). The results showed that soil texture did not significantly affect the soil properties studied, whereas land management did. This preliminary test proved that, despite a possible effect of soil texture due to possible differences within the study area, soil texture was not the driver of the observed differences in soil properties. Three internal replicates were sampled in each plot to account for spatial heterogeneity of the plot. We collected a total of 63 soil samples (7 treatments x 3 blocks x 3 internal-replicates).

### 2.3. Soil physico-chemical analysis

Fresh soil samples were taken in the 0-10 cm layer using a 7cm diameter cylinders, then weighed and dried at 105 °C for 24 h to measure soil moisture and bulk density (BD). For other soil analyses, soils were sampled with an auger in the 0-10 cm soil layer and most of the analyses were performed following Peerawat et al. (2018) at the soil laboratory of the Office of Science for Land Development at Land Development Department, Bangkok. Briefly, soil samples were air-dried and then sieved at 2 mm. Soil texture was determined by the Bouyoucos Hydrometer method adapted from Gee and Bauder (1986). The pH was determined in distilled water (1:1 soil-water ratio). Available phosphorus was determined using the Bray II method (Bray and Kurtz, 1945). K, Ca and Mg in soil solution were extracted with neutral 1 N ammonium acetate (Chapman, 1965) and analysed with a flame photometer (Sherwood model 420) for K and Ca and a Shimadzu AA 6200 atomic absorption spectrophotometer for Mg. Analysis of soil available nitrogen ($N_{av}$) and nitrate adsorbed on ion exchange membrane (AEMNO3) were analysed as described in Thoumazeau et al. (2019). Briefly, $N_{av}$ consisted in extracting soil available nitrogen with a 1 M KCl solution and analysing $NO_3^-$ and $NH_4^+$. AEMNO3 consisted in using an anion exchange membrane (Qian and Schoenau, 2002) to analyse $NO_3^-$ adsorbed on the membrane. The membranes were incubated for 19 days. For nutrient quantitative analysis in the Eco&Sols laboratory (Montpellier, France), we used a continuous flow analyser (SAN++, Skalar, Breda, The Netherlands). For soil organic carbon (SOC) and soil total nitrogen (Ntot), 2-mm sub-samples of sieved bulk soils were ground (<150 mm) and analysed either using the Rock-Eval® method for SOC (**see part 2.4**) or the dry combustion method using an elemental CHN analyser for Ntot (Thermo Flash 2000, analysed at Eco&Sols laboratory in Montpelllier, France).

### 2.4. Rock-Eval® analyses

We analyzed the set of soil samples by Rock-Eval® thermal analysis. The 63 soil samples were analyzed in the University of Lausanne with Rock-Eval 6 device (Vinci Technologies). The method uses a ramped pyrolysis of organic matter under artificial air supply ($N_2$) between 200 and 650°C , then a combustion of residual carbon in oxidative conditions between 300 and 850°C. The released gases are quantified using a flame ionisation detector (FID) for hydrocarbon compounds (HC) and infrared detectors (IR) for CO and $CO_2$. Qualitative and quantitative parameters are calculated by integrating the amounts of hydrocarbons, CO, and $CO_2$ produced during thermal cracking of organic matter, between defined temperature limits (Behar et al., 2001; Feller et al., 2010; Lafargue et al., 1998a). This technique has been recommended for the characterisation of soil organic matter (Derenne and Quénéa, 2015; Disnar et al., 2003) and recently proved to be relevant in a similar context (Thoumazeau et al., 2020). Thermograms are presented in **Supplementary material 4**. Soil organic carbon (SOC) content was calculated by including the amounts of C moities produced during thermal cracking and combustion of OC between defined temperature limits (Behar et al., 2001; Lafargue et al., 1998b). Soil organic carbon quality was assessed with the R-index calculated as the relative HC contribution of the most thermally resistant organic fraction (i.e. thermal cracking above 400°C; see Disnar et al., 2003; Sebag et al., 2016, 2006). The higher the R-index, the more organic fractions are thermally resistant. Recent application of the R-index proved its interest in agricultural management systems in tropical areas (Malou et al., 2020).

### 2.5. Calculations and statistical analysis

All statistical analysis were performed with R software version 3.6.1 (R Development Core Team, 2008). First, univariate analysis was run on each of the soil physico-chemical parameters using a linear-mixed effects model (lme4 package, Bates et al., 2019). Treatment was defined as fixed factor and plots/inner-replicates as random factors to take into account the nested design of the experiment. After checking the normality of the model residuals (Shapiro test) and the homoscedasticity of residuals of variance (Levene test), ANOVAs were run using the car package (Fox and Weisberg, 2011). Variables were sometimes log or square root transformed to validate our initial assumptions. In some cases, our assumptions regarding the response of the mixed model on normality and heteroscedasticity were not confirmed (i.e. for Mg, Ca, pH). In these cases, a standard linear model was run on plot average. All the tests were followed by post hoc mean comparisons using a Tukey's test with Bonferroni correction (Hothorn et al., 2008). Second, multivariate analysis was computed with a principal component analysis (PCA) including all physico-chemical variables (FactomineR package, Husson et al., 2019) based on the mean of the replicates for three plots (**Supplementary material 5**). We used the missMDA package to estimate the data that were not available for $N_{av}$ and

AEMNO3 in R1y. Third, we calculated a soil quality index (SQI), using the methodology defined by Obriot et al. (2016). We selected appropriate and non-redundant variables (Obriot et al., 2016) that led to the removal of (i) pH (not sensitive to land management) and (ii) $N_{av}$ and Ca that were strongly correlated with SOC and Ntot respectively (redundancy; R > 0.8). All variables results were normalized between 0 and 1 following a "the more the better" scoring functions, except bulk density for which a higher value was given to the lower values ("the less the better"). The SQI was calculated according to equations (1) and (2), with a weighting of the transformed variables using the PCA eigenvectors and the percentages of total variability explained by each principal component:

$$\text{Wi} = \sum_{j=1}^{p} \lambda j \times fj \qquad \text{Eq. (1)}$$

$$\text{SQI} = \sum_{i=1}^{n} \text{Si} \times \text{Wi} \qquad \text{Eq. (2)}$$

Fij=relative percentage of total variability attributed to each PC; λj= sum of squared coordinates on each eigenvector; Si= Normalized indicator scores; Wi= weighted factors"

To assess the transition dynamics, we calculated two indexes of logging and the long-term effects from the data of SQI. For the three rubber rotations, the "logging effect" was calculated as the difference in soil quality between the land use before logging and that of new rubber plantation. The "long term effect" was calculated as the difference between the quality of the soil in the natural forest and the quality of the soil under the mature rubber tree plantation in the three rubber rotations. All combinations of differences between the two stages were included (n=9). After checking the normality of the model residuals and homoscedasticity of variance, ANOVAs and Tukey's post-hoc tests were computed on the data sets. Rock-Eval results were analysed with ANOVA or with a t-test to compare rubber plantations rotations with the reference forest.

# 3. Results

## 3.1. Impacts on individual soil parameters

Most of the soil parameter were sensitive to land management, except for pH (**Table 1**). A strong effect of deforestation was observed for SOC content, with a significant difference only between land uses (Forest vs Rubber). Thereafter, a continuous decrease was observed from forest to the third rotation for most of soil parameters. The decrease was particularly apparent for soil total nitrogen (Ntot) with a 3-fold lower concentration in the old plantations during the third rotation (R3o) than in Forest. Other nutrients (K, Ca, Mg) were also significantly depleted in the last rotation with 10-fold lower concentrations compared to the reference forest. The trend was inverted for BD, where higher values are observed in the third rubber rotation. When we compared young and old plantations, soil parameters were generally not sensitive to the age of the plantation. Only soil $P_{av}$ content was significantly higher in young plantations in R1 and R2 rotations. A trend towards an increase in SOC, $N_{av}$ and AEMNO3 was also observed in old plantations compared to in young ones.

## 3.2. Impacts on soil quality

### 3.2.1. Modifications along the chronosequence

All soil parameters were combined in the PCA multivariate analysis shown in **Figure 1**. The two first axes of the PCA explained 76% of the total variability of the data set. The two dimensions were contrasted in terms of percentage of inertia, with Dim 1 explaining 56% and Dim 2 explaining only 20% (**Figure 1a**). The first dimension highlighted both (i) the effect of forest deforestation (F to R1y-R1o) and (ii) the effect of long-term rubber rotations following a continuum of rotation 1 and 2 (R1y-R1o-R2y-R2o) distinguishable from rotation 3 (R3y-R3o). Most of the variables were positively correlated with the first dimension of the PCA (i.e., Ca, K, Mg, Ntot, $N_{av}$, TOC) highlighting the change in land use and the effect of rotation (**Figure 1b**). The second dimension mostly represented the effect of plantation age, with old (mature) rubber plantations (R1o, R2o, R3o) that were distinct from young (immature) plantations (R1y, R2y, R3y). $P_{av}$ and AEMNO3 parameters mostly explained the second dimension with a low relative contribution to the overall PCA (**Figure 1b**).

### 3.2.2. Assessment of the transition using indexes

A significant decrease in soil quality linked to the shift from natural forest to rubber plantations is showed in **Figure 2a**. A second decrease can be observed between the two first rubber rotations and the third one, and the soil quality under the third rotation was much lower. These results are summarised in **Figure 2b,** in which high “logging effects” were calculated for the first and third rotation whereas a relatively limited effect of logging was observed between the first and second rubber rotations (**Figure 2b**). The long-term effect of rubber tree plantations on soil quality was highlighted in the third rotation (**Figure 2c**). No age effect of the plantation was observed on soil quality in the three rotations, and young immature plantations had a similar score to that of old mature plantations.

### 3.3. Impacts on soil carbon dynamics

As the effect of stand age was negligible compared to the effects of the other factors, **Figure 3** focuses on deforestation and long-term effects by combining rubber stand ages. In our context with relatively low organic carbon contents, the impact of the conversion from a natural forest to rubber plantations on SOC was clear (**Figure 3a**). A decrease of about half the initial SOC content in the forest was observed in the first rubber plantation rotation. The long-term effect of rotation on SOC was not significant, despite a trend toward a decrease between the first rotation (R1) and the third rotation (R3) ($p < 0.1$). The R-index did not differ significantly between F and R1-R2 **(Figure 3b),** implying that the marked decrease in SOC content between forest and rubber plantations was not related to a decrease in the quality of SOC. However, the R-index identified a significant change in the quality of SOC in the 0-10 cm soil layer over successive rubber rotations. A significant increase in the thermally resistant fraction of SOC was observed with successive rotations (R1<R2<R3, **Figure 3b**).

## 4. Discussion

### 4.1. Strengths and limits of the experiment

This study aimed to tackle a key challenge for perennial cropping system that is the effect of long-term successive cultivation on soil quality. Very few studies exist in the literature focusing on this long-term change. Our results could be fruitful for land planning decisions in historical production area of 25-30 years stand perennial cropping systems (e.g. rubber and oil palm). The experiment made it possible to consider local agricultural systems of repeated rubber cultivation for 75 years. To this end, we followed a space-for-time approach based on plot selection from surveys over farmer's plots. Those preliminary surveys aimed at i. understanding land management practices linked to rubber rotations, together with ii. limiting spatial variation between the plots. One of the key challenge for space-for-time experiments among farmer plots is the difficulty to have fully spatially randomized design. Thus, there is a need to verify and limit the effect of possible cofounded inherent factors that are independent to the land management targeted in space-for-time experiments. Our question focused on topsoil assessment and we chose the proxy of soil texture to characterize the soil inherent properties that may have influenced the results. In this specific case, our statistical analysis based on variance partition (**Supplementary material 3**) showed that topsoil assessment were only driven by changes of land management, and not by soil texture. This statistical analysis made it possible to discard an eventual cofounded effects of soil inherent properties on the topsoil property change observed. However, to have a full understanding of the soil functioning and linkages with tree productivity, it would have been interesting to implement analyses and observations at deeper layer (e.g. soil depth, soil type, bedrock type…).

### 4.2. Deforestation degrades different soil physico-chemical parameters simultaneously

In the soil-climatic context of this study, changing land use from a forest to rubber plantations had a negative effect on most of the soil quality variables measured (**Table 1**). This confirms the results of other studies focused on depletion of SOC (Guillaume et al., 2015; Straaten et al., 2015), Ntot (Allen et al., 2015) and an increase in soil BD (Li et al., 2012) after deforestation. When analysed independently, other soil quality variables ($N_{av}$, K, $P_{av}$, Ca) were affected to a lower extend by forest conversion into rubber plantations. The results reinforce the site specificities of the effects of changes in land use associated to the fact that remaining natural forests in a land use change dynamic are often located on soils with low quality (Veldkamp et al., 2020). In our case, fertilisation in rubber plantations may also have counterbalanced soil nutrient depletion linked to deforestation (Chambon et al., 2018; Vrignon-Brenas et al., 2019). Interestingly, despite the clear drop in SOC content associated with deforestation, refractory carbon pools were not affected by this transition (**Figure 3**). In the 0-10 cm soil layer, the change in land use mostly affected labile carbon pools. This may be explained by a flush of labile organic matter mineralisation after deforestation (Fujisaki et al., 2017). Aggregating all variables through multivariate analysis identified a clear and significant gap between soil quality in natural forest and rubber plantations (**Figure 2**). This result is consistent with our previous results on soil quality in rubber tree plantations located in another soil-climatic context (Thoumazeau et al., 2019a). The present study confirmed that rubber tree plantations do not have the same soil characteristics as natural forests, even at the mature stage (R1o). Preserving forest soil physico-chemical properties and the intensity of related ecosystem services (carbon sequestration, nutrient cycling) seems to be a key challenge that is not met with monospecific plantations.

### 4.3. Restoration during each rotation does not compensate for long-term negative effects

The expected recovery of soil quality during each rotation was not observed and was counterbalanced by deteriorating soil quality over time. This could firstly be explain by the relative variance explanation by each of the factor tested, with deforestation and rotation effects overtaking the effects of stand age. We observed that long-term successive rubber cultivation has a detrimental effect on soil quality and there was a significant drop in quality after the second consecutive rubber rotation (**Figure 2**). This decline after consecutive rotations has also been reported in other tropical perennial cropping systems with a shorter stand period (Selvaraj et al., 2017). The degradation in soil quality was associated with a general decrease in SOC content over successive plantations, as also reported in other systems (Zhang et al., 2009, 2004). Interestingly, we found an increase in soil carbon thermally resistant pools over successive rotations (**Figure 3**). This result is in line with that of Zhang et al. (2009) who also reported a decline in SOC quality in successive rotations of Chinese fir. In our study, this decline may be linked to disturbance of the topsoil layer (with a higher labile carbon content) caused by the heavy machinery used during clear cutting and land preparation. These disturbances increased the thermally resistant fraction of SOC originating from the subsoil (Zhang et al., 2009), as illustrated with Sebag et al., (2016) soil references. Thus, successive rotations of plantation rubber result in homogenisation of SOC quality between the topsoil and the subsoil. Such soil degradation over time may have considerable impacts on soil nutrient dynamics and tree productivity. O'Hehir and Nambiar (2010) also reported this "second rotation decline" in tree biomass after two successive rotations. In addition to tree productivity, other soil ecosystem services are certainly affected including soil biodiversity (Xu et al., 2020; Zhu et al., 2019). In our case study, the age of the rubber tree stand did only significantly affected few soil physico-chemical properties. It was especially interesting to highlight the $P_{av}$ decrease over plantations age, that was also observed by Liu et al. (2018); Wang et al. (2017), and could be explained by fertilization practices, tree uptake needs evolution and micro-climatic plantation changes. We did no detect an effect of rubber tree age with multivariate analysis, which advocate the fact that deforestation and rotation effects overtaking the effects of stand age. Moreover the soil parameters selected are known to be sensitive to long-term changes rather than to rapid micro-climatic differences that could by caused by the difference in the age of the rubber trees. Integrating functional and dynamic indicators linked to soil biota diversity and activities that are more sensitive to rubber age structural changes (soil water content, temperature, litter input, etc.), may have increased the impacts of rubber stand age (Liu et al., 2019; Peerawat et al., 2018; Thoumazeau et al., 2019a). It is noteworthy to note that our results only focused on the topsoil (0-10cm). This layer was relevant in our case as it is the part of the soil that is the most sensitive to land management changes, especially integrating both soil disturbance (replanting) and carbon input from litter fall that is key for soil restoration processes along rubber stand age (Blagodatsky et al., 2016; Thoumazeau et al., 2019a). To better understand processes and SOC/nutrient stocks, we advocate to enlarge this study with deeper soil layer analyses.

### 4.4. Toward less disruptive replanting practices to limit soil degradation

Here we show that current long-term rubber production is not sustainable as far as soil quality is concerned. Successive rotations degraded soil quality and altered soil carbon dynamics. It is important to state that, in this context of forest conversion into rubber plantations, smallholders usually started to cut the forest in lands that were more fertile and appropriate for rubber production. Then they moved to the forest and less optimal condition for production with time. This trends especially leads to the fact that remaining natural forests are located on heavily weathered soils with low fertility (Veldkamp et al., 2020). In our case, topsoil quality even follow the opposite trends, highlighting and eventual even stronger effect of long term management practices on soil properties. This can mainly be explained by intensive logging activities at the end of life of the rubber trees. In Eucalyptus plantations, Chen et al. (2013) also highlighted the need to limit soil disturbance during replanting. Current rubber replanting practices are very disruptive for soils, with deep soil mechanical disturbance caused by extracting as much as possible of the rubber tree rooting system (see pictures in **Supplementary material 6**), which alters the soil physico-chemical properties. Those disturbance were less detrimental in preceding rotations (for R2 and R3), as previous traditional practices did not involve mechanical uprooting. In addition, in the context of traditional rubber production systems in Thailand, the entire rubber wood from logging activities is exported, mostly for the rubberwood industry (Petsri et al., 2013). Only some of the residues (leaves, branches and roots) representing about 25% of the total biomass (Hytönen et al., 2019) are left in the plot. Wood biomass removal is known to be detrimental to soil quality (Hardiyanto and Sadanandan Nambiar, 2014; Perron et al., 2021a). According to Perron et al. (2021b), exporting biomass may lead to a critical lack of nutrients in rubber plantations. Fertilisation practices may overcome this loss for the second rotation, but may not be sufficient to restore overall soil characteristics. In previous rotations (for R2 and R3), all residues were mostly burnt as the plots were not easily accessible. Those logging practices changes and intensification with time reinforce the concerns on soil quality degradation. Under the current logging practices, soil quality of the next generations would be even more jeopardized (Perron et al., 2021a). Huong et al. (2015) identified an opportunity to increase and sustain production of tree plantations over at least three rotations through better management practices. For example, in Eucalyptus and Prince Ruprecht's larch, Zhang et al. (2015) and Zhao et al. (2019) observed a long-term improvement in soil quality with reduced soil disturbance during logging, keeping understory coverage and litter retention. These general recommendations need to be tested under local agronomic constraints (e.g. pest pressures) and socio-economic bottlenecks (e.g. shortfall in timber sales) that have to be included in any changes made in smallholder plantations. For example, the use of legume cover-crops, which is widespread in industrial rubber plantations, is seldom used by Thai smallholders, mostly due to labour constraints (Hougni et al., 2018; Langenberger et al., 2017). As a result, in mountainous regions, soil erosion during the mature phase of rubber plantations is huge (Neyret et al., 2020).

## Conclusion

This study highlights the long-term impact of rubber plantations on topsoil quality. In addition to the effects of deforestation, we observed a detrimental effect of three successive rotations on soil properties. The soil system was still resilient after one rotation, but failed after the second rotation, which is equivalent to about 50 years of monoclonal plantation. To avoid the detrimental effect of the second rotation and to substantially increase rubber plantation sustainability, we suggest either reviewing replanting practices or changing the land use in landscapes that already undergone three rubber rotations, which is the case in historical rubber producing areas in Thailand.

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**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

No potential conflict of interest are declared. All financial and partnership aspects are presented in the acknowledgments of the manuscript:

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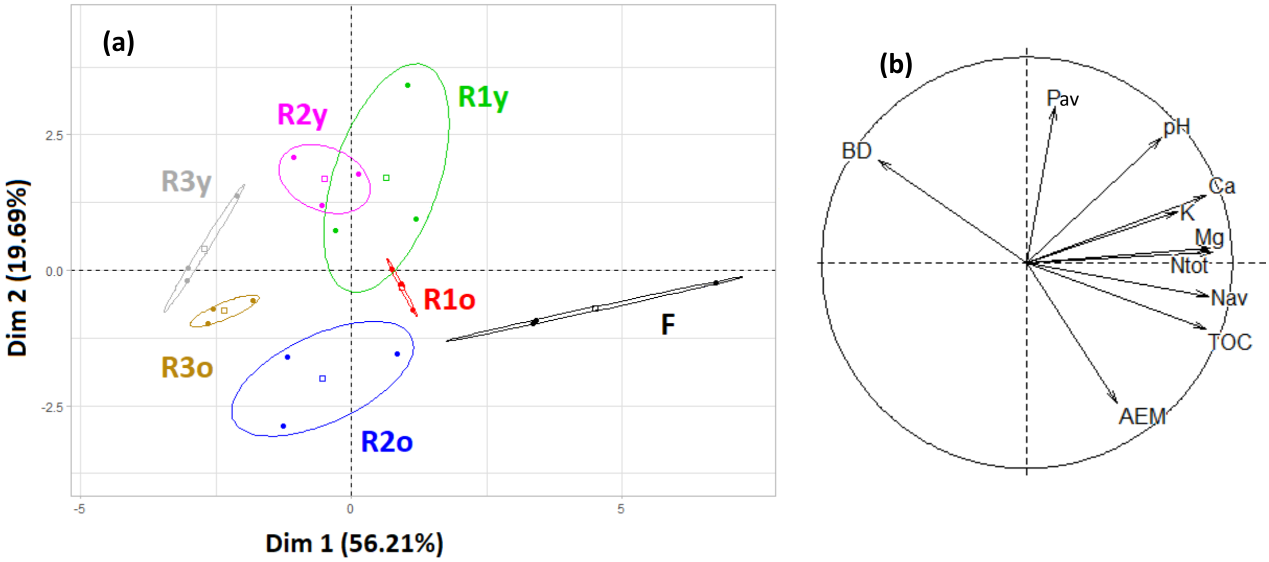


**Figure 1:** Principal component analysis of soil quality parameters. (a) presents individuals with average per plot, n=3 replicates tested. F: Forest, R1y: 1st rotation of 3-6yo rubber, R1o: 1st rotation of 18-22yo rubber, R2y: 2nd rotation of 3-6yo rubber, R2o: 2nd rotation of 18-22yo rubber, R3y: 3rd rotation of 3-6yo rubber, R3o: 3rd rotation of 18-22yo rubber. (b) presents individuals correlations, see table 1 for details. Bartlett's test of sphericity < 0.05. Kaiser-Meyer-Olkin Statistics = 0.65. PCA factor loadings are presented in supplementary material 5.

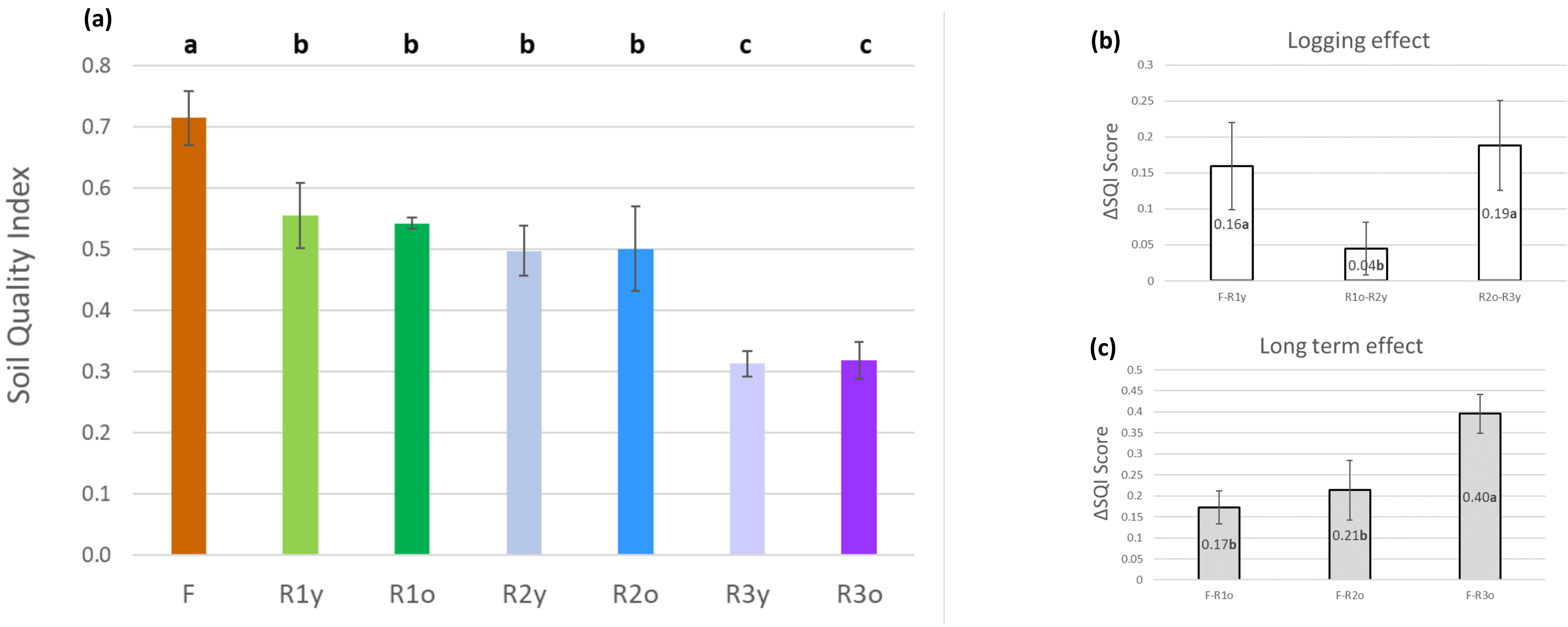


**Figure 2:** (a) results of Soil Quality Index following the procedure described by Obriot et al. (2016). For each type of land management, n=3 replicates tested ± SD. Letters indicate significant differences between types of land management according to Tukey's post-hoc test. F: Forest, R1y: 1st rotation of 3-6yo rubber, R1o: 1st rotation of 18-22yo rubber, R2y: 2nd rotation of 3-6yo rubber, R2o: 2nd rotation of 18-22yo rubber, R3y: 3rd rotation of 3-6yo rubber, R3o: 3rd rotation of 18-22yo rubber. (b) logging effect assessed through score value differences from (a), all combinations were used and n=9 ±SD. (c) long term effect assessed through differences in scores from (a), all combinations were used and n=9 ±SD.

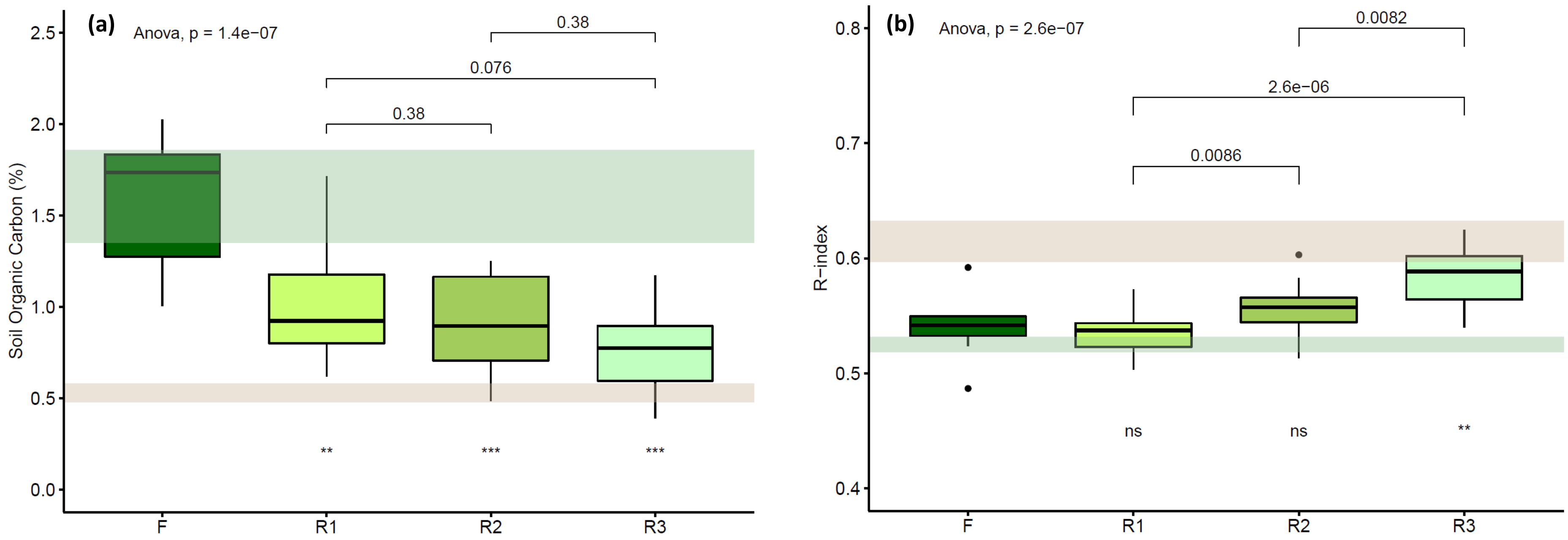


**Figure 3:** SOC and R-index from Rock-Eval® analysis. The higher the R-index, the more organic fractions are thermally resistant is. Boxplots were computed with all the data sets (n=9 for forest and n=18 for rubber plantations). F: Forest, R1: 1st rotation including the two rubber plantation ages, R2: 2nd rotation including the two ages of rubber plantations, R3: 3rd rotation including the two rubber plantation ages. Asterisks below the boxplots indicate differences between the plantations and the forest ("***", $p < 0.001$, "**", $p < 0.01$, "*", $p < 0.05$); p-values above the boxplots indicate differences between rotations. Coloured bands correspond to Rock-Eval references for organic layer (green) and top soil (brown) presented in Sebag et al. (2016).

| Land management | SOC (g.kg$^{-1}$) | Ntot (g.kg-1) | $N_{av}$ (mg.kg$^{-1}$) | AEMNO3 (µg.cm$^{-2}$.d$^{-1}$) | K (mg.kg$^{-1}$) | $P_{av}$ (mg.kg$^{-1}$) | Ca (mg.kg$^{-1}$) | Mg (mg.kg$^{-1}$) | pH | BD (g.cm$^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| F | 14.59 **a** (±3.15) | 1.79 **a** (±0.12) | 26.30 **a** (±5.99) | 5.40 **ab** (±0.29) | 99.56 **a** (±11.02) | 7.36 **ab** (±1.35) | 359.17 **a** (±226.30) | 102.28 **a** (±14.43) | 5.33 **ns** (±0.52) | 1.11 **c** (±0.04) |
| R1y | 8.53 **b** (±1.59) | 1.34 **ab** (±0.19) | NA | NA | 72.00 **a** (±19.39) | 22.43 **a** (±11.88) | 224.72 **ab** (±60.52) | 47.50 **b** (±12.99) | 5.44 **ns** (±0.35) | 1.31 **ac** (±0.03) |
| R1o | 9.71 **b** (±0.61) | 1.28 **ac** (±0.11) | 17.86 **ab** (±3.08) | 4.08 **bc** (±1.52) | 66.50 **a** (±20.27) | 3.96 **b** (±0.78) | 187.95 **abc** (±37.00) | 47.33 **b** (±1.00) | 5.44 **ns** (±0.02) | 1.24 **ab** (±0.05) |
| R2y | 7.36 **b** (±2.09) | 0.90 **bcd** (±0.31) | 8.84 **bc** (±1.82) | 2.39 **cd** (±1.49) | 85.22 **a** (±45.65) | 21.26 **a** (±7.73) | 179.39 **abc** (±26.55) | 36.06 **bc** (±4.70) | 5.26 **ns** (±0.46) | 1.33 **bc** (±0.05) |
| R2o | 9.06 **b** (±0.80) | 0.89 **ce** (±0.24) | 13.09 **bc** (±7.53) | 7.57 **a** (±0.72) | 49.89 **ab** (±46.59) | 5.32 **b** (±4.46) | 59.83 **cd** (±17.84) | 21.61 **bc** (±2.50) | 4.88 **ns** (±0.18) | 1.19 **ab** (±0.13) |
| R3y | 6.75 **b** (±0.30) | 0.53 **e** (±0.09) | 4.58 **bc** (±1.01) | 0.90 **d** (±0.43) | 18.22 **b** (±4.27) | 3.98 **b** (±2.51) | 80.22 **bcd** (±57.91) | 27.50 **bc** (±25.69) | 5.04 **ns** (±0.29) | 1.39 **ab** (±0.11) |
| R3o | 8.08 **b** (±0.63) | 0.78 **de** (±0.06) | 10.23 **c** (±3.04) | 2.29 **cd** (±0.75) | 15.61 **b** (±4.43) | 3.81 **b** (±3.81) | 33.11 **d** (±16.36) | 12.11 **c** (±2.99) | 4.76 **ns** (±0.12) | 1.34 **a** (±0.02) |

**Table 1:** Univariate analysis of the impact of land management on soil physico-chemical properties. n=3 (average of plots) + SD. Different letters indicate significant differences between land management after ANOVA analysis of the nested design. F : Forest, R1y : 1st rotation of 3-6yo rubber, R1o: 1st rotation of 18-22yo rubber, R2y: 2nd rotation of 3-6yo rubber, R2o: 2nd rotation of 18-22yo rubber, R3y: 3rd rotation of 3-6yo rubber, R3o = 3rd rotation of 18-22yo rubber.