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**Conversion of tropical secondary forest into agricultural land: consequences for soil health and environmental stability**

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**Abstract**

The objective of the study was to address the impacts of tropical forest conversion into agricultural land on changes in invertebrates' communities, as well as soil chemical properties across 2-4 texturally distinct soils in La Mé and Grand Lahou, Côte d'Ivoire. The fieldwork was carried out in the humid period on two study sites: 1- rubber landscape (secondary forest, 7-, 12- and 25-year-old rubber plantations) and 2- oil palm landscape (secondary forest, 13-, 20- and 39-year-old oil palm plantations). Three sampling stands were established on each land-use type and age class, for a total of 24 sampling stands. Over a 40-50 m transect, topsoil (0-10 cm) invertebrates were sampled by using monoliths (50 cm × 50 cm × 10 cm), following the modified 'Tropical soil biology and fertility' method. Soils chemical properties were also determined. The results highlighted a decrease in taxonomic richness (-35 % and -42 %), Shannon index (-32 % and -37 %), Margalef index (-34 % and -41 %), soil carbon stock (-41 % and -15 %), nitrogen stock (-38 % and -11 %) and carbon sequestration (-41 % and -15 %), respectively, after the transformation of secondary forests into rubber and oil palm plantations. The clay soils and clay sandy soils favored the development and emergence of the soil invertebrates, and allowed a higher carbon and nitrogen storage, as well as a greater carbon sequestration. Whatever the site, the soil quality was more degraded under the monoculture tree plantations compared to the secondary forests. Our findings suggest leaving residues of the previous crop on the soil surface and the incorporation of woody trees with an understory of smaller trees during the early establishment periods of monoculture tree plantations, which can create a sustainable agroforestry system with improved nutrient recycling and soil fertility.

**Keywords:** Soil Chemical Properties, Soil Fauna, Forests Conversion, Agrosystems, Soil Quality

**Academic Discipline and Sub-Disciplines:** Ecology-Agroforestry-Soil health

**Type (Method/Approach):** Land use change and soil quality assessment

## 1. Introduction

Invertebrates play a key role in the ecological functioning of soils (Moulin *et al.,* 2007; Kerfahi *et al.,* 2014). Indeed, composed of different shapes and sizes with various trophic guilds (Frouz, 2018; Omondi *et al.,* 2020), these organisms influence organic matter inputs in the soil (Bray *et al.,* 2019). They improve the soil structure by promoting water infiltration and storage, stimulating plant growth and maintaining biodiversity (Moulin *et al.,* 2007; Ruiz, 2012). Earthworms, termites, ants, isopods and diplopods provide many ecosystem services such as fragmentation, decomposition and organic matter mineralization, nutrients recycling and maintaining of favorable soil physical properties to plants (Ouédraogo, 2004; Yang and Chen, 2009). Thus, macroinvertebrates are defined as excellent bioindicators of soil health (Ruiz, 2012). Despite their diversity and specific ecosystem services provided by each species, some invertebrates such as araneae are predators and play a major role in regulating insect populations (Meijaard *et al.,* 2018). Subsequently, soils may be considered as biological entities with complex biochemical reactions (Swarnalatha, 2010). Plant life including trees is essential for maintaining the integrity of the soil. If plants are removed (deforestation), then the soil is more at risk for erosion (Swarnalatha, 2010).

The large scale transformation of rainforests into monoculture plantation systems, such as oil palm and rubber, is one of the main drivers for biodiversity loss in tropical region (Swarnalatha, 2010; Beckendorff, 2016; Drescher *et al.,* 2016). This transition leads to various environmental changes which influence the soil fauna biodiversity

(Beckendorff, 2016). The decline in plant diversity and thereby the loss of litter and root resources negatively impacts the soil carbon and nitrogen stocks (DeBlécourt *et al.,* 2013; Demessie *et al.,* 2013; Chiti *et al.,* 2014; Allen *et al.,* 2015). This degradation lowers the resilience of forest ecosystems and makes it more difficult for them to cope with changing environmental conditions, as monoculture tree plantations have a twofold impact globally: loss of biodiversity and net emitters of carbon (Swarnalatha, 2010).

In Côte d'Ivoire, the plant cover has declined significantly since independence, thus positioning it in second place among the African countries most affected by deforestation after Madagascar (Bakayoko *et al.,* 2011). The main perennial crops that cause deforestation in the country remain cocoa, coffee, rubber and oil palm (Tondoh *et al.,* 2015; Yéo *et al.,* 2020; Adiko, 2021). In recent decades, these crops have boomed in the humid tropics due to growing demand from the population. The financial returns provided by these crops are considerable and decisive for the economies of producing countries (Despréaux and Nicolas, 2001). The rubber production system occupied 165 000 farmers and an area of 600 000 hectares (Commodafrica, 2018) with an annual production estimated at 990 000 tones in 2019 (Ndiaye and Fainke, 2020), which makes Côte d'Ivoire the leading African producing country and the sixth world producer of natural rubber (Adiko, 2021). Planted on an area of 250 000 hectares in Côte d'Ivoire, the average annual production of crude palm oil is estimated at 550 000 tones (Fages, 2019). With a 3.13% contribution to the gross domestic product, oil palm has become a major component in the country's economy (Palmafrique, 2017).

Beyond their major roles in the economy of Côte d'Ivoire, the conversion of forests into monoculture plantations affects the viability, persistence and resilience of ecosystems (Swarnalatha, 2010) given the soil quality degradation (DeBlécourt *et al.,* 2013; Demessie *et al.,* 2013; Chiti *et al.,* 2014; Allen *et al.,* 2015; Conti, 2015; Vrignon-Brenas *et al.,* 2019; Hemati *et al.,* 2020). However, studies investigating the response of soil biota to forests transformation into plantations and considering a wide range of taxonomic and functional groups are scare. Some scientific works did not provide complete systematic information on soil properties, such as texture and nutrients status (Vrignon-Brenas *et al.,* 2019). Information on the effect that the replacement of natural forests with tree plantations has on carbon and nitrogen stocks after deforestation is still lacking, particularly in the humid tropical zone. Nonetheless, it may be possible to find a sustainable balance between the needs of humans and nature by using the Integrated Nutrient Management (INM) approach (Vrignon-Brenas *et al.,* 2019), where three main soil cover management systems can be considered: (1) management of spontaneous vegetation, (2) use of cover crops like legumes or grasses, and (3) cultivation of annual or perennial crops, as intercropping.

The objective of study was to address the impacts of tropical forest conversion into agricultural land on changes in invertebrates' communities, as well as soil chemical properties across 2–4 texturally distinct soils in La Mé and Grand Lahou, Côte d'Ivoire. We hypothesized that (i) soil invertebrates abundance, taxonomic richness and diversity will be higher in the reference land uses (secondary forests of Grand Lahou; secondary forests of La Mé) compared to agricultural lands (rubber plantations; oil palm plantations), (ii) soil carbon and nitrogen stocks, and carbon sequestration will be higher in the reference land uses compared to agricultural lands, and (iii) soil chemical and biological properties will be more stabilized in the clay and clay sandy textures compared to sandy clay and sandy soil textures.

## 2. Materials and Methods

### 2.1. Description of the sites

This investigation was carried out in 2013 and 2017 during the humid period in Côte d'Ivoire, and through two study sites. The first site hosting the rubber landscapes is based in the department of Grand Lahou (5°13'N; 5°03'W) situated in southern Côte d'Ivoire about 140 km of Abidjan. The second site, characterized by the oil palm landscape is located in the La Mé Station (5°26'N, 3°50'W) in south-eastern of Côte d'Ivoire, ~30 km from Abidjan (Figure 1). The climate of the two study sites is an equatorial type with four seasons: a long dry season from December to March, a long wet season from April to July, a short dry season from August to September, and a short wet season from October to November (Péné and Assa, 2003; Ettian *et al.*, 2009). During the fieldwork on the site of Grand Lahou (site 1), the monthly rainfall ranged from 0 mm in January to 282 mm in June, with an annual total of 1,085 mm. Monthly mean temperature varied between 25°C in August and 29°C in February and March, with an annual average of 27°C. This site is characterized by a rainforest vegetation type, and various land uses such as secondary forests, rural domains and fallow systems (Ettian *et al.*, 2009). It contains various tree species more than 25 m high with several lianas and herbaceous plants. *Diospyros* spp and *Mapania* spp. are among the dominant plants. On the La Mé site (site 2), the monthly rainfall during the sampling ranged from 18 mm in January to 486 mm in June, with an annual total of 1,915 mm. Likewise, the monthly mean temperature varied between 25°C in August and 29°C in February and March, with an annual average of 27°C. The natural vegetation of this site is ombrophilous type dominated by the woody species *Turraeanthus africanus* and *Heisteria parvifolia* (Traoré and Péné, 2016). These forests have been highly degraded since the past half century, and this due to many agricultural activities carried out there. Indeed, a part of these forests has been transformed into agricultural land dominated by the rubber and oil palm plantations. In the rubber plantations, litter is abundant, whereas undergrowth and herbaceous stratum are absent, even if few species of *Elaeis* *guineensis* (Arecaceae), *Pueraria phaseoloides* (Papilionaceae), *Thaumatococcus daniellii* (Marantaceae), *Uapaca guineensis* (Euphorbiaceae), and *Turraeanthus africanus* (Meliaceae) are observed in some places. Weed species characterize the principal understory vegetation in the oil palm plantations (Traoré and Péné, 2016), and it was twice as tall in young plantations, but leaf litter depth and total epiphyte abundance were double in old plantations. The topsoils of the two study sites are ferrallitic type (Perraud, 1971; Yeboua and Ballo, 2000) with variable textures. Clay, clay sandy, sandy clay and sandy textures characterize the soils of the site of Grand Lahou, whereas clay sandy and sandy textures make up the soils of the site of La Mé.

**2.2. Production system of oil palm and rubber plantations in Côte d'Ivoire**

*Oil palm production* — Site preparation including clear-cutting, burning and terracing takes place between October and February (Konan *et al.*, 2006). Then, a leguminous cover (*Pueraria javanica*) is sown to protect the soil from erosion and direct exposure to sunshine (Yeboua and Ballo, 2000) and to inhibit the growth of invasive plants (Jacquemard, 2011). After 9–10 months of seedling growth, the oil palm planting takes place during the humid period, particularly in April, May and June. All plantations are carried out with identical 9 m × 9 m palm spacing in a triangular formation by offsetting every second row (Yeboua and Ballo, 2000; Konan *et al.*, 2006; Luskin and Potts, 2011), for a density of 143 palms trees per hectare. Simple or compound fertilizers with nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) are applied to soil under the plants during the first 2 years and at the end of the fifth year. Clearing is done twice per year and within a radius of 1.5–2 m around the plants during the first 4 years of planting, and then once a year beyond the fourth year. Pruning is practiced at the end of the third year and it takes place once every 12 months in 4–12-year-old plantations and then once every 6–8 months in plantations older than 12 years. This operation consists in cleaning the palm crown to prepare the first harvest, and suppressing all dry low palm fronds, old male inflorescences and small rotten fruit bunches. All organic residues (palm fronds and understory vegetation) from clear-cutting and pruning are stacked in the inter-row to improve soil fertility for future crop rotation. Harvest can be done one to three times per month, using bags, baskets, wheelbarrows and carts (Konan *et al.*, 2006). Three management zones are observed in oil palm plantations: weeded circle zone; understory

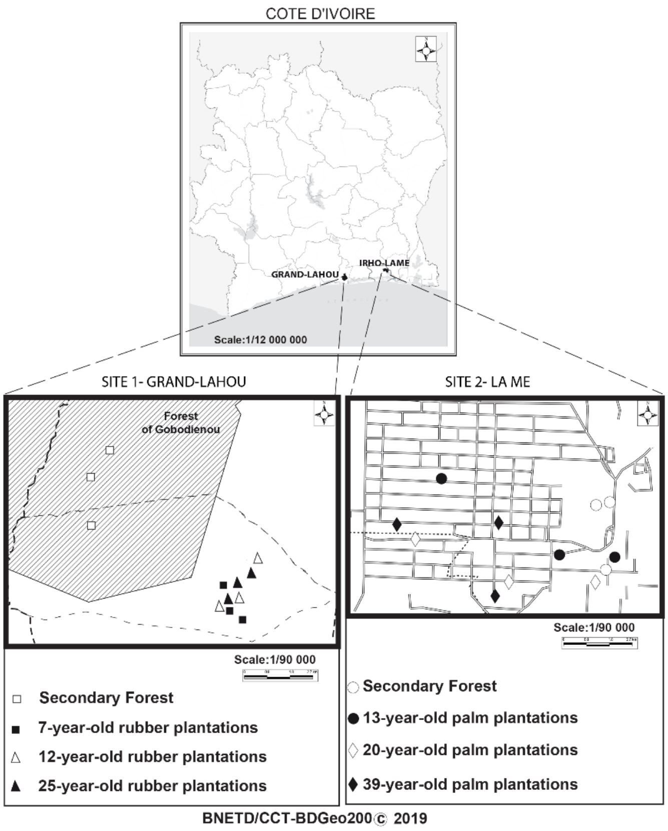


**Figure 1:** Location of the study sites in Côte d'Ivoire and design of the selected plots

vegetation with pruned fronds in inter-row areas; and harvest paths. Fusarium wilt is treated by replacing diseased trees with a more tolerant variety (Diabaté *et al.*, 2014, 2015). Oil palm pests are most commonly treated by application of deltamethrin, cypermethrin and maneb (Konan *et al.*, 2006).

*Rubber production* — Land preparation depends on the type of initial vegetation (forest, fallow, savannah) colonizing the plot (FIRCA, 2012). In the case of a forest, the land is cleared from October to December and consists of cutting the undergrowth and then the shrubs and tall trees. After clearing, plant debris should be burned and gathered in between the lines in January. Concerning shrub fallows, the clearing is done during the period from December to January and picketing in February-March depending on the planting design. If it is a savannah (herbaceous fallow), the clearing is done during the period from February to March. In this last case, if *Imperata cylindrica* is dominant, the use of herbicide (Round Up, Arsenal) is necessary. However, if *Chromolaena odorata* is dominant, it must be cleared in January or February and burnt in March and the treatment must be made in March with one of the herbicides (Obouayeba *et al*., 2006). In pure culture, the sowing of cover crops, in particular *Pueraria phaseolides* is recommended to avoid soil erosion and weeds (Obouayeba *et al.,* 2006). The tree densities recommended for planting are: (i) 510 trees per hectare « 7 m inter-rows and 2.80 m between plants », (ii) 555 trees per hectare « 6 m inter-rows and 3 m between plants », and (iii) 666 trees per hectare « 5 m inter-rows and 3 m between plants » (Obouayeba *et al*., 2006). After the first rains, holes of 40 cm × 40 cm × 60 cm or 40 cm × 40 cm × 40 cm are dug to receive the plants (FIRCA, 2012). The planting is done by hand and takes place at the beginning of the rainy seasons. During the year of planting, phosphate fertilizer must be brought into the planting hole; nitrogen and potassium fertilizers applied directly above the crown (November-December). For the second and third year of planting, fertilizers should be applied in a circle directly above the crown. Thereafter, bring the fertilizers on the fly in the inter-rows (Obouayeba *et al*., 2006). The fertilization of the soils of the rubber trees in production is done on warning, after the leaf diagnosis and soil analysis to determine the needs. (Obouayeba *et al*., 2006). The maintenance of the plots consists in undergrowth regular weeding. Chemical (with fungicide) and preventive control is recommended to treat the diseases that attack the leaves and stems, while curative control is recommended to treat the diseases that attack the roots (root rot). The harvest of the latex is done by an incision in the bark (bleeding) (Obouayeba *et al*., 2006). After the productive period (35–40 years), rubber trees are uprooted and a new crop is planted after a few years of lying fallow.

### 2.3. Sampling design and environmental characteristics

In order to analyze the response of edaphic invertebrates' community structure as well as soil chemical properties following the transition of secondary forests into agrosystem, three secondary forests (baseline) and nine rubber plantations (7-, 12- and 25-year-old) were selected on the site of Grand Lahou, for a total of 12 sampling stands (Table 1). We applied the same method on the site of La Mé, where the oil palm plantations were 13-, 20-, and 39-year-old. A total of 24 sampling stands was selected throughout the two study sites. On each stand from the site of Grand Lahou, data were collected along a 40 m transect, whilst on the La Mé site, sampling was performed along a 50 m transect. This difference in transect length favored the formation of monoliths in the inter-rows (fertile zone) of plantations. According to Koffi (2019), the soils under the secondary forests of Grand Lahou (29.12 ± 3.95%) contained higher moisture than those of the other land use types. The soil bulk density was lower in the secondary forests of Grand Lahou (0.95 ± 0.05 g $cm^{-3}$) and La Mé (0.91 ± 0.04 g $cm^{-3}$). Soil pH ranged from 4.43 ± 0.08 (secondary forests of Grand Lahou) to 5.37 ± 0.13 (oil palm plantations). Whatever the study site, the soil organic carbon, total nitrogen and organic matter were higher in the secondary forests of Grand Lahou (SOC: 22.90 ± 3.31 g $kg^{-1}$ soil, TN: 2.00 ± 0.29 g $kg^{-1}$ soil, SOM: 38.93 ± 5.63 g $kg^{-1}$ soil) and La Mé (SOC: 19.55 ± 1.33 g $kg^{-1}$ soil, TN: 1.60 ± 0.09 g $kg^{-1}$ soil, SOM: 33.23 ± 2.27 g $kg^{-1}$ soil).

### 2.4. Soil dwelling invertebrates' collection

Soil invertebrates were sampled along the 40–50 m transect following the modified method of 'Tropical soil biology and fertility' (Anderson and Ingram, 1993). In each stand, three monoliths (50 cm × 50 cm × 10 cm) were delimited along the transect with 20–25 m interval between two consecutive monoliths. The monoliths were hand-sorted in trays. The Oligochaeta were preserved in diluted formalin (4%), whereas the other invertebrates were fixed in diluted alcohol (70%) in the field and brought back to the laboratory for identification. In total, 72 monoliths were sampled throughout the 24 sampling stands. In the laboratory, soil invertebrates were identified under binocular loupe (Leica, Wetzlar, Germany) to the Order level according to keys and illustrations provided by Bachelier (1978).

### 2.5. Data treatment

Four land use types (*SFG* secondary forests of Grand Lahou, *RBP* rubber plantations of 7-25 years, *SFL* secondary forests of La Mé, and *OPP* oil palm plantations of 13-39 years) were considered during the data analysis. The abundance of soil invertebrates was expressed as the mean number of individuals per $m^2$. The taxonomic abundance was also studied. Mean taxonomic richness, Shannon index, Margalef diversity index and evenness were used to characterize the community's diversity. The trophic guilds were used to analyze functional groups (Yang and Chen 2009). Carbon and nitrogen stocks were calculated according to the following equation (Tondoh *et al.,* 2015):

$$\text{C Stock} = \text{SOC} \times \rho \times d$$

Where C stock is the stock of SOC in g $m^{-2}$; SOC is the concentration of carbon in g $g^{-1}$ soil, ρ the soil bulk density in g $cm^{-3}$ and d, the thickness of soil layer (10 cm).

**Table 1:** Previous cropping and soil characteristics of the selected plots. Soil physico-chemical values (mean ± standard error) were presented

| Land use types | Age (years) | Soil type | Soil texture | BD (g $cm^{-3}$) | WC (%) | SOC (g $kg^{-1}$ soil) | TN (g $kg^{-1}$ soil) | C/N | SOM (g $kg^{-1}$ soil) | $pH\text{-}H_2O$ | Previous cropping |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Site of Grand Lahou | | | | | | | | | | | |
| rubber | 7 | ferrallitic | sandy clay | 1.23 ± 0.05 | 10.88 ± 1.95 | 6.40 ± 0.92 | 0.60 ± 0.05 | 10.56 ± 0.53 | 10.88 ± 1.57 | 5.36 ± 0.09 | secondary forest-older palm tree |
| rubber | 7 | ferrallitic | clay sandy | 1.25 ± 0.04 | 7.80 ± 0.53 | 8.60 ± 0.80 | 0.85 ± 0.08 | 10.13 ± 0.08 | 14.62 ± 1.37 | 6.08 ± 0.06 | secondary forest-coffee |
| rubber | 7 | ferrallitic | sandy | 1.33 ± 0.01 | 14.36 ± 0.68 | 7.50 ± 0.05 | 0.72 ± 0.01 | 10.35 ± 0.28 | 12.75 ± 0.09 | 6.17 ± 0.13 | secondary forest-older palm tree |
| rubber | 12 | ferrallitic | clay | 1.20 ± 0.01 | 12.16 ± 0.40 | 7.50 ± 0.05 | 0.72 ± 0.01 | 10.35 ± 0.28 | 12.75 ± 0.09 | 4.72 ± 0.01 | secondary forest-older palm tree |
| rubber | 12 | ferrallitic | sandy clay | 1.11 ± 0.02 | 19.47 ± 0.72 | 16.40 ± 1.55 | 1.45 ± 0.14 | 11.32 ± 0.05 | 27.88 ± 2.65 | 4.84 ± 0.06 | secondary forest |
| rubber | 12 | ferrallitic | sandy clay | 1.23 ± 0.04 | 24.93 ± 3.63 | 10.00 ± 0.69 | 1.00 ± 0.05 | 9.98 ± 0.11 | 17.00 ± 1.17 | 4.45 ± 0.02 | secondary forest-cocoa |
| rubber | 25 | ferrallitic | clay | 1.29 ± 0.01 | 13.41 ± 0.01 | 13.65 ± 2.56 | 1.10 ± 0.17 | 12.27 ± 0.41 | 23.20 ± 4.36 | 4.51 ± 0.10 | secondary forest-older palm tree |
| rubber | 25 | ferrallitic | sandy clay | 1.32 ± 0.02 | 12.55 ± 0.34 | 11.82 ± 1.63 | 1.05 ± 0.11 | 11.19 ± 0.32 | 20.10 ± 2.77 | 5.24 ± 0.01 | secondary forest |
| rubber | 25 | ferrallitic | sandy clay | 1.06 ± 0.01 | 34.74 ± 0.95 | 8.20 ± 0.57 | 0.75 ± 0.02 | 10.90 ± 0.35 | 13.94 ± 0.98 | 4.66 ± 0.01 | secondary forest |
| secondary forest | 100 | ferrallitic | sandy clay | 1.16 ± 0.06 | 23.41 ± 2.17 | 13.75 ± 1.81 | 1.20 ± 0.05 | 11.36 ± 0.97 | 23.37 ± 3.09 | 4.64 ± 0.17 | primary forest |
| secondary forest | 100 | ferrallitic | sandy clay | 0.82 ± 0.01 | 36.78 ± 11.10 | 32.05 ± 6.32 | 2.80 ± 0.57 | 11.49 ± 0.11 | 54.48 ± 10.74 | 4.30 ± 0.17 | primary forest |
| secondary forest | 100 | ferrallitic | sandy clay | 0.86 ± 0.02 | 27.17 ± 3.41 | 22.90 ± 2.25 | 2.00 ± 0.25 | 11.54 ± 0.38 | 38.93 ± 3.82 | 4.50 ± 0.05 | primary forest |
| Site of La Mé | | | | | | | | | | | |
| oil palm | 13 | ferrallitic | sandy | 1.42 ± 0.02 | 12.50 ± 0.73 | 10.05 ± 0.02 | 1.05 ± 0.02 | 9.58 ± 0.23 | 17.08 ± 0.04 | 5.28 ± 0.15 | primary forest-older palm tree |
| oil palm | 13 | ferrallitic | sandy | 1.00 ± 0.02 | 9.94 ± 2.21 | 12.80 ± 1.09 | 1.70 ± 0.46 | 8.50 ± 1.86 | 21.76 ± 1.86 | 6.60 ± 0.66 | primary forest-older palm tree |
| oil palm | 13 | ferrallitic | sandy clay | 1.16 ± 0.08 | 10.43 ± 0.96 | 11.42 ± 0.53 | 1.37 ± 0.21 | 8.62 ± 1.00 | 19.42 ± 0.90 | 5.94 ± 0.40 | primary forest-older palm tree |
| oil palm | 20 | ferrallitic | sandy | 1.05 ± 0.09 | 15.73 ± 4.74 | 17.50 ± 0.02 | 1.80 ± 0.05 | 9.74 ± 0.32 | 29.75 ± 0.04 | 4.80 ± 0.16 | primary forest-older palm tree |
| oil palm | 20 | ferrallitic | sandy | 1.23 ± 0.09 | 10.97 ± 0.81 | 23.90 ± 0.57 | 0.90 ± 0.05 | 26.86 ± 2.37 | 40.63 ± 0.98 | 5.02 ± 0.12 | primary forest-older palm tree |
| oil palm | 20 | ferrallitic | sandy clay | 0.92 ± 0.07 | 22.32 ± 1.67 | 11.10 ± 0.63 | 1.35 ± 1.57 | 8.22 ± 0.47 | 18.87 ± 1.07 | 4.91 ± 0.02 | primary forest-older palm tree |
| oil palm | 39 | ferrallitic | sandy clay | 1.37 ± 0.05 | 10.50 ± 0.15 | 19.55 ± 2.16 | 0.90 ± 0.05 | 21.59 ± 1.02 | 33.23 ± 3.68 | 4.98 ± 0.05 | primary forest-maize-fallow |
| oil palm | 39 | ferrallitic | sandy clay | 1.15 ± 0.05 | 7.45 ± 1.16 | 27.90 ± 3.52 | 2.10 ± 0.28 | 13.32 ± 0.15 | 47.43 ± 5.98 | 5.57 ± 0.02 | primary forest-cassava-fallow |
| oil palm | 39 | ferrallitic | sandy clay | 0.59 ± 0.09 | 24.06 ± 7.84 | 11.20 ± 0.80 | 1.50 ± 0.17 | 7.54 ± 0.33 | 19.04 ± 1.37 | 5.27 ± 0.01 | primary forest |
| secondary forest | 150 | ferrallitic | sandy clay | 1.00 ± 0.07 | 13.30 ± 3.17 | 15.85 ± 1.64 | 1.45 ± 0.20 | 11.04 ± 0.41 | 26.94 ± 2.79 | 5.43 ± 0.26 | primary forest |
| secondary forest | 150 | ferrallitic | sandy clay | 0.96 ± 0.07 | 9.87 ± 1.68 | 23.25 ± 1.58 | 1.75 ± 0.14 | 13.31 ± 0.19 | 39.52 ± 2.69 | 4.57 ± 0.01 | primary forest |
| secondary forest | 150 | ferrallitic | sandy clay | 0.76 ± 0.02 | 12.88 ± 1.12 | 19.55 ± 1.61 | 1.60 ± 0.17 | 12.28 ± 0.32 | 33.23 ± 2.74 | 5.00 ± 0.13 | primary forest |

*BD* bulk density, *WC* water content, *TN* total nitrogen, *SOC* soil organic carbon, *SOM* soil organic matter, *$pH\text{-}H_2O$* potential of hydrogen-water, *C/N* carbon nitrogen ratio

SOC stock was further converted into t C $ha^{-1}$. The same calculation was applied for total N stock. In order to account for differences in soil bulk densities between the forest and plantation stands, we adjusted the thickness of soil layer beneath the rubber or oil palm fields by applying the following equation (Dawoe *et al.,* 2014; Tondoh *et al.,* 2015):

$$\text{d corrected} = (\rho \text{ forest} / \rho \text{ rubber or oil palm fields}) \times \text{d}$$

where, d corrected is the adjusted thickness of a sample soil layer under plantations, ρ forest: the bulk density of the sampled soil layer under the forest, ρ rubber or oil palm fields: the bulk density of the sampled soil layer under rubber or oil palm land use and d the thickness of soil layer used during field sampling.

The amount of carbon and nitrogen accumulated in soil per year (Kongsager *et al.,* 2013), and soil carbon sequestration (Bazezew *et al.,* 2015) were estimated for each land use type. The response of the soil properties induced by the soil textural change was investigated. The soil degradation index (DI) was used to assess the impact from the transition of secondary forests into agrosystems (Dawoe *et al.,* 2014). The DI for each soil parameter was calculated as the difference between the mean value of the soil parameter under the agrosystems and the baseline value of the same soil parameter under the secondary forests, expressed as a percentage of the mean value under the secondary forests. Then a cumulative DI was obtained by summing the resultant positive and negative DIs of the individual soil parameters for each agrosystem to be used as an index of the soil-quality responses to forest clearing and the establishment of perennial crops.

### 2.6. Statistical analysis

The values of soil properties were normalized if necessary following the formula ln(x+1), after verification of the homogeneity test (Batlett test). A one-way analysis of variance (ANOVA) associated with the Tukey's HSD test was used to examine the effects of land-use types on soil chemical and biological characteristics. This analysis was carried out both within and between land use types. The same test (one-way ANOVA) was performed in order to assess the impact of soil texture on the soil properties in the site of Grand Lahou whereas on the site of La Mé, a t-test of Student was applied. All tests were realized by using R software. The General Linear Mixed Model (GLMM) was used to explore the effects of land use types and study sites on the soil biological properties, and this by the intermediate of the software Statistica 7.1 (StatSoft Inc., Tulsa, USA).

## 3. Results

### 3.1. Soil invertebrates' density

The high total means densities recorded in the secondary forests of Grand Lahou (375.11 ± 57.61 ind $m^{-2}$) and La Mé (375.56 ± 28.41 ind $m^{-2}$) were nearly similar. The soils under agrosystems contained the lower densities. The mean density of soil invertebrates varied significantly within the rubber plantations ($F = 4.77$; $p < 0.0500$), except the other land use types. However, the mean density did not differ significantly between ($F = 1.33$; $p > 0.0500$) the land use types. This density decreased (−8 % and −27 %), respectively, after the conversion of secondary forests into rubber and oil palm plantations.

In total, 18 taxa were detected in the soil (Table 2). The individual taxonomic density decreased in general, after the transformation of secondary forests into rubber and oil palm plantations, except the Hymenoptera (secondary forests of Grand Lahou: 19.11 ± 5.64 ind $m^{-2}$ vs. rubber plantations : 20.00 ± 6.28 ind $m^{-2}$ ; secondary forests of La Mé : 91.55 ± 22.09 ind $m^{-2}$ vs. oil palm plantations : 124.14 ± 18.07 ind $m^{-2}$) and the Oligochaeta (secondary forests of Grand Lahou : 85.77 ± 15.55 ind $m^{-2}$ vs. rubber plantations : 138.81 ± 26.56 ind $m^{-2}$ ; secondary forests of La Mé : 23.11 ± 4.36 ind $m^{-2}$ vs. oil palm plantations : 35.55 ± 5.10 ind $m^{-2}$) which show an increasing trend. The density of Araneae ($F = 7.28$; $p < 0.0010$), Isopoda ($F = 7.98$; $p < 0.0010$), Diplopoda ($F = 6.49$; $p < 0.0100$), Diplura ($F = 17.72$; $p < 0.0010$), Hymenoptera ($F = 14.71$; $p < 0.0010$), Homoptera ($F = 19.15$; $p < 0.0010$), Mollusca ($F = 4.99$; $p < 0.0100$), Orthoptera ($F = 5.06$; $p < 0.0100$) and Oligochaeta ($F = 10.36$; $p < 0.0010$) differed significantly between the land use types, except the other taxa.

**Table 2:** Density (means with standard errors in parentheses) of soil invertebrates recorded through the land use types

| Taxa | Soil dwelling to 0–10 cm depth (individuals per m²) | | | | *P* value |
|---|---|---|---|---|---|
| | SFG | RBP | SFL | OPP | |
| Araneae | 21.33 (4.16)ᵃ | 9.77 (2.18)ᵇ | 9.33 (3.82)ᵇ | 1.77 (0.57)ᵇ | 0.0007*** |
| Chilopoda | 17.77 (5.54)ᵃ | 16.00 (4.16)ᵃ | 16.44 (2.15)ᵃ | 5.03 (1.21)ᵃ | 0.0710 |
| Coleoptera | 12.88 (2.28)ᵃ | 8.14 (0.96)ᵃ | 12.88 (2.18)ᵃ | 8.14 (1.34)ᵃ | 0.1007 |
| Collembola | 0.00 (0.00)ᵃ | 0.00 (0.00)ᵃ | 0.00 (0.00)ᵃ | 0.29 (0.20)ᵃ | 0.0975 |
| Dictyoptera | 0.00 (0.00)ᵃ | 0.00 (0.00)ᵃ | 0.88 (0.58)ᵃ | 0.00 (0.00)ᵃ | 0.0975 |
| Diplopoda | 24.88 (3.11)ᵃ | 18.51 (4.20)ᵃᵇ | 33.33 (8.84)ᵃ | 1.92 (0.88)ᵇ | 0.0014** |
| Diplura | 11.11 (2.08)ᵇ | 2.51 (0.93)ᵇ | 37.77 (7.80)ᵃ | 0.59 (0.41)ᵇ | 0.0001*** |
| Diptera | 3.11 (1.73)ᵃ | 1.03 (0.40)ᵃ | 1.33 (0.94)ᵃ | 0.00 (0.00)ᵃ | 0.2045 |
| Hemiptera | 0.00 (0.00)ᵃ | 0.59 (0.46)ᵃ | 2.66 (1.88)ᵃ | 1.48 (0.57)ᵃ | 0.2797 |
| Homoptera | 10.22 (2.32)ᵃ | 0.00 (0.00)ᵇ | 0.00 (0.00)ᵇ | 0.14 (0.14)ᵇ | 0.0001*** |
| Hymenoptera | 19.11 (5.64)ᵇ | 20.00 (6.28)ᵇ | 91.55 (22.09)ᵃ | 124.14 (18.07)ᵃ | 0.0001*** |
| Isopoda | 17.33 (3.59)ᵃᵇ | 1.48 (0.77)ᶜ | 24.88 (7.20)ᵃ | 2.51 (0.77)ᵇᶜ | 0.0004*** |
| Isoptera | 127.11 (55.76)ᵃ | 119.40 (67.84)ᵃ | 119.55 (27.40)ᵃ | 90.96 (24.72)ᵃ | 0.9504 |
| Mollusca | 21.77 (8.84)ᵃ | 5.33 (1.53)ᵃᵇ | 1.33 (0.94)ᵇ | 0.00 (0.00)ᵇ | 0.0059** |
| Oligochaeta | 85.77 (15.55)ᵃ | 138.81 (26.56)ᵃ | 23.11 (4.36)ᵇ | 35.55 (5.10)ᵇ | 0.0001*** |
| Orthoptera | 2.22 (0.96)ᵃᵇ | 2.96 (0.78)ᵃ | 0.00 (0.00)ᵇ | 0.29 (0.20)ᵇ | 0.0055** |
| Pauropoda | 0.00 (0.00)ᵃ | 0.00 (0.00)ᵃ | 0.00 (0.00)ᵃ | 0.14 (0.14)ᵃ | 0.4055 |
| Protura | 0.44 (0.44)ᵃ | 0.00 (0.00)ᵃ | 0.44 (0.44)ᵃ | 0.00 (0.00)ᵃ | 0.5787 |
| Total density | 375.11 (57.61)ᵃ | 344.60 (78.00)ᵃ | 375.56 (28.41)ᵃ | 273.00 (35.11)ᵃ | 0.2810 |

*SFG* secondary forests of Grand Lahou, *RBP* rubber plantations of 7-25 years, *SFL* secondary forests of La Mé, *OPP* oil palm plantations of 13-39 years. Soil N = 72; one-way ANOVA test.

**P < 0.01; ***P < 0.001 Within rows, means followed by the same letter are not significantly different at *P* = 0.05 level (Tukey's HSD test).

### 3.2. Trophic groups

Six trophic groups were observed in the soil invertebrates (fongivorous, carnivorous, phytophagous, omnivorous, detritivorous, and humivorous). The detritivorous (38 to 51 %) represented the dominant trophic group of soil (Figure 2). The intermediate trophic groups were the phytophagous (1 to 9 %), carnivorous (3 to 17 %), humivorous (6 to 40 %) and the omnivorous (5 to 45 %). Fongivorous taxa (less of 1 %) were weakly represented across the land use types. The individual density of trophic groups indicated that the carnivorous and the detritivorous were largely observed in the landscape of the two study sites. The phytophagous and humivorous boomed in the landscape of Grand Lahou whereas the omnivorous dominated the landscape of La Mé. Whatever the study site, fongivorous taxa were weakly observed (Figure 3). The density of carnivorous ($F = 16.18$; $p < 0.0010$), phytophagous ($F = 9.54$; $p < 0.0010$), omnivorous ($F = 14.72$; $p < 0.0010$) and humivorous ($F = 10.36$; $p < 0.0010$) was significantly modified through the land use types, except the other trophic groups. The land use types (Lut) and the interaction Site × Lut impacted significantly the density of carnivorous, phytophagous and humivorous (Table 3). The study sites significantly affected the density of carnivorous, phytophagous, omnivorous and humivorous. The distribution of detritivorous taxa was made independently to environmental factors.

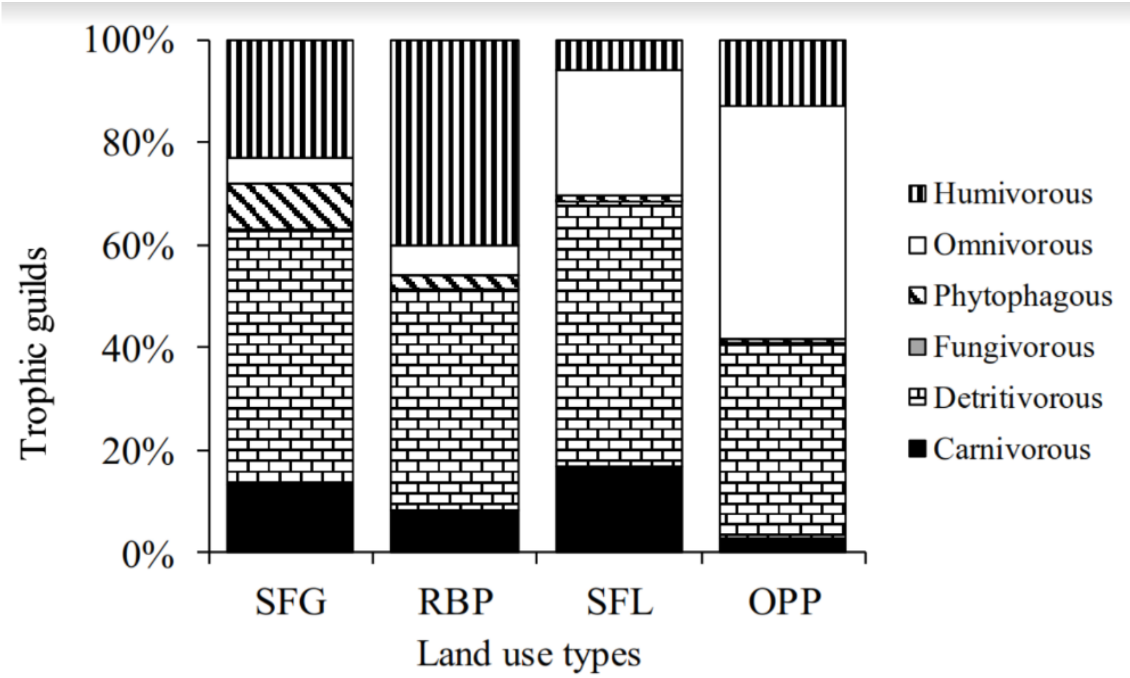


**Figure 2:** Relative abundance of trophic guilds estimated in the soil invertebrates' community. *SFG* secondary forests of Grand Lahou, *RBP* rubber plantations of 7-25 years, *SFL* secondary forests of La Mé, *OPP* oil palm plantations of 13-39 years.

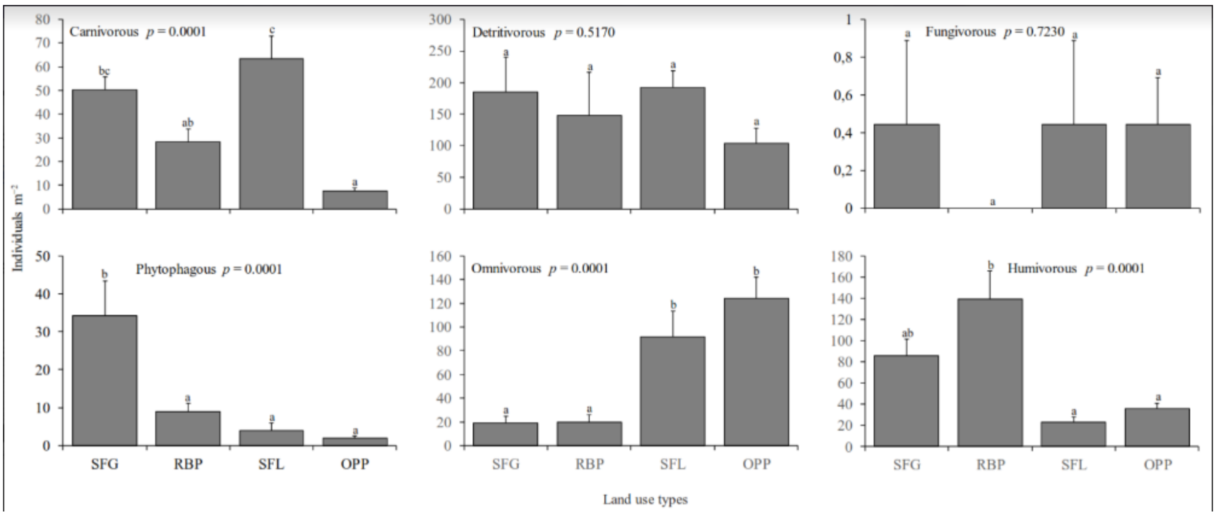


**Figure 3:** Change in density of the different trophic guilds observed through the land use types. *SFG* secondary forests of Grand Lahou, *RBP* rubber plantations of 7-25 years, *SFL* secondary forests of La Mé, *OPP* oil palm plantations of 13-39 years. One-way ANOVA test. Means followed by the same lowercase letter are not significantly different at the 0.05 level (Tukey's HSD test)

### 3.3. Taxonomic diversity indices

Whatever the study sites, the secondary forests were more rich in taxa (secondary forests of Grand Lahou: 11.33 ± 0.44 taxa; secondary forests of La Mé: 9.00 ± 0.29 taxa), widely diversified (secondary forests of Grand Lahou: 1.86 ± 0.10; secondary forests of La Mé: 1.68 ± 0.09) and more heterogeneous (secondary forests of Grand Lahou: 1.77 ± 0.08; secondary forests of La Mé: 1.35 ± 0.04) by comparison to rubber and oil palm plantations (Table 4). All the biological parameters did not significantly vary within the land use types (all, $p > 0.0500$). However, these parameters significantly changed between the land use types (taxonomic richness: $F = 53.34$, $p < 0.0010$; Shannon–Wiener index: $F = 16.72$, $p < 0.0010$; Margalef

**Table 3:** Anova table of general linear mixed model (GLMM) effects on soil trophic guilds across the site and land use type. F-values and the corresponding *p*-values are displayed.

| | | Soil dwelling to 0-10 cm depth | | | | | |
|---|---|---|---|---|---|---|---|
| | | *Carnivorous* | *Detritivorous* | *Fungivorous* | *Phytophagous* | *Omnivorous* | *humivorous* |
| Factors | df | F | F | F | F | F | F |
| Site | 1 | 6.43* | 0.31 | 1.89 | 20.26*** | 39.68*** | 25.11*** |
| Lut | 3 | 17.54*** | 0.8 | 0.77 | 7.10*** | 1.79 | 4.81** |
| Site × Lut | 3 | 3.75* | 0.77 | 0.77 | 4.73** | 0.81 | 3.49* |

* *P* < 0.05, ** *P* < 0.01, *** *P* < 0.001

diversity index: F = 37.58; p < 0.0010; Evenness: F = 3.38, p < 0.0500). The total number of individuals in the rubber and oil palm plantations was distributed less evenly among the taxa. The taxonomic richness (–35 % and –42 %), Shannon index (–32 % and –37 %) and Margalef index (–34 % and –41 %) dropped, respectively, after the conversion of secondary forests into rubber and oil palm plantations. The land use types (Lut) significantly impacted all the soil biological parameters. However, taxonomic richness, Shannon index and the Margalef index were the only parameters significantly affected by the study sites (Table 5). The interaction Site × Lut did not significantly impact the biological parameters of soil invertebrates.

**Table 4:** Diversity index values (mean ± standard error) of soil invertebrates recorded through the land-use types

| | 0-10 cm soil depth | | | | |
|---|---|---|---|---|---|
| Parameters | SFG | RBP | SFL | OPP | *P* value |
| Taxonomic richness | 11.33 ± 0.44[d] | 7.33 ± 0.39[b] | 9.00 ± 0.29[c] | 5.26 ± 0.25[a] | 0.0001*** |
| Shannon index | 1.86 ± 0.10[b] | 1.26 ± 0.10[a] | 1.68 ± 0.09[b] | 1.06 ± 0.04[a] | 0.0001*** |
| Margalef index | 1.77 ± 0.08[c] | 1.16 ± 0.08[b] | 1.35 ± 0.04[b] | 0.79 ± 0.03[a] | 0.0001*** |
| Evenness | 0.77 ± 0.04[b] | 0.64 ± 0.05[a] | 0.76 ± 0.03[b] | 0.65 ± 0.02[a] | 0.0299* |

*SFG* secondary forests of Grand Lahou, *RBP* rubber plantations of 7-25 years, *SFL* secondary forests of La Mé, *OPP* oil palm plantations of 13-39 years. N = 72; one-way ANOVA test.

* *P* < 0.05, *** *P* < 0.001; different superscript lowercase letters indicate significant variations between the land use types (Tukey's HSD test)

**Table 5:** Anova table of general linear mixed model (GLMM) effects on soil biological parameters across the site and land use type. F-values and the corresponding *p*-values are displayed.

| | | Soil dwelling to 0-10 cm depth | | | | |
|---|---|---|---|---|---|---|
| | | *Density* | *Mean taxonomic richness* | *Shannon-Wiener index* | *Margalef diversity index* | *Evenness* |
| Factors | df | F | F | F | F | F |
| Site | 1 | 0.91 | 37.46*** | 4.26* | 34.05*** | 0.01 |
| Lut | 3 | 3.48* | 30.96*** | 12.32*** | 21.78*** | 4.43** |
| Site × Lut | 3 | 1.19 | 0.73 | 1.92 | 2.07 | 1.12 |

* *P* < 0.05, ** *P* < 0.01, *** *P* < 0.001

### 3.4. Soil chemical properties

From one study site to another, the means values of carbon stock (secondary forests of Grand Lahou: 20.82 ± 2.27 t ha$^{-1}$; secondary forests of La Mé: 17.64 ± 1.33 t ha$^{-1}$), nitrogen stock (secondary forests of Grand Lahou: 1.81 ± 0.19 t ha$^{-1}$; secondary forests of La Mé: 1.44 ± 0.10 t ha$^{-1}$) and carbon sequestration (secondary forests of Grand Lahou: 76.36 ± 8.33 Mg $CO_2$ eq ha$^{-1}$; secondary forests of La Mé: 64.70 ± 4.89 Mg $CO_2$ eq ha$^{-1}$) were higher in the secondary forests than in the rubber and oil palm plantations (Table 6). However, the amounts of carbon (rubber plantations: 1.01 ± 0.08 t ha$^{-1}$ year$^{-1}$; oil palm plantations: 0.69 ± 0.05 t ha$^{-1}$ year$^{-1}$) and nitrogen (rubber plantations: 0.09 ± 0.01 t ha$^{-1}$ year$^{-1}$; oil palm plantations: 0.06 ± 0.01 t ha$^{-1}$ year$^{-1}$) annually accumulated were greater in the agrosystems than in secondary forests. Unlike the nitrogen stock, carbon stock varied significantly within the secondary forests of La Mé (F = 7.99; p < 0.0500) and the oil palm plantations (F = 3.77; p < 0.0500). Carbon stock (F = 5.11; p < 0.0100), nitrogen stock (F = 5.89; p < 0.0100), and carbon sequestration (F = 5.11; p < 0.0100), as well as the amounts of carbon (F = 73.46; p < 0.0010) and nitrogen (F = 95.74; p < 0.0010) annually accumulated significantly differed through or between the land use types. The soil carbon stock (−41 % and −15 %), nitrogen stock (−38 % and −11 %) and carbon sequestration (−41 % and −15 %) decreased, respectively, after the transformation of secondary forests into rubber and oil palm plantations

**Table 6:** Soil chemical properties (mean ± standard error) measured through the land use types

| | Carbon stock (t ha$^{-1}$) | Nitrogen stock (t ha$^{-1}$) | Nitrogen accumulation (t ha$^{-1}$ year$^{-1}$) | Carbon accumulation (t ha$^{-1}$ year$^{-1}$) | Carbon sequestration (Mg $CO_2$ eq ha$^{-1}$) |
|---|---|---|---|---|---|
| SFG | 20.82 ± 2.27$^{b}$ | 1.81 ± 0.19$^{b}$ | 0.02 ± 0.00$^{a}$ | 0.20 ± 0.02$^{a}$ | 76.36 ± 8.33$^{b}$ |
| RBP | 12.23 ± 0.85$^{a}$ | 1.12 ± 0.06$^{a}$ | 0.09 ± 0.01$^{c}$ | 1.01 ± 0.08$^{c}$ | 44.85 ± 3.14$^{a}$ |
| SFL | 17.64 ± 1.33$^{ab}$ | 1.44 ± 0.10$^{ab}$ | 0.01 ± 0.00$^{a}$ | 0.12 ± 0.01$^{a}$ | 64.70 ± 4.89$^{ab}$ |
| OPP | 14.97 ± 1.32$^{ab}$ | 1.28 ± 0.09$^{a}$ | 0.06 ± 0.01$^{b}$ | 0.69 ± 0.05$^{b}$ | 54.90 ± 4.85$^{ab}$ |
| *P* value | 0.0052$^{**}$ | 0.0025$^{**}$ | 0.0001$^{***}$ | 0.0001$^{***}$ | 0.0052$^{**}$ |

*SFG* secondary forests of Grand Lahou, *RBP* rubber plantations of 7-25 years, *SFL* secondary forests of La Mé, *OPP* oil palm plantations of 13-39 years. *N* = 72, One-way ANOVA test

$^{**}$ $P < 0.01$, $^{***}$ $P < 0.001$; different superscript lowercase letters indicate significant variations between the land use types (Tukey's HSD test)

### 3.5. Modification of soil biological and chemical properties following the soil texture variation

On the site of Grand Lahou, clay soils (430 ± 40 ind m$^{-2}$) and clay sandy soils (390 ± 110 ind m$^{-2}$) favored the development and emergence of the edaphic invertebrates given their high density (Table 7). These two soil textures contained a high carbon (*CL* 12.96 ± 1.62 t ha$^{-1}$; *SC* 15.76 ± 0.50 t ha$^{-1}$) and nitrogen storage (*CL* 1.11 ± 0.12 t ha$^{-1}$; *SC* 1.41 ± 0.06 t ha$^{-1}$), as well as a greater carbon sequestration (*CL* 47.54 ± 5.97 Mg $CO_2$ eq ha$^{-1}$; *SC* 57.79 ± 1.86 Mg $CO_2$ eq ha$^{-1}$). Respectively, the soils of sandy clay and sandy textures favored a high carbon (*CS* 1.50 ± 0.07 t ha$^{-1}$ year$^{-1}$; *SA* 1.43 ± 0.01 t ha$^{-1}$ year$^{-1}$) and nitrogen (*CS* 0.15 ± 0.01 t ha$^{-1}$ year$^{-1}$; *SA* 0.13 ± 0.00 t ha$^{-1}$ year$^{-1}$) accumulation. Apart from the taxonomic richness, the other soil properties significantly changed through the four textures (all, $p < 0.0500$). On the site of La Mé (Table 8), soil properties did not significantly vary across the two soil textures, except the carbon ($p < 0.0500$) and nitrogen ($p < 0.0500$) annually accumulated which were significantly higher in the sandy soils.

### 3.6. Soil degradation index

The means values of soil degradation index were negatives, except the bulk density that presented the positive values with a maximum recorded under the rubber plantations. In other words, the soils under the rubber and oil palm plantations were more compacted. The establishment of oil palm plantations leads to soil invertebrates' community degradation whereas the soil under rubber plantations more altered the soil chemical properties (Table 9). The cumulative degradation index indicated that the rubber plantations (−370.1) more degraded the soil by comparison to the oil palm plantations (−214.4).

**Table 7:** Change in soil chemical and biological (mean ± standard error) characteristics through the soil textures of the site of Grand Lahou

| Soil characteristics | Soil textures | | | | |
|---|---|---|---|---|---|
| | SC | CL | CS | SA | *P* value |
| Total density (10$^{3}$ ind m$^{-2}$) | 0.39 ± 0.11$^{ab}$ | 0.43 ± 0.04$^{b}$ | 0.12 ± 0.01$^{a}$ | 0.13 ± 0.06$^{a}$ | 0.0172$^{*}$ |
| Taxonomic richness | 9.00 ± 0.19$^{a}$ | 6.83 ± 0.60$^{a}$ | 8.00 ± 0.58$^{a}$ | 6.33 ± 1.45$^{a}$ | 0.1900 |
| Carbon stock (t ha$^{-1}$) | 15.76 ± 0.50$^{b}$ | 12.96 ± 1.62$^{ab}$ | 10.52 ± 0.53$^{a}$ | 10.01 ± 0.06$^{a}$ | 0.0068$^{**}$ |
| Nitrogen stock (t ha$^{-1}$) | 1.41 ± 0.06$^{b}$ | 1.11 ± 0.12$^{ab}$ | 1.03 ± 0.06$^{a}$ | 0.96 ± 0.02$^{a}$ | 0.0143$^{*}$ |
| Nitrogen accumulation (t ha$^{-1}$ year$^{-1}$) | 0.06 ± 0.01$^{a}$ | 0.06 ± 0.01$^{a}$ | 0.15 ± 0.01$^{b}$ | 0.13 ± 0.00$^{b}$ | 0.0001$^{***}$ |
| Carbon accumulation (t ha$^{-1}$ year$^{-1}$) | 0.67 ± 0.01$^{a}$ | 0.70 ± 0.06$^{a}$ | 1.50 ± 0.07$^{b}$ | 1.43 ± 0.01$^{b}$ | 0.0001$^{***}$ |
| Carbon sequestration (Mg $CO_2$ eq ha$^{-1}$) | 57.79 ± 1.86$^{b}$ | 47.54 ± 5.97$^{ab}$ | 38.60 ± 1.96$^{a}$ | 36.72 ± 0.23$^{a}$ | 0.0068$^{**}$ |

*SC* clay sandy, *CL* clay, *CS* sandy clay, *SA* sandy, *N* = 72, One-way ANOVA test

$^{*}$ $P < 0.05$, $^{**}$ $P < 0.01$, $^{***}$ $P < 0.001$; different superscript lowercase letters indicate significant variations between the soil textures (Tukey's HSD test)

**Table 8:** Modification in soil chemical and biological (mean ± standard error) characteristics across the soil textures of the site of La Mé

| Soil characteristics | Soil textures | | P value |
|---|---|---|---|
| | SC | SA | |
| Total density ($10^3$ ind $m^{-2}$) | 0.32 ± $0.02^a$ | 0.26 ± $0.01^a$ | 0.0770 |
| Taxonomic richness | 6.75 ± $0.38^a$ | 5.08 ± $0.46^a$ | 0.0522 |
| Carbon stock (t $ha^{-1}$) | 15.56 ± $0.79^a$ | 15.79 ± $1.01^a$ | 0.8686 |
| Nitrogen stock (t $ha^{-1}$) | 1.30 ± $0.06^a$ | 1.36 ± $0.16^a$ | 0.7722 |
| Nitrogen accumulation (t $ha^{-1}$ $year^{-1}$) | 0.03 ± $0.00^a$ | 0.08 ± $0.01^b$ | $0.0475^*$ |
| Carbon accumulation (t $ha^{-1}$ $year^{-1}$) | 0.35 ± $0.01^a$ | 0.94 ± $0.06^b$ | $0.0104^*$ |
| Carbon sequestration (Mg $CO_2$ eq $ha^{-1}$) | 57.06 ± $2.90^a$ | 57.90 ± $3.70^a$ | 0.8686 |

*SC* clay sandy, *SA* sandy, *N* = 72, t-test of Student.

$^*$ $P < 0.05$; different superscript lowercase letters indicate significant variations between the soil textures

## 4. Discussion

### 4.1. Soil invertebrates' structure following the transformation of secondary forests into rubber and oil palm plantations

Overall, the conversion of forests into rubber and oil palm plantations is characterized by a decrease in the abundance and diversity of soil invertebrates (Oke *et al.*, 2008; Sabrina *et al.*, 2009; Brühl and Eltz, 2010; Foster *et al.*, 2011; Edwards *et al.*, 2014; Luke *et al.*, 2014; Mumme *et al.*, 2015; Drescher *et al.*, 2016; N'Dri and N'Guessan, 2018; Tondoh *et al.*, 2019). This trend is in line with our data. In fact, the results showed a decrease in total density (−8 % and −27 %), taxonomic richness (−35 % and −42 %), Shannon index (−32 % and −37 %) and the Margalef index (−34 % and −41 %) following the conversion of secondary forests into rubber and oil palm plantations. The drop in total abundance of soil invertebrates detected in the rubber and oil palm plantations might be explained by the lower living tree density and plant biomass recorded in these agrosystems (Foster *et al.*, 2011; Drescher *et al.*, 2016; Singh *et al.*, 2021). The tree density (secondary forest of Grand Lahou: 540 tree $ha^{-1}$; secondary forest of La Mé: 532 tree $ha^{-1}$) and biomass (secondary forest of Grand Lahou: 946 t $ha^{-1}$; secondary forest of La Mé: 924 t $ha^{-1}$) of forests are largely superiors to those of rubber (density: 510–666 tree $ha^{-1}$; biomass: 398 t $ha^{-1}$) and oil palm (density: 143 tree $ha^{-1}$; biomass: 74–105 t $ha^{-1}$) plantations (Manhan, 2015; Séka, 2016; Ahui, 2018; Yéo, 2018). The root systems of trees play a critical role in the ecosystem functions, as the nutrient and organic matter input to soil through roots maintains soil fertility and carbon sequestration (Pransiska *et al.*, 2016). The decomposition of coarse roots has been regarded as an important component providing a slow delivery of C and nutrients to the soil and soil biota influencing the long-term ecosystem productivity (Pransiska *et al.*, 2016).

Vertically, a forest comprises multi-story vegetation in different strata owing to the distribution of understory grasses and shrubs and over story trees of varying heights (Singh *et al.*, 2021). Unlike to monospecific plantations, the contiguous crown of forest trees allows the interception of incident light, which contributes to maintaining soil moisture (Sulistyorini *et al.*, 2018; Ali *et al.*, 2021; Singh *et al.*, 2021). Forests have the lowest light penetration value (0.15 $m^2$ $m^{-2}$) compared to rubber (0.2 $m^2$ $m^{-2}$) and oil palm (0.32 $m^2$ $m^{-2}$) plantations, indicating an increase in photosynthetic capacity at the lower part of the canopy (Ali *et al.*, 2021). Soil temperature perceived as one of the soil physics factors that determine the occurrence and abundance of soil organisms was higher in monoculture plantations and lower in primary forest, probably due to the reduction of living tree density by regular land clearance and understory vegetation removal in the first one (Sulistyorini *et al.*, 2018; Hemati *et al.*, 2020; Singh *et al.*, 2021). According to authors, high soil temperatures in turn negatively affect the water content. The reduction of soil litter in monospecific plantations contributes to habitats and trophic resources limitation for edaphic invertebrates (Beckendorff, 2016; Perron *et al.*, 2021; Singh *et al.*, 2021).

The taxonomic richness and diversity of soil invertebrates were higher in secondary forests than in rubber and oil palm plantations. These observations were supported by the investigation made on invertebrate communities (Mumme *et al.*, 2015), macroinvertebrates (N'Dri and N'Guessan, 2018), Isoptera (Foster *et al.*, 2011; Luke *et al.*, 2014), Oligochaeta (Tondoh *et al.*, 2019), Hymenoptera (Brühl and Eltz, 2010), Coleoptera (Foster *et al.*, 2011; Edwards *et al.*, 2014) and Mollusca (Oke *et al.*, 2008). This trend could be explained by the fact that the forest is a complex, self-regenerating system, encompassing soil, water, microclimate, energy, and a wide variety of plants and animals in mutual relation (Swarnalatha, 2010; Foster *et al.*, 2011). It provides more diverse shelter and food for animals (Singh *et al.*, 2021). The conversion of forests to rubber plantations is clearly viewed as an acute threat to plant diversity (Foster *et al.*, 2011; Drescher *et al.*, 2016; Singh *et al.*, 2021). With the decline in vascular plant diversity in monoculture plantations, soil organisms' diversity also declines along the transformation (Foster *et al.,* 2011; Tondoh *et al.,* 2015; Drescher *et al.,* 2016; Singh *et al.,* 2021).

**4.2. Soil quality after the transition of secondary forests into rubber and oil palm plantations**

Soil physico-chemical and biological properties are highly driven by trees abundance and diversity (Hemati *et al.,* 2020; Singh *et al.,* 2021). Beyond to plant diversity, the concentration of soil nutrients and activities of soil fauna are highly influenced by the weather (Hemati *et al.,* 2020). However, conversion of forests to farm lands without trees or in monoculture tree plantations leads to a decline in soil organic carbon (SOC), nitrogen (N) stocks and carbon sequestration (Foster *et al.,* 2011; Demessi *et al.,* 2013; Chiti *et al.,* 2014; Tondoh *et al.,* 2015; Tondoh *et al.,* 2019; Nguyen *et al.,* 2020). These observations are consistent with our results which showed a dropped in the soil carbon stock (−41 % and −15 %), nitrogen stock (−38 % and −11 %) and carbon sequestration (−41 % and −15 %), respectively, after the transformation of secondary forests into rubber and oil palm plantations.

The potential of soil carbon sequestration in agroforestry systems depends on the prevailing environmental condition, the plant species used and the management practices involved (Demessi *et al.,* 2013). A forest has a denser canopy cover than a tree plantation owing to the higher density and distribution of lianas and other vegetation. Contrastingly, lianas distribution in tree plantations is minimal because of weedicide application and regular vegetation cleaning (Foster *et al.,* 2011; Singh *et al.,* 2021). The difference in soil nutrients may be explained by the high soil compaction in monoculture plantation, which highlights a decrease in soil porosity and therefore low water retention (Demessie *et al.,* 2013; Nguyen *et al.,* 2020). The replacement of natural forests into monoculture tree plantations with low canopy cover, less ground cover and less leaf litter biomass alters the soil quality (Sabrina *et al.,* 2009; Nguyen *et al.,* 2020). Indeed, the crown of the younger rubber and oil palm tree does not fully cover the soil surface, thus, the sunlight may directly radiate onto the soil surface, which results in a lower soil moisture content than in soil under natural forests (Sabrina *et al.,* 2009; Nguyen *et al.*, 2020). These assertions are supported by the work of Allen *et al.* (2015) conducted in Indonesia, and where an increase in soil bulk density (+10% and +20%), was detected, respectively, in rubber and oil palm plantations derived from forests. The higher bulk density in the upper layer of agroforestry and agricultural farms as compared to natural forest may be attributed to lower SOC content and soil compaction caused by cultivation practices (Demessie *et al.,* 2013; Nguyen *et al.,* 2020).

**Table 9:** Degradation indexes (%) for 0–10 cm soil layer in rubber and oil palm plantations, respectively, at 7-25-, and 13-39-years of cultivation following conversion of secondary forests

| Soil parameters | Land use types | |
|---|---|---|
| | RBP | OPP |
| Total density (ind $m^{-2}$) | −8.1 | −27.3 |
| Mean taxonomic richness | −35.3 | −41.6 |
| Shannon-wiener index | −33.0 | −36.7 |
| Margalef diversity index | −34.8 | −41.6 |
| Bulk density (g $cm^{-3}$) | +28.7 | +21.1 |
| Total nitrogen (g $kg^{-1}$ soil) | −54.2 | −12.0 |
| Soil organic carbon (g $kg^{-1}$ soil) | −56.3 | −17.3 |
| Soil organic matter (g $kg^{-1}$ soil) | −56.3 | −17.3 |
| Carbon stock (t $ha^{-1}$) | −41.3 | −15.1 |
| Nitrogen stock (t $ha^{-1}$) | −38.3 | −11.2 |
| Carbon sequestration (Mg $CO_2$ eq $ha^{-1}$) | −41.3 | −15.1 |
| Cumulative DI | −370.1 | −214.4 |

*RBP* rubber plantations of 7-25 years, *OPP* oil palm plantations of 13-39 years

The highest SOC losses in the 0–30 cm layer were caused by the conversion of primary forests to tree plantations: cocoa −61% of the original SOC stock, coconut −55%, rubber −35% and oil palm −28% (Chiti *et al.,* 2014). These observations were consistent with the research of Guillaume *et al.* (2015) which showed a decline in organic carbon and total nitrogen up to 70% in the oil palm and 62% in the rubber plantations. The high amount of soil organic carbon, total nitrogen and organic matter in secondary forests may be probably due to the continuous and greater litter input from diverse vegetation as compared to monocultural system (Demessie *et al.,* 2013; Beckendorff, 2016; Vrignon-Brenas *et al.*, 2019; Singh *et al.,* 2021). Plant litter is a vital component of tropical ecosystems and represents the primary base material for nutrient cycling (Singh *et al.,* 2021). It also plays an important role in controlling soil erosion and runoff (Vrignon-Brenas *et al.,* 2019). Most of the organic matter added through leaf fall, crop residues and root litter were retained in the upper layers (Demessi *et al.,* 2013). Unfortunately, the litter layer is reduced during clearing and tillage in monoculture tree plantations (Beckendorff, 2016). The removal of organic residues can in turn over reduce C stocks in the topsoil, which might affect soil biological activity and the long-term sustainability of tropical plantations (Chiti *et al.,* 2014; Perron *et al.,* 2021). Furthermore, the relationships between carbon (C) and nitrogen (N) stocks in the root biomass were related to the total aboveground tree biomass, which decrease with increasing land-use intensity together with aboveground tree biomass (Pransiska *et al.,* 2016). Subsequently, carbon and nutrient stocks in the root system were over 50% lower in the monoculture plantations compared to the natural forest (Pransiska *et al.,* 2016).

This study pointed out that clay soils and clay sandy soils favored the development and emergence of the soil invertebrates, and contained a high carbon and nitrogen storage as well as a greater carbon sequestration. Whatever the site, the soil quality was more degraded under the monoculture tree plantations compared to the secondary forests. To limit the risk of nutrient losses, it is essential to adapt the recommendations to the difference between the nutrients available in the soil and those required by the trees, as supported by the Integrated Nutrient Management (Vrignon-Brenas *et al.,* 2019). Increasing productivity of tree plantations to reduce the need for new lands for production is a valid alternative to gaining land to be reforested, and it seems to represent the only option in tropical areas where tree plantations are in most cases used for the needs of local populations (Chiti *et al.,* 2014). Moreover, the incorporation of woody trees with an understory of smaller trees during the early establishment periods of monoculture tree plantations can create a sustainable agroforestry system with improved land functionality, especially in low-fertility soils (Hemati *et al*., 2020; Nguyen *et al.,* 2020; Perron *et al.,* 2021). The reduction or absence of tillage and the use of permanent soil cover crop have clear demonstrated positive effects on soil stability, including the improvement of physical and chemical properties, the decrease of water run-off and wind erosion, and an increase of water retention (Conti, 2015). Alternatively, leaving residues of the previous crop on the soil surface is likely to enhance nutrient recycling and soil fertility (Vrignon-Brenas *et al.,* 2019; Perron *et al.,* 2021).

### 5. Conflicts of Interest

The authors have no conflict of interest to declare.

### 6. Acknowledgments

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