Modification of Topsoil Physico-Chemical Characteristics and Macroinvertebrates Structure Consecutive to the Conversion of Secondary Forests into Rubber Plantations in Grand-Lahou, Côte d'Ivoire

Julien Kouadio N'Dri[1,2*], Kévin Kouadio N'Guessan[1]

[1]Unité de Formation et de Recherche (UFR) des Sciences de la Nature / Université Nangui Abrogoua, 02 BP 801 Abidjan 02, Côte d'Ivoire

ndri_jk@yahoo.fr, kevinktresor@gmail.com

[2]Centre de Recherche en Ecologie, 08 BP 109 Abidjan 08, Côte d'Ivoire.

ndri_jk@yahoo.fr

Abstract

The objective of this investigation was to assess the modifications of topsoil physico-chemical characteristics and macroinvertebrates structure consecutive to the conversion of secondary forests into rubber plantations and how these change with the aging of the plantations and the season. The sampling design was constituted of four treatments: secondary forest referred to as baseline land-use, 7-, 12- and 25-year-old rubber plantations. Three replications per land use type were randomly established in each of the selected treatments, thus totaling 12 sampling areas. On each sampling area, a 40 m transect was established. The litter dwelling and topsoil (0–10 cm) macroinvertebrates were sampled, respectively, by using the pitfall traps and monoliths (50 cm × 50 cm × 10 cm) following the Tropical Soil Biology and Fertility method. The soil physical and chemical parameters were measured along the 40 m transect. The results showed that the conversion of secondary forest into plantations was characterized by a modification of the density of soil macroinvertebrates (dry season: −50 and −24% vs. rainy season: −61 and +32%), taxonomic richness of soil macroinvertebrates (dry season: +7 and −14% vs. rainy season: −21 and −14%), water content (dry season: −41 and −5% vs. rainy season: −62 and −31%), bulk density (dry season: +6 and −3% vs. rainy season: +33 and +29%), soil organic carbon (dry season: −73 and −59% vs. rainy season: −67 and −51%) and total nitrogen (dry season: −68 and −58% vs. rainy season: −64 and −52%), respectively, after about 7 and 25 years of conversion. The restoration processes did not cause significant changes in the soil physico-chemical and biological characteristics after 25 years of forests conversion. However, the study highlighted the improvement in the soil ecological quality due to a reduction in soil degradation, and an increase in the density of macroinvertebrates (+235%), taxonomic richness (+9%), water content (+84%), soil organic carbon (+50%) and total nitrogen (+33%) in the 25-year-old plantations compared to the 7-year-old plantations.

Introduction

Forests play an important role in maintaining biodiversity and mitigating climate change (Hedde, 2006). However, the issue of biodiversity erosion due to forest conversion into agrosystem has become a global one and a major environmental challenge (Hooper *et al.*, 2005). The results of the latest Global Forest Resources Assessment by the Food and Agriculture Organization of the United Nations (FAO) indicate that between 1990 and 2015 the total forest area declined by 3%, from 4,128 M ha to 3,999 M ha, and the annual rate of net forest loss halved from 7.3 M ha yr^{-1} in the 1990s to 3.3 M ha yr^{-1} between 2010 and 2015 (Keenan *et al.*, 2015). According to authors, the loss of forest area occurred largely in the tropics, from 1,966 M ha in 1990 to 1,770 M ha in 2015. Despite the international and governmental conventions on the biodiversity conservation in recent decades (Redford and Richter, 1999), about 1.7 billion tons of carbon is released annually, due to land use change (IPCC, 2001). The deforestation represents, on the one hand, 20%–25% of current global carbon emissions (IPCC, 2001), and on the other hand, it corresponds to 70% of the CO2 emissions in Africa (FAO, 2005). The different land-use patterns and the structure of plant species communities are some factors that determine the distribution and the diversity of soil organisms (Bardgett, 2005; Hedde, 2006; Hasegawa *et al.*, 2012; N'Dri *et al.*, 2017a). The soil, perceived as the biodiversity reservoir (Hedde, 2006; Decaëns, 2010) does not escape this deterioration. The destruction of forests, the erosion of soil biodiversity and the disturbance of biogeochemical cycles remain the consequences from the establishment of perennial crops (Hooper *et al.*, 2005; Dawoe *et al.*, 2014; Tondoh *et al.*, 2015). Subsequently, the modification of soil physico-chemical and biological characteristics was observed (Dawoe *et al.*, 2014; Marichal *et al.*, 2014; Tondoh *et al.*, 2015).

Introduced in Côte d'Ivoire in the 1950s, rubber cultivation has become a major perennial crop in the southern part of the country (Ruf, 2009). With estimated production more than 300 000 tons in 2012 (CNRA, 2013), Côte d'Ivoire is ranked first rubber producer country (Obouayeba *et al.*, 2006; Ruf, 2009). However, the involvement of rubber plantations in soil degradation and climate change is a highly discussed topic in view of its overproduction and of its large cultivation area. The forests remain more complex with a large litter fall and a low stock of litter consecutive to a high decomposition rate compared to agrosystems (Martius *et al.*, 2004). However, at an advanced age, the agrosystems provide favorable niches and conditions for soil biodiversity (Dash and Behera, 2013; N'Dri *et al.*, 2017a), and can perform an ecological function similar to those of a forest (Martius *et al.*, 2004). According to Bardgett (2005) the relationships between plant diversity and soil biological properties are unpredictable, and depend largely on the ecophysiological traits of individuals, and often dominant plant species that are present within the community or on changes in net primary productivity.

The biological compartment plays an essential role in soil functioning and providing ecosystem services (Gilot *et al.*, 1995; Marichal *et al.*, 2014). The huge niche partitions in soil associated to the diversity of microhabitats and to spatial and temporal segregation between species promote the maintenance of the biodiversity (Decaëns, 2010). Whatever the level of hierarchical classification, the macroinvertebrates interacting with the microfauna and mesofauna, actively participate in the litter decomposition and mineral recycling in soil (Coleman *et al.*, 2004; Tardif, 2013). Plant species differ greatly in their basic ecological traits. This variation is reflected in differences in the quantity and quality of resources that they produce, in terms of litter inputs, which impact on soil food webs over relatively long timescales and large spatial scales (Bardgett, 2005). As results of their biological activity (Chaudhuri *et al.*, 2009), the annual cast production in the rubber plantation was higher than those recorded in the mixed forest. Then, the authors found that the amounts of organic matter, potassium and phosphorus in casts were greater than those of the surrounding soil. The invasion of the species *Pontoscolex corethrurus* in rubber plantations could be due to several factors, especially anthropogenic disturbances, competitive interaction between the exotic and the endemic species and their reproductive strategies (Nath and Chaudhuri, 2010). *Pontoscolex corethrurus* could effectively contribute to the redistribution of labile organic carbon along soil profile and between the protected and unprotected area by aggregates (Zhang *et al.*, 2010). The trophic sources diversity from termites is very essential in soil

restructuring and the distribution of organic matter (Dosso *et al.*, 2013). Highly dependent on moisture and calcium, the communities of diplopoda are greatly influenced by the leaves litter fall (Coleman *et al.*, 2004).

In Ivoirian land, most of the investigations involving the soil physico-chemical parameters, agrosystems and macroinvertebrates diversity concerned the plantations of cocoa and teak (Tondoh *et al.*, 2011, 2015). Very few studies were devoted to the impact of rubber plantations on the soil ecological quality in Côte d'Ivoire. Thus, the objective of this investigation was to assess the modifications of topsoil physico-chemical characteristics and macroinvertebrates structure consecutive to the conversion of secondary forests into rubber plantations and how these change with the aging of the plantations and the season. We hypothesized that the disturbance imposed on macroinvertebrate communities during site preparation and planting would be compensated for by the reduction of the soil degradation index as the rubber plantations age. We expected over time that the community structure of macroinvertebrates and the soil physico-chemical parameters in rubber plantations would reach similar conditions as in secondary forest.

Materials and Methods

Description of the study site

The study was carried out in 2013 and 2015 in the department of Grand-Lahou (5°13′ N; 5°03′ W) situated in southern Côte d'Ivoire about 140 km from Abidjan. This department has an equatorial climate 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 (Ettian *et al.*, 2009). The annual rainfall during the field works was about 1,085 mm whereas the average monthly temperature was about 27 °C. The vegetation is a rainforest type with different aspects, *i.e.* secondary forests, rural domains, and fallow systems (Ettian *et al.*, 2009). Despite its status of protected area, the human interferences are strongly observed in the Gobodiénou forest. The few existing islets of secondary forests do not exceed 10 ha each, in terms of area. Farmers suggested that most of the zone we investigated was secondary forest since 1980 (33 years before the field works) and was converted to rubber plantations in 1988. A portion of the previous vegetation of rubber plantations less than 10 years old was used for cocoa, coffee or oil palm plantations in the former rotation. The attractive price of latex during the past decade caused a larger conversion of the agricultural plots and natural forests into rubber plantations. *Hevea brasiliensis* (GTI variety) is the most cultivated crop (Obouayeba *et al.*, 2006). Most conspicuous is the absence of undergrowth and herbaceous stratum in the rubber plantations, 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. Ferrallitic soils are observed across the rubber chronosequence.

Sampling design

The study was conducted using a randomized design with four treatments: secondary forest considered as baseline land-use, 7-, 12- and 25-year-old rubber plantations. Each plantation area ranged from 1 to 2 ha. Three replications per treatment or land use type were selected (Table 1). 7 years marks the beginning of the latex harvest. At 12 years the plantations reach their maximum production level, whereas at 25 years latex production begins to decrease. After the productive period (35–40 years), the rubber trees are uprooted and a new crop is planted after a few years of fallow. On each sampling area, a 40 m transect was defined where five sampling points were allocated every 10-m interval between two consecutive points. At 2 m on each side and each sampling point, two pitfall traps were realized at the end of rainy season, whether 10 pitfall traps by transect. A total of 120 pitfall traps were performed across the 12 sampling areas. 48 hours after trapping, the pitfall traps were removed, cleared of mud and other detritus, well labeled and stored in packages. The endogenous macroinvertebrates were sampled in both dry and rainy season following the Tropical Soil Biology and Fertility method (Anderson and Ingram, 1993). Three monoliths (50 cm × 50 cm × 10 cm) were delimited along each transect with 20 m interval between two consecutive points. The monoliths were manually sorted in trays. The earthworms were preserved in formalin diluted (4%), whereas the other

macroinvertebrates were fixed in alcohol diluted (70%). A total of 72 monoliths was sampled through the 12 sampling areas and two seasons. On each sampling area and following the same transect, three composite soil samples were taken with 20 m intervals between two consecutive points for chemical measurements. Along the transect, three soil cores (non composite samples) were taken with 20 m intervals between two consecutive points using the cylinder method (Assié *et al.*, 2008) for physical measurements. A total of 72 composite soil samples and 72 non-composite soil samples were taken for the physico-chemical measurements.

Table 1: Description of the different sampling areas selected

Land use type	Age (year)	Area (ha)	Soil type	Soil texture	Fertilizers	Previous cropping
Rubber	7	1.5	Ferrallitic	Sandy clay	Urea	Secondary forest, Oil palm
Rubber	7	1.5	Ferrallitic	Clay Sandy	Urea	Secondary forest, Coffee
Rubber	7	1	Ferrallitic	Sandy	Urea	Secondary forest, Oil palm
Rubber	12	1	Ferrallitic	Clay	Urea	Secondary forest, Oil palm
Rubber	12	1	Ferrallitic	Sandy clay	Urea	Secondary forest
Rubber	12	1	Ferrallitic	Sandy clay	Urea	Secondary forest, Cocoa
Rubber	25	2	Ferrallitic	Clay	Urea	Secondary forest, Oil palm
Rubber	25	1	Ferrallitic	Sandy clay	Urea	Secondary forest
Rubber	25	1	Ferrallitic	Sandy clay	Urea	Secondary forest
Secondary forest	80	8	Ferrallitic	Sandy clay	-	Primary forest
Secondary forest	80	9	Ferrallitic	Sandy clay	-	Primary forest
Secondary forest	80	10	Ferrallitic	Sandy clay	-	Primary forest

Land use types analysis

Larger organisms, in general, appear to be more sensitive to disturbance than smaller ones (Wardle, 1995). The impact of human interference (rubber production) on soil macroinvertebrates was estimated by using an index of change V (Wardle, 1995) for each organisms group. This index compares the relative increase or decrease in organism abundance between rubber plantations and secondary forests. The index was calculated by the formula:

$$V = \frac{2M_{CN}}{M_{CN} + M_{NT}} - 1$$

where M_{CN} and M_{NT} were the abundance observed respectively in the rubber plantations and the secondary forests. The index V ranges from −1 when the organisms occur only in secondary forests to +1 when organisms occur only in rubber plantations with 0 representing equal abundance in both secondary forests

and rubber plantations. The magnitude of response to human interference was expressed by the following categories:

extreme inhibition by rubber plantations V < −0.67;

moderate inhibition by rubber plantations −0.67 < V < −0.33;

mild inhibition by rubber plantations −0.33 < V < 0;

mild stimulation by rubber plantations 0 < V < 0.33;

moderate stimulation by rubber plantations 0.33 < V < 0.67;

extreme stimulation by rubber plantations V > 0.67.

The soil degradation index was also used to evaluate the impact from the conversion of secondary forests into rubber plantations (Dawoe *et al.*, 2014). The soil degradation index for each soil parameters was calculated as the difference between mean values of soil parameters under the rubber plantations chronosequence and the baseline values of similar soil parameters under the secondary forest expressed as a percentage of the mean values under the secondary forest. Then a cumulative DI was obtained by summing up the resultant positive and negative DI's of the individual soil parameters for each rubber plantation to be used as an index of the soil quality responses to forest clearing and the establishment of perennial crops. The analyses were conducted with data from the rainy season, because ten humid months were observed in the study area due to climate change.

Statistical analysis

The abundance and diversity of endogenous macroinvertebrates were estimated both in dry and rainy season whereas those from litter were evaluated only in rainy season. General indexes such as the mean taxonomic richness, cumulative taxonomic richness, Margalef diversity index, Shannon index, Evenness, and the Berger Parker index were used to characterize the diversity of the macroinvertebrates. A particular interest was devoted to litter (ants, coleoptera, orthoptera, and araneae) and soil (earthworms, termites, and ants) major taxa due to their abundance and their key role in the ecosystems functioning. Subsequently, the beta diversity (i) between the land use types was calculated by the Sorensen dissimilarity (1 − Sørensen similarity index) expressed in % (Chao *et al.*, 2005) and (ii) within monoliths by the Euclidean, Sørensen and Jaccard distance (Chao *et al.*, 2005; N'Dri *et al.*, 2017a, b). The Euclidean distance (d_{ED}) was estimated with the formula:

$$d_{ED} = \sqrt{\sum_{j=1}^{p}(X_{1j} - X_{2j})^2}$$

with X_1 = the number of individuals from a taxon X in the first monolith; X_2 = the number of individuals of the same taxon X in the second monolith; p = the total number of taxon.

The trophical groups (Yang and Chen, 2009) were used to analyze the functional diversity. Soil bulk density was estimated using the cylinder method (Assié *et al.*, 2008). Soil water content was determined after drying at 105°C for 48 h. Soil pH-H_2O was measured by means of a glass electrode in 1:2.5 soil: water (Tondoh *et al.*, 2015). The Walkley and Black (1934) method was used to determine soil organic carbon, namely a wet oxidation of organic carbon in an acid dichromate solution, followed by back titration of the remaining dichromate with ferrous ammonium sulfate. Total nitrogen was determined using the Kjeldahl method, and the C/N ratio was also calculated. As the data did not follow a normal distribution (Shapiro-Wilk test), the impact of land use types on the abundance of macroinvertebrates was evaluated by using a Kruskal−Wallis test. A one-way ANOVA associated with the post-hoc Tukey's test was performed to examine the effects of land use types on the soil physico-chemical and diversity parameters. The factorial Anova added to general linear mixed (GLM) model was used to explore the effects of season and age of plantations on the soil

biological, physical and chemical parameters along the rubber chronosequence. The relations between the communities of macroinvertebrates and the soil characteristics were examined by using the Pearson correlation. All tests were conducted by using the software Statistica 7.1 (StatSoft Inc., Tulsa, USA). The cumulative taxonomic richness (Sob) from each land use type was computed by using the software Estimates 7.5 (Colwell, 2005).

Results

Soil physico-chemical parameters

Whatever the season, the soil physico-chemical parameters varied significantly across the land use types, except for the bulk density and water content in dry season (Table 2). The amount of soil organic carbon, total nitrogen and water content was higher in secondary forests. The water content increased with the increasing age of rubber plantations. The conversion of secondary forests into rubber plantations was characterized by a modification of water content (dry season: −41 and −5% vs. rainy season: −62 and −31%), bulk density (dry season: +6 and −3% vs. rainy season: +33 and +29%), soil organic carbon (dry season: −73 and −59% vs. rainy season: −67 and −51%), and total nitrogen (dry season: −68 and −58% vs. rainy season: −64 and −52%), respectively, after about 7 and 25 years of conversion.

Table 2: Soil physico-chemical characteristics and means values ± SE observed along the land use types.

	Land use types				
	SF	R7	R12	R25	p value
Dry season					
Bulk density (g cm^{-3})	1.19 ± 0.03^a	1.26 ± 0.02^a	1.16 ± 0.02^a	1.16 ± 0.04^a	0.0755^{ns}
Water content (%)	14.4 ± 1.55^a	8.51 ± 0.85^a	9.86 ± 0.97^a	13.7 ± 2.69^a	0.0502^{ns}
Soil organic C (g kg^{-1} soil)	26.3 ± 3.13^b	7.10 ± 0.16^a	11.9 ± 0.43^a	10.9 ± 1.99^a	0.0001***
Total nitrogen (g kg^{-1} soil)	2.40 ± 0.27^b	0.77 ± 0.01^a	1.20 ± 0.04^a	1.01 ± 0.15^a	0.0001***
C/N ratio	10.9 ± 0.09^b	9.16 ± 0.15^c	9.94 ± 0.06^a	10.5 ± 0.36^{ab}	0.0001***
pH-H$_2$O	5.00 ± 0.17^{ab}	5.91 ± 0.17^c	4.71 ± 0.08^a	5.14 ± 0.10^b	0.0001***
Rainy season					
Bulk density (g cm^{-3})	0.95 ± 0.06^b	1.27 ± 0.03^a	1.18 ± 0.02^a	1.23 ± 0.04^a	0.0001***
Water content (%)	29.1 ± 3.95^c	11.0 ± 1.13^a	18.9 ± 2.14^{ab}	20.2 ± 3.64^b	0.0017**
Soil organic C (g kg^{-1} soil)	22.9 ± 3.31^b	7.50 ± 0.47^a	11.3 ± 1.41^a	11.2 ± 1.20^a	0.0001***
Total nitrogen (g kg^{-1} soil)	2.00 ± 0.29^b	0.72 ± 0.04^a	1.05 ± 0.11^a	0.96 ± 0.08^a	0.0001***
C/N ratio	11.5 ± 0.30^b	10.3 ± 0.18^a	10.5 ± 0.21^a	11.4 ± 0.27^b	0.0037**
pH-H$_2$O	4.48 ± 0.09^c	5.87 ± 0.14^a	4.67 ± 0.06^{bc}	4.81 ± 0.12^b	0.0001***

** $p < 0.01$, *** $p < 0.001$; means values followed by the same superscript lowercase letter within row are not significantly different at the 0.05 level (Tukey's multiple-comparison test)

The factorial analysis applied indicated that the bulk density and water content were significantly affected by the age of the plantations, the soil texture, and the season-soil texture interaction. The chemical parameters were significantly modified by the age of the plantations (Table 3). The water content and pH were significantly impacted, respectively, by the season and soil texture.

Table 3: Anova table of general linear mixed (GLM) effect models on LN(x+1)-transformed soil characteristics across the season, soil type, and age of plantations. F-values and the corresponding p-values are displayed.

		Bulk density	Water content	Organic carbon	Total nitrogen	pH
	df	F	F	F	F	F
Season	1	1.69	15.82***	0.01	1.34	2.31
Age	2	5.34**	6.08**	11.71***	10.50***	59.84***
Soil texture	3	8.66***	8.72***	2.49	1.79	36.72***
Season × Age	2	0.45	1.06	0.52	0.32	1.35
Season × Soil texture	3	7.27***	8.30***	0.26	0.12	0.27

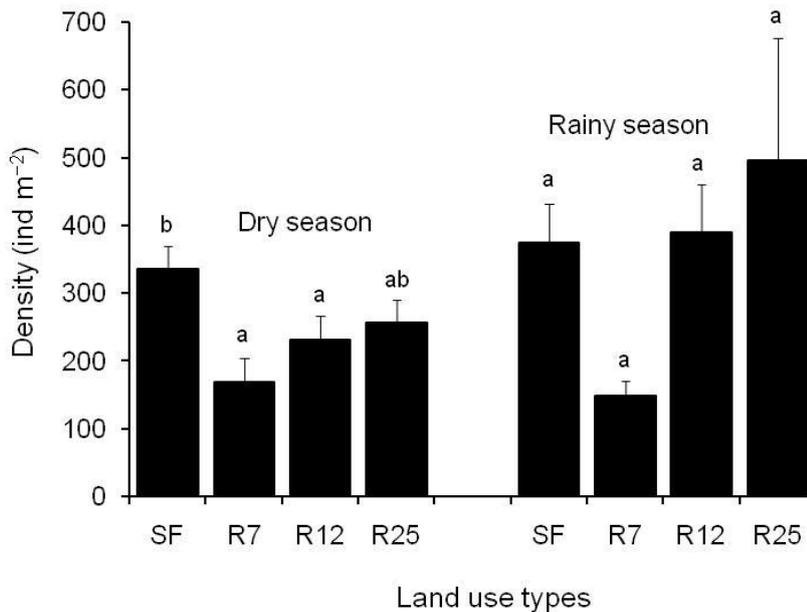** $p < 0.01$, *** $p < 0.001$

Abundance of macroinvertebrates

The mean densities of macroinvertebrates in litter did not vary significantly (Kruskal−Wallis test, $p = 0.369$) along the land use types. Nevertheless, these densities increased with the increasing age of rubber plantations. The abundance was higher (304 ± 55 individuals) in the 25-year-old rubber plantations and lower (99.33 ± 24 individuals) in the secondary forests. Except in dry season (Kruskal−Wallis test, $p = 0.017$), the mean densities of macroinvertebrates in the soil did not change significantly (Kruskal−Wallis test, $p = 0.124$) during the rainy season. Whatever the season, the mean densities increased with the aging of the rubber plantations (Figure 1). The highest densities were observed in secondary forests (335.56 ± 34.13 ind m⁻²) and in the 25-year-old rubber plantations (495.56 ± 180.34 ind m⁻²), respectively in dry and rainy season. During the dry season, the mean densities of macroinvertebrates in the soil decreased by −50 and −24%, respectively, in 7-, and 25-year-old rubber plantations compared to the secondary forests. In rainy season, the mean densities of macroinvertebrates in the soil decreased by −61% and increased by +32%, respectively, in 7-, and 25-year-old rubber plantations compared to the secondary forests.

Major taxa variation

Apart from the coleoptera and orthoptera, the abundance of epigeous ants and araneae was significantly modified across the land use types. The abundance of epigeous ants (131 ± 32.04 individuals) and araneae (70 ± 1.5 individuals) was higher in the 12-year-old rubber plantations whereas, the larger abundance of coleoptera (223 ± 50.23 individuals) and orthoptera (19 ± 6.9 individuals) was observed in 25-year-old rubber

plantations. The density of endogenous major taxa did not vary significantly through the land use types during the dry season (Table 4). The highest density of endogenous earthworms (126.2 ± 51 ind m^{-2}) and termites (73.8 ± 27.2 ind m^{-2}) was recorded in the 25-year-old rubber plantations, while the largest density of endogenous ants was observed in secondary forests (48 ± 24.3 ind m^{-2}). During the rainy season, only the density of endogenous earthworms differed significantly through the land use types. In the same season, the highest density of endogenous termites (204.9 ± 199.4 ind m^{-2}) and ants (33.8 ± 17.4 ind m^{-2}) was recorded in the 25-year-old rubber plantations whereas the largest density of endogenous earthworms (200 ± 40.2 ind m^{-2}) was observed in the 12-year-old rubber plantations.

Figure 1: Density (mean and SE) of soil macroinvertebrates across the land use types and the season. *SF* Secondary forest, *R7* 7-year-old rubber plantations, *R12* 12-year-old rubber plantations, *R25* 25-year-old rubber plantations. Soil depth: 0–10 cm, *N* = 72, Kruskal–Wallis test, *p* < 0.05. For each season, means followed by the same lowercase letter are not significantly different at the 0.05 level (post hoc multiple comparison, bilateral test)

Diversity of macroinvertebrates

Except for the cumulated taxonomic richness, the diversity parameters measured in litter did not vary significantly along the land use types. The taxonomic richness of epigeous macroinvertebrates ranged from 7 in 25-year-old rubber plantations to 9 in 7- and 12-year-old rubber plantations (Table 5). Apart from the Berger Parker index, the diversity parameters of endogenous macroinvertebrates differed significantly across the land use types. The taxonomic richness of endogenous macroinvertebrates varied from 12 in 25-year-old rubber plantations to 15 in 7-year-old rubber plantations (dry season) and from 11 in 7- and 12-year-old rubber plantations to 14 in secondary forests (rainy season). During the dry season, the taxonomic richness of endogenous macroinvertebrates increased by +7% and decreased by −14%, respectively, in 7-, and 25-year-old rubber plantations compared to the secondary forest. In rainy season, the taxonomic richness of endogenous macroinvertebrates decreased by −21 and −14%, respectively, in 7-, and 25-year-old rubber plantations compared to the secondary forests. The factorial analysis showed that the density and diversity of soil macroinvertebrates were significantly affected by the age of the plantations and soil texture except for the taxonomic richness (Table 6).

Diversity of trophical groups

17 taxa consisted of eight trophical groups (detritivorous and humivorous, saprophagous and omnivorous, detritivorous, saprophagous, omnivorous, phytophagous, carnivorous, and fungivorous) were observed during the study (Table 7). The detritivorous and humivorous taxa were largely represented in the soil (dry season: 64, 72, 83 and 58% vs. rainy season: 68, 85, 81 and 68%) whereas the saprophagous and omnivorous taxa were largely dominant in the litter (71, 64, 89 and 73%), respectively in 7-, 12- and 25-year-old rubber plantations and in secondary forests. The fungivorous taxa were absent in litter and weakly represented (1%) in the soil under the secondary forests and the 7-year-old rubber plantations.

Table 4: Abundance of epigeous (means values ± SE individuals per stand) and endogenous (means values ± SE individuals per square meter) major taxa estimated along the land use types.

Majors taxa	Land use types				p value
	SF	R7	R12	R25	
Rainy season-Litter					
Ants	44.7 ± 11.3	117.0 ± 40.4	131 ± 32.0	33.0 ± 3.5	0.026^*
Coleoptera	10.0 ± 0.6	21.0 ± 7.5	20.0 ± 10.4	223.0 ± 50.2	0.083^{ns}
Orthoptera	9.3 ± 2.0	14.0 ± 5.8	10.0 ± 2.3	19.0 ± 6.9	0.721^{ns}
Araneae	9.7 ± 1.8	38.0 ± 11.5	70 ± 1.5	10.0 ± 0.0	0.007^{**}
Dry season-Soil					
Earthworms	56.0 ± 12.5	24.9 ± 5.6	73.3 ± 17.9	126.2 ± 51.0	0.548^{ns}
Termites	50.7 ± 13.0	58.2 ± 28.7	65.8 ± 21.8	73.8 ± 27.2	0.390^{ns}
Ants	48.0 ± 24.3	16.0 ± 7.2	9.3 ± 2.1	13.8 ± 5.6	0.953^{ns}
Rainy season-Soil					
Earthworms	85.8 ± 15.6	40.0 ± 9.5	200.0 ± 40.2	176.4 ± 57.5	0.025^*
Termites	127.1 ± 55.8	34.2 ± 17.3	119.1 ± 54.6	204.9 ± 199.4	0.122^{ns}
Ants	19.1 ± 5.6	10.2 ± 4.1	16.0 ± 5.2	33.8 ± 17.4	0.746^{ns}

SF Secondary forest, *R7* 7-year-old rubber plantations, *R12* 12-year-old rubber plantations, *R25* 25-year-old rubber plantations. Soil depth: 0–10 cm, Litter (pitfall traps) N = 120, Soil (monoliths) N = 72, Kruskal–Wallis test, $p < 0.05$.

* $p < 0.05$, ** $p < 0.01$

Beta diversity

Whatever the season, the distances between land use types did not exceed 20%. However, at the monoliths scale (Table 8), the distances differed significantly across the land use types, except for the Euclidean distance during the dry and rainy season and the Sørensen distance in rainy season.

Relationship between the communities of macroinvertebrates and the soil characteristics

The soil physico-chemical parameters influenced differently the abundance of macroinvertebrates. In the dry season, the soil organic carbon ($r = 0.999$; $p = 0.013$) and total nitrogen ($r = 0.999$; $p = 0.026$) governed significantly the density of macroinvertebrates in the secondary forests. The bulk density impacted significantly the density of macroinvertebrates ($r = -0.699$; $p = 0.036$) in 7-25-year-old rubber plantations (Table 9). In the

Table 5: Diversity and means values ± SE of epigeous and endogenous macroinvertebrates across the land use types.

Diversity parameters	Land use types				p value
	SF	R7	R12	R25	
Rainy season-Litter					
Mean taxonomic richness	9.00 ± 0.00[a]	8.33 ± 0.88[a]	8.33 ± 0.88[a]	7.67 ± 0.33[a]	0.5700[ns]
Shannon-Wiener Index H'	1.58 ± 0.07[a]	1.32 ± 0.19[a]	1.15 ± 0.14[a]	0.98 ± 0.09[a]	0.0640[ns]
Sobs cumulated	8.00 ± 0.24[b]	9.00 ± 0.26[a]	9.00 ± 0.3[a]	7.00 ± 0.17[b]	0.0001[***]
Evenness J	0.72 ± 0.01[a]	0.63 ± 0.05[a]	0.55 ± 0.04[a]	0.48 ± 0.02[a]	0.1310[ns]
Dry season-Soil					
Mean taxonomic richness	10.11 ± 0.42[b]	7.33 ± 0.47[a]	8.00 ± 0.70[a]	6.55 ± 0.72[a]	0.0014[**]
Margalef diversity index	1.58 ± 0.08[b]	1.27 ± 0.09[ab]	1.30 ± 0.10[ab]	1.03 ± 0.14[a]	0.0001[***]
Shannon-Wiener Index H'	1.95 ± 0.04[c]	1.54 ± 0.10[a]	1.50 ± 0.13[a]	1.10 ± 0.18[b]	0.0001[***]
Sobs cumulated	14.00 ± 0.42[a]	15.00 ± 0.82[a]	14.00 ± 0.66[a]	12.00 ± 0.59[b]	0.0001[***]
Evenness J	0.84 ± 0.01[a]	0.78 ± 0.04[a]	0.72 ± 0.04[a]	0.56 ± 0.07[b]	0.0042[**]
Berger Parker index	0.30 ± 0.02[a]	0.43 ± 0.05[a]	0.48 ± 0.04[a]	0.65 ± 0.06[a]	0.0510[ns]
Rainy season-Soil					
Mean taxonomic richness	11.33 ± 0.44[b]	7.66 ± 0.66[a]	6.88 ± 0.75[a]	7.44 ± 0.37[a]	0.0001[***]
Margalef diversity index	1.77 ± 0.08[c]	1.34 ± 0.11[a]	0.99 ± 0.12[b]	1.12 ± 0.08[ab]	0.0145[*]
Shannon-Wiener Index H'	1.87 ± 0.10[c]	1.59 ± 0.10[ac]	1.02 ± 0.18[b]	1.15 ± 0.20[ab]	0.0016[***]
Sobs cumulated	14.00 ± 0.28[b]	11.00 ± 0.36[a]	11.00 ± 0.44[a]	12.00 ± 0.52[a]	0.0416[*]
Evenness J	0.77 ± 0.04[a]	0.79 ± 0.04[a]	0.56 ± 0.08[b]	0.57 ± 0.09[b]	0.0310[*]
Berger Parker index	0.40 ± 0.04[a]	0.42 ± 0.04[a]	0.63 ± 0.07[a]	0.60 ± 0.08[a]	0.1490[ns]

SF Secondary forest, *R7* 7-year-old rubber plantations, *R12* 12-year-old rubber plantations, *R25* 25-year-old rubber plantations. Soil depth: 0–10 cm, Litter (pitfall traps) $N = 120$, soil (monoliths) $N = 36$, one-way ANOVA test, $p < 0.05$.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; means values followed by the same superscript lowercase letter within row are not significantly different at the 0.05 level (Tukey's multiple-comparison test)

rainy season, the water content was significantly correlated to the density of macroinvertebrates in the 7-year-old rubber plantations ($r = 0.999$; $p = 0.010$) and in the 7-25-year-old rubber plantations ($r = 0.666$; $p = 0.049$). The taxonomic richness of macroinvertebrates was significantly ($r = -0.999$; $p = 0.001$) influenced by the soil water content in the 12-year-old rubber plantations. Whatever the season, the densities of major taxa (earthworms, termites, and ants) were significantly modified by the soil physico-chemical parameters.

Table 6: Anova table of general linear mixed (GLM) effect models on LN(x+1)-transformed macroinvertebrates parameters across the season, soil type, and age of the plantations. F-values and the corresponding *p*-values are displayed.

		Density	Taxonomic richness	Shannon index	Evenness	Berger Parker index
	df	F	F	F	F	F
Season	1	1.96	0.01	1.05	0.94	0.26
Age	2	7.04**	0.29	4.19*	5.18**	4.51*
Soil texture	3	4.48**	0.84	7.23***	10.62***	8.19***
Season × Age	2	0.95	1.43	1.84	1.12	1.15
Season × Soil texture	3	1.15	0.32	0.66	1.44	0.95

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Response of the abundance of soil macroinvertebrates to the establishment of rubber plantations

The response of the abundance of soil macroinvertebrates to the establishment of rubber plantations varied according to the taxa and the age of the plantations (Table 10). In general, the abundance of macroinvertebrates was negatively modified along the rubber chronosequence compared to the secondary forests. Nevertheless, this inhibition decreased following the aging of the rubber plantations (R7: V = −0.39 ± 0.14; R12: V = −0.42 ± 0.11; R25: V = −0.18 ± 0.14). The reverse trend was observed in 25-year-old rubber plantations, where the abundance of earthworms (R25: V = +0.35), termites (R25: V = +0.23), ants (R25: V = +0.28), chilopoda (R25: V = +0.08), and orthoptera (R25: V = +0.09) were positively changed compared to the secondary forests.

Soil degradation index

The analysis of soil degradation index following the depth-wise 0−10 cm indicated that the soil quality deteriorated (Cumulative DI = −190.5, −109.3, −76.4) respectively 7-, 12-, and 25-years after conversion of the secondary forests (Table 11). However, the degradation of soil quality decreased with the aging of the rubber plantations. Whatever the age of the plantations, the taxonomic richness, soil organic carbon, and the total nitrogen significantly deteriorated and negatively contributed to the cumulative DI.

Discussion

Abundance, taxonomic richness and structure of macroinvertebrates

Whatever the season and the studied layers (mineral soil or litter), the abundance and taxonomic richness of macroinvertebrates varied across the land use types. The endogenous macroinvertebrates were more abundant and diversified than those from litter. Indeed, in addition to endogenous macroinvertebrates, some organisms living in litter would spend part of their life cycle in the soil (Bachelier, 1978). The abundance of ecological niches in the soil limits the competition and predation, which is not the case with the macroinvertebrates living in litter. The increase in total abundance of macroinvertebrates with the increasing age of rubber plantations could be explained by the high availability of trophic resources due to an increase in

Table 7: Trophical groups and absolute abundances of macroinvertebrate communities through the land use types and the season

Taxa	Trophical groups	Rainy season-Litter				Dry season-Soil				Rainy season-Soil			
		SF	R7	R12	R25	SF	R7	R12	R25	SF	R7	R12	R25
Ants	Omnivorous	134	351	392	99	108	36	21	31	43	23	36	76
Arachnida	Carnivorous	29	114	209	30	59	27	22	22	48	13	22	31
Chilopoda	Carnivorous	0	2	5	2	44	30	39	26	40	20	41	47
Coleoptera	Saprophagous	30	78	60	669	23	11	18	8	29	17	18	20
Collembola	Fungivorous	0	0	0	0	2	1	0	0	0	0	0	0
Diplopoda	Detritivorous	1	12	3	5	107	46	34	22	56	59	23	43
Diplura	Carnivorous	2	0	0	0	34	3	19	7	25	0	13	4
Diptera	Saprophagous and Omnivorous	52	9	3	45	2	1	5	1	7	3	0	4
Earthworms	Detritivorous and Humivorous	0	0	0	0	126	56	165	284	193	90	450	397
Hemiptera	Phytophagous	7	0	0	0	1	0	4	1	0	3	0	1
Homoptera	Phytophagous	0	0	0	0	0	3	15	0	23	0	0	0
Isopoda	Detritivorous	2	5	9	0	90	12	26	6	39	1	3	6
Mollusca	Phytophagous	2	3	2	0	36	19	3	4	49	15	2	19
Orthoptera	Phytophagous	28	42	30	57	9	3	1	0	5	12	2	6
Pauropoda	Fungivorous	0	0	0	0	0	1	0	0	0	0	0	0
Protura	Fungivorous	0	0	0	0	0	0	0	0	1	0	0	0
Termites	Detritivorous	10	3	2	5	114	131	148	166	286	77	268	461

SF Secondary forest, *R7* 7-year-old rubber plantations, *R12* 12-year-old rubber plantations, *R25* 25-year-old rubber plantations. Each data represented the absolute abundance of each taxa observed in each selected treatment. Soil (monoliths) *N* = 72, litter (pitfall traps) *N* = 120.

litter biomass. The research made by Yéo (2017) on the same rubber plantations showed an increase of litterfall production with the increasing age of rubber plantations (7-year-old rubber plantations: 3.88 ± 0.14 t ha^{-1} yr^{-1}, 12-year-old rubber plantations: 3.86 ± 0.71 t ha^{-1} yr^{-1}, 25-year-old rubber plantations: 5.11 ± 0.60 t ha^{-1} yr^{-1}). The same trend was observed by Chaudhuri *et al.* (2013). The authors recorded an increase of litterfall production (3 years: 2.8 g m^{-2}, 10 years: 200–700 g m^{-2}, 14 years: 750–1400 g m^{-2}, 25 years: 800–1500 g m^{-2}), and a decreasing polyphenol (3 years: 90 µg mg^{-1}, 10 years: 300 µg mg^{-1}, 14 years: 30 µg mg^{-1}, 25 years: 45 µg mg^{-1} dry matter) and lignin (3 years: 1.4 g, 10 years: 2.7 g, 14 years: 0.6 g, 25 years: 1.2 g per 100 g dry matter) content in leaf litters with the increasing age of rubber plantations. The availability of nutrients and the improvement of the soil physical parameters with the increasing age of rubber plantations allowed the establishment of favorable edaphic microclimate to the development of soil organisms (Dash and Behera, 2013; N'Dri *et al.*, 2017a). However, this observation was contrary to the data collected in industrial plantations by Gilot *et al.* (1995), especially as the author recorded a decrease in the abundance of soil macroinvertebrates with the aging of rubber plantations.

The taxonomic richness of macroinvertebrates did not vary significantly with the increasing age of rubber plantations. In fact, the distances between land use types did not exceed 20%, confirming a strong resemblance between the taxonomic compositions. However, at the monoliths scale, the distances between land use types varied significantly across the rubber chronosequence. A similar case was observed by Gilot *et al.* (1995) where 15 to 17 taxa were recorded in 5-30-year-old rubber plantations. During the investigation made by Marichal *et al.* (2014), 18 taxa were observed on crops plots in Brazil while 14 to 15 taxa were collected on agroforestry plots in Colombia.

Eight trophical groups of macroinvertebrates were defined: detritivorous and humivorous, saprophagous and omnivorous, detritivorous, saprophagous, omnivorous, phytophagous, carnivorous, and fungivorous. The detritivorous and humivorous were the highest in the soil whereas saprophagous and omnivorous were dominant in litter.

Table 8: Variation of the distance across the land use types and the season

Land use types	Euclidean distance	Sørensen distance	Jaccard distance
Dry season			
Secondary forest	137.70 ± 18.30[a]	0.16 ± 0.02[b]	0.27 ± 0.03[b]
7-year-old rubber plantations	112.40 ± 23.70[a]	0.31 ± 0.03[a]	0.47 ± 0.04[a]
12-year-old rubber plantations	110.70 ± 16.20[a]	0.32 ± 0.04[a]	0.47 ± 0.05[a]
25-year-old rubber plantations	124.20 ± 22.10[a]	0.31 ± 0.05[a]	0.45 ± 0.06[a]
p value	0.7684[ns]	0.0444[*]	0.0273[*]
Rainy season			
Secondary forest	213.20 ± 57.70[a]	0.10 ± 0.01[a]	0.19 ± 0.01[b]
7-year-old rubber plantations	91.50 ± 17.30[a]	0.22 ± 0.03[a]	0.36 ± 0.03[ab]
12-year-old rubber plantations	205.40 ± 41.40[a]	0.31 ± 0.07[a]	0.44 ± 0.07[a]

	25-year-old rubber plantations	478.90 ± 246.20^{a}	0.25 ± 0.06^{a}	0.36 ± 0.08^{ab}
p value		0.2009^{ns}	0.0668^{ns}	0.0495^{*}

Soil depth: 0–10 cm, $N = 36$, one-way ANOVA test, $p < 0.05$.
* $p < 0.05$; means values followed by the same superscript lowercase letter within column are not significantly different at the 0.05 level (Tukey's multiple-comparison test)

Absent in litter, the fungivorous were weakly represented along the land use types, respectively, in forest soils (1%) and in 7-year-old rubber plantations (1%). Indeed, the nests of fungi in rubber plantations are often vectors of diseases such as fomes (Obouayeba *et al.*, 2006) and thus systematically eradicated by the farmers. Whatever the season, the density of termites increased with the aging of the rubber plantations. The same trend was observed with the density of ants and earthworms, respectively, during the rainy and the dry season. The positive effect of the increasing age of plantations on the abundance and species richness of ants has been demonstrated by Yéo *et al.* (2011) during investigations made in Oumé (Côte d'Ivoire). Likewise, a positive impact of the aging of the rubber plantations on the abundance and biomass of earthworms was confirmed by several researches performed in India (Nath and Chaudhuri, 2010; Chaudhuri *et al.*, 2013). The low abundance of earthworms and termites in soil from 7-year-old rubber plantations indicate that the young plantations are still at the first stages of their colonization by earthworms and termite's species which do not have special adaptation to habitats yet. In young rubber plantations, the extent of soil alteration caused by the previous cropping during the former rotation was hugely marked (Walker *et al.*, 2010; N'Dri *et al.*, 2017a). A long-term exposure of 7-year-old rubber plantations to sunlight increases soil drought and consequently limits litter decomposition processes and the availability of nutrients for soil organisms. The abundance of beetles or coleoptera in litter from 25-year-old rubber plantations might be explained by the high availability of organic matter due to an increase in litter biomass, and which is perceived as a trophic resource, especially young and tender leaves (Sabu and Vinod, 2009). Parallel to this group, the diplopoda are major consumers of fallen leaf litter, and may process some 15–25% of calcium input into hardwood forest floors (Coleman *et al.*, 2004). The increasing plant richness could positively affect the diversity of soil biota through increased probability of plants with different root morphological characteristics and chemical properties (Bardgett, 2005). These differences may result in a greater diversity of food resources and habitat heterogeneity, creating available niches supporting diverse biotic assemblages, which enhance both decomposition and nutrient mineralization (Martius *et al.*, 2004; Bardgett, 2005). This explanatory approach associated to the reduction of soil degradation index favors a better understanding of the high diversity of macroinvertebrates in secondary forests.

Table 9: Pearson correlation between the characteristics of macroinvertebrates and the soil physico-chemical parameters

	SF		R7		R12		R25		R7-R25	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Dry season										
Total density										
Bulk density	0.179	0.885	−0.763	0.447	−0.558	0.623	0.742	0.467	−0.699	0.036 *
Soil organic carbon	0.999	0.013 *	0.612	0.581	−0.542	0.635	−0.254	0.837	0.488	0.183

Total nitrogen	0.999	0.026 *	0.623	0.572	−0.550	0.629	−0.236	0.848	0.353	0.351
Majors taxa density										
Termites										
Bulk density	0.368	0.759	−0.775	0.436	−0.917	0.261	0.999	0.031 *	−0.480	0.190
Earthworms										
Bulk density	0.973	0.148	−0.177	0.887	−0.239	0.846	−0.631	0.565	−0.817	0.007 **
Water content	−0.959	0.184	−0.559	0.622	0.259	0.833	0.605	0.586	0.825	0.006 **
Soil organic carbon	−0.035	0.978	−0.991	0.085	−0.221	0.858	0.953	0.196	0.729	0.026 *
Ants										
Soil organic carbon	0.894	0.295	0.999	0.033 *	−0.487	0.676	−0.814	0.395	−0.337	0.375
Total nitrogen	0.904	0.281	0.999	0.024 *	−0.479	0.682	−0.824	0.384	−0.453	0.220
pH-H_2O	−0.928	0.242	0.999	0.026 *	−0.469	0.689	0.840	0.384	0.459	0.213
Rainy season										
Total density										
Water content	−0.546	0.631	0.999	0.010 *	−0.989	0.093	−0.438	0.712	0.666	0.049 *
pH-H_2O	−0.653	0.547	0.792	0.418	0.002	0.999	0.857	0.344	−0.715	0.030 *
Taxonomic richness										
Water content	0.081	0.949	0.952	0.198	−0.999	0.001 **	−0.960	0.180	−0.144	0.712
Majors taxa density										
Termites										
Bulk density	0.155	0.901	0.998	0.043 *	−0.533	0.643	0.971	0.153	−0.026	0.947
Water content	−0.257	0.835	−0.660	0.541	−0.999	0.008 **	−0.789	0.420	−0.153	0.694
Soil organic carbon	−0.415	0.728	0.977	0.137	−0.140	0.910	−0.999	0.009 **	−0.418	0.264
Total nitrogen	−0.411	0.730	−0.979	0.132	−0.134	0.915	−0.999	0.034 *	−0.365	0.334
Earthworms										
Bulk density	0.593	0.596	−0.490	0.674	−0.844	0.360	−0.866	0.334	−0.821	0.007 **
Water content	−0.506	0.662	−0.393	0.743	−0.898	0.290	0.995	0.066	0.859	0.003 **
Soil organic carbon	−0.355	0.769	−0.228	0.854	0.298	0.807	0.733	0.477	0.841	0.005 **

Total nitrogen	−0.358	0.767	0.235	0.849	0.304	0.803	0.758	0.452	0.840	0.005 [**]
pH-H$_2$O	−0.387	0.747	0.234	0.849	0.307	0.801	−0.777	0.433	−0.945	0.001 [***]

SF Secondary forest, *R7* 7-year-old rubber plantations, *R12* 12-year-old rubber plantations, *R25* 25-year-old rubber plantations, *R7-R25* 7-25-year-old rubber plantations. Land use type N = 9, rubber chronosequence N = 27, $p < 0.05$. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Soil ecological quality

The conversion of secondary forests into rubber plantations was followed by a degradation of the soil quality, as evidenced by the large negative values of the cumulative degradation index, which decreased with the increasing age of plantations. This option was successfully tested in Ghana by Dawoe *et al.* (2014) across a chronosequence of cocoa plantations converted from semi-deciduous forests. According to Tondoh *et al.* (2015), soil degradation resulted in plant diversity and species richness loss due to the disappearance of a huge number of native species and the significant decline in organic carbon and total nitrogen. Soil organisms play a key role in the ecosystem functioning (Hedde, 2006; Decaëns, 2010; Marichal *et al.*, 2014). However, their response to the impact of environmental factors varied, depending on each taxon (Hedde, 2006; Marichal *et al.*, 2014).

Table 10: Impact of rubber plantations on the abundance of soil macroinvertebrates

	Land use types		
Taxa	R7	R12	R25
Ants	−0.30	−0.09	+0.28
Araneae	−0.57	−0.37	−0.22
Chilopoda	−0.33	+0.01	+0.08
Coleoptera	−0.26	−0.23	−0.18
Diplopoda	+0.03	−0.42	−0.13
Diplura	−1.00	−0.32	−0.72
Diptera	−0.40	−1.00	−0.27
Earthworms	−0.36	+0.40	+0.35
Hemiptera	+1.00	+0.00	+1.00
Homoptera	−1.00	−1.00	−1.00
Isopoda	−0.95	−0.86	−0.73
Mollusca	−0.53	−0.92	−0.44
Orthoptera	+0.41	−0.43	+0.09
Protura	−1.00	−1.00	−1.00

Termites	−0.58	−0.03	+0.23
Mean index V	−0.39 ± 0.14	−0.42 ± 0.11	−0.18 ± 0.14

Index V ranges from −1 to +1 and is increasingly negative or positive as the group under consideration is increasingly decreased or increased in rubber plantations compared to secondary forest. *R7* 7-year-old rubber plantations, *R12* 12-year-old rubber plantations, *R25* 25-year-old rubber plantations.

The increasing of abundance of earthworms, termites, and ants in soil, after 25 years of plantation could be probably due to the improving soil quality, which was characterized by an increase of soil organic matter and water content (Yéo, 2017). In terrestrial ecosystems, the litter is the starting point of the nutrient cycle and often considered as a determining factor in the soil carbon storage (Martius *et al.*, 2004). The litter contributes to maintaining the productivity of the agrosystems (Tardif, 2013) by providing a source of energy for soil decomposers (Martius *et al.*, 2004). Therefore, its decomposition, based on 2 concomitant stages (fragmentation of litter by detritivorous and mineralization of fragments) is considered as the main key of ecological processes (Tardif, 2013). The microclimate was perceived as an important factor than biomass in the determination of litter decomposition rate and the activity of soil organisms (Kurzatkowsk *et al.*, 2004). However, the climate has a predominant effect on decomposition rates on a regional scale, whereas on a local scale, it is the quality of litter (physico-chemical properties of leaves) which plays a more important role (Aerts, 1997). The release of energy and nutrients stored in dead organic matter strongly depends on the proportion of support tissues rich in lignin and lignocelluloses, the proportion of secondary chemical compounds, such as tannins or polyphenols, and the ratio of nutrients to carbon (Bardgett, 2005). Annual litter mass decomposition observed in the same plantations was significantly different along the rubber chronosequence and represented $3.78 ± 0.11$ t ha^{-1} yr^{-1}, $2.73 ± 0.31$ t ha^{-1} yr^{-1}, and $4.21 ± 0.34$ t ha^{-1} yr^{-1}, respectively, in 7-, 12-, and 25-year-old rubber plantations (Yéo, 2017). The carbon stock would increase with the plantation age (Dawoe *et al.*, 2014; Tondoh *et al.*, 2015; Yéo, 2017), but it would be affected by the plant species (Bardgett, 2005; Yéo, 2017). The investigation made by Chaudhuri and Nath (2011) showed that the density of earthworms increased in the 15-25-year-old rubber plantations compared to mixed forests.

Table 11: Degradation indexes (%) for 0–10 cm soil layer along a chronosequence of rubber plantations at 7-, 12-, and 25-years of cultivation following conversion of secondary forests in the Grand-Lahou department of Côte d'Ivoire

	Land use types		
Parameters	R7	R12	R25
Density (ind m^{-2})	−60.5	+4.0	+32.3
Taxonomic richness	−32.4	−39.3	−34.3
Bulk density (g cm^{-3})	+33.7	+24.1	+28.6
Total nitrogen (g kg^{-1}soil)	−64.0	−47.5	−52.0
Soil organic carbon (g kg^{-1}soil)	−67.2	−50.7	−51.0
Cumulative DI	−190.5	−109.3	−76.4

The main reasons remained (i) the improvement of edaphic microclimate: temperature 27°C, water content 23%, pH = 4.57, organic matter 1.34%, a retention capacity 36% (Chaudhuri and Nath, 2011), (ii) the

proliferation of the exotic species, such as *Pontoscolex corethrurus* (Chaudhuri *et al.*, 2008), and (iii) the emergence of earthworm's species adapted to degraded lands (Tondoh *et al.*, 2015) with ecological roles of compacting and decompacting (Guéi *et al.*, 2012). According to Chaudhuri *et al.* (2009), the annual cast production by earthworms in rubber plantation (24 t ha^{-1}) was higher than those observed in the mixed forest (21.3 t ha^{-1}). The species *Pontoscolex corethrurus* would contribute effectively to the redistribution of labile organic carbon along soil profile and between the protected and unprotected areas by aggregates and affect long-term soil carbon cycling (Zhang *et al.*, 2010). Subsequently, the amount of carbon input (2.32 ± 0.18 t ha^{-1} yr^{-1}) and the amount of nitrogen input (0.10 ± 0.008 t ha^{-1} yr^{-1}) in the soil were more concentrated in 25-year-old rubber plantations as observed by Yéo (2017). The improvement of soil physico-chemical and biological parameters over time in rubber plantations confers to the old plantations a regenerative role of the soil quality.

Conclusion

The results showed that the conversion of secondary forests into rubber plantations was characterized by a modification of the density of soil macroinvertebrates (dry season: −50 and −24% vs. rainy season: −61 and +32%), taxonomic richness of soil macroinvertebrates (dry season: +7 and −14% vs. rainy season: −21 and −14%), water content (dry season: −41 and −5% vs. rainy season: −62 and −31%), bulk density (dry season: +6 and −3% vs. rainy season: +33 and +29%), soil organic carbon (dry season: −73 and −59% vs. rainy season: −67 and −51%) and total nitrogen (dry season: −68 and −58% vs. rainy season: −64 and −52%), respectively, after about 7 and 25 years of conversion. The restoration processes did not cause significant changes in the soil physico-chemical and biological characteristics after 25 years of forests conversion. However, this investigation highlighted the improvement in soil ecological quality due to a reduction in soil degradation with the increasing age of rubber plantations over time. This assertion is supported by an increase in the density of macroinvertebrates (+235%), taxonomic richness of macroinvertebrates (+9%), water content (+84%), soil organic carbon (+50%) and total nitrogen (+33%) in the 25-year-old rubber plantations compared to the 7-year-old rubber plantations.

Acknowledgements

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