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Annual changes in earthworm communities along a gradient of forest disturbance

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Abstract

Annual variation in both earthworm abundance and diversity was studied along a land-use gradient in West-Centre region of Côte d'Ivoire. The aim was to assess the impact of human activities on earthworm abundance and diversity, in order to design sustainable management strategies for agricultural land-use. We mainly checked for an increasing trend in earthworm communities, along a gradient of forest disturbance during the first sampling year (2016). For this reason, earthworm populations were sampled in the following year (2017) during the same period, using similar sampling procedure. Both earthworm density and biomass were 108.0±7.8 ind.m^{-2} and 21.6±2g.m^{-2}, respectively in 2016. These values were higher than those obtained in 2017, which were 65.4±7.6 ind.m^{-2} and 10.5±1.1g.m^{-2}, respectively. A similar trend was observed in earthworm diversity. Species richness varied from 5.2±0.2 in 2016 to 3.2±0.2 in 2017, the Shannon index from 1.8±0.0 to 1.2±0.1 and cumulative species from 11 to 12 species. The trend in 2016 was confirmed in 2017, with earthworm abundance and diversity increasing from primary forest to annual crop fields. The fallow systems showed higher abundance and diversity, whereas forest soils had lower values. Between-analyses revealed the prominence of land management impact over the temporal effect. The earthworm species, such as *Hyperiodrilus africanus*, was the most common in annual crop fields (52.3±12.6 ind.m^{-2} in 2016 *vs* 19.2±4.1 ind.m^{-2} in 2017), making this species a good indicator of disturbed ecosystems.

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Introduction

Several studies have shown considerable interest in the assessment of land-use effects on soil macrofauna, for almost two decades (Barros *et al.*, 2002; Decaëns *et al.*, 2003; N'Dri and N'Guessan, 2018). This increasing awareness started by the recognition that disturbance, as a result of agricultural intensification, had a great impact on the communities of belowground invertebrates and regulates ecosystem functioning (N'Dri and N'Guessan, 2018). Earthworms are a key component of the soil macrofauna, in term of biomass, and they play an important role in soil biogeochemical cycles, gas dynamic and soil structure (Blanchart *et al.*, 2004; Lavelle *et al.*, 2006; Cole *et al.*, 2008). This macro-invertebrate group may be used as a natural resource of agronomic interest for improving the productivity and sustainability of low-input agricultural systems (Lavelle *et al.*, 1998). Earthworms communities vary with time and this variation is strongly controled by environmental factors, such as temperature and soil water content (Lavelle and Spain, 2001). The annual variability needs to be considered in the assessment of land-use effects on soil macrofauna, as factors controlling their abundance and distribution may be subjected to the influence of rainfall and soil water content (Tondoh *et al.*, 2006), which are, in turn, sensitive to land-use systems (Golchin and Asgari, 2008).

In Côte d'Ivoire, very few investigations have considered, simultaneously both land-use and annual variation, as major sources of earthworm communities variation. Most studies have focused on a one-year base study, except for a recent investigation in India that showed the impact of seasonal variation on soil macrofauna abundance and diversity (Rossi and Blanchart, 2005).

In Côte d'Ivoire, the need to check the trend toward an increase in earthworm abundance and diversity from forest to food crop system lands, the most disturbed agrosystems (Tondoh *et al*, 2007), has brought about an investigation on the impact of land-use on earthworm communities during a two-year period. The objectives of this study were: (1) to assess the impact of human-induced forest disturbance on earthworm communities, over a two-year period, in a semi-deciduous forest in Ivory Coast, and (2) to determine factors controlling the annual variation in the communities of these macro-invertebrates. Furthermore, we checked the hypothesis that rainfall and soil water content are determining factors controlling earthworm community structure and abundance (Tondoh, 2006), regardless of land-use type. To achieve these goals, a between-classes Principal Component Analysis (PCA) (Dolédec and Chessel, 1989; 1991) was used to describe land-use effects upon earthworm communities and examine how land management affects their annual variability.

Materials and methods

Study site

The study was conducted in a semi-deciduous forest area in the Centre-West Region of Côte d'Ivoire (6°30'N latitude and 5°31'W longitude). Most of the area was cleared for agricultural activities and consisted of mosaics of 8 land-use systems distributed over a landscape of 400 ha: primary forest (41.8ha), secondary forest (111.2ha), multispecies plantations (84.4ha), 1994-teak plantations (27.9ha), 2000-teak plantations (36.1 ha), cocoa plantations (16.5), recurrent fallows (25.7ha) and mixed crop fields (20.5ha).

The climate is of a subequatorial type, with 4 seasons: a long dry season, from November to February; a long wet season, from March to June; a short dry season, from July to August and a short wet season, from September to October. Average rainfall, over 27 year period (1988-2015), ranged from 849 to 1764mm, whereas annual rainfalls, in 2016 and 2017, were about 1541 and 1471mm, respectively. Average monthly temperature was 26°C, from 1988 to 2015.

Soils are classified as moderately desaturated-ferrallitic (World Soil Reference, 2006), with differences related to topography. The organic layer is thin (20-30cm) and friable (resistance to penetration varied between 200 and 1,000 kPa). Soils chemical and organic parameters were measured in each sampling plot from a composite sample in July 2016.

Soils were acid in the top 20cm (pH water < 6.5). Organic matter and nutrient contents were low and they decreased rapidly from the upper soil layers (0-10cm) to 20cm depth (Table 1) (Assié *et al.*, 2008). These parameters did not vary significantly across land-use types, except for nitrogen (Kruskal-Wallis test, $p < 0.05$) in the upper soil layer. Its value was highest in forest soil, intermediate in 1994-teak and fallow, and lowest in mixed-crop fields, multispecies, 2000-teak and cocoa plantations.

Table 1. Chemical and organic matter characteristics of soils from different land-use types in Goulikao (oumé) (Assié *et al.*, 2008). PF primary forest, MSP multi-specific plantations, TP94 1994-teak plantations, TP00 2000-teak plantations, CP cocoa plantations, F fallows, MC mixed-crop fields. Standard errors in parentheses.

Soil chemical parameters	Soil depth (cm)	Land-use types						
		PF	MSP	TP94	TP00	CP	F	MC
pH water	0-10	6 (0.1)	6 (0.4)	6 (0.2)	5.8 (0.2)	5.7 (0.3)	5.8 (0.5)	5.2 (0.2)
	10-20	5.9 (0.2)	6 (0.4)	6.2 (0.3)	5.6 (0.2)	5.8 (0)	6.2 (0.3)	5 (0.1)
Organic C (%)	0-10	2.7 (0.5)	1.4 (0.2)	2.1 (0.4)	1.3 (0.5)	1.1 (0.5)	2.4 (0.3)	1.5 (0.7)
	10-20	1 (0.1)	0.7 (0.1)	0.5 (0.1)	0.7 (0.2)	0.9 (0.2)	0.8 (0.1)	0.7 (0.2)
Total N (%)	0-10	0.3 (0)	0.1 (0)	0.2 (0)	0.1 (0)	0.1 (0.1)	0.2 (0)	0.1 (0)
	10-20	0.1 (0)	0.1 (0)	0.1 (0)	0.1 (0)	0.1 (0)	0.1 (0)	0.1 (0)
Available P (ppm)	0-10	9.7 (1.2)	9 (3.5)	10 (3.5)	10.3 (8)	6 (3)	7.7 (7.2)	9.7 (7.7)
	10-20	5.3 (1.9)	9 (3.6)	9.3 (1.3)	4.3 (2.4)	9.7 (6.2)	8 (7)	8.3 (5.8)
CEC ($cmol_c.kg^{-1}$)	0-10	10.9 (1.6)	7.3 (0.6)	10.1 (2.7)	9.5 (1.3)	9.6 (1.6)	9.9 (1.9)	7.1 (1.8)
	10-20	7.7 (1.5)	5.4 (0.5)	4.8 (0.8)	6.5 (0.5)	8.5 (1.2)	10.1 (1.9)	8.3 (3.7)
Ca ($cmol_c.kg^{-1}$)	0-10	5.1 (1.3)	2.4 (0.6)	7.2 (4.5)	2.8 (1.2)	1.4 (0.1)	4.4 (1.8)	1.4 (0.4)
	10-20	2.4 (0.1)	1.7 (0.3)	3.2 (1.9)	1.3 (0.4)	10.5 (5.9)	3.9 (0.4)	4.9 (1.9)
Mg ($cmol_c.kg^{-1}$)	0-10	2.1 (0.3)	1.3 (0.2)	3.7 (2.6)	1.4 (0.5)	0.8 (0.2)	1.5 (0.6)	0.5 (0.1)
	10-20	1.1 (0.1)	0.9 (0)	1.1 (0.6)	0.7 (0.2)	1 (0.4)	1 (0.1)	1.2 (0.5)
K ($cmol_c.kg^{-1}$)	0-10	0.5 (0.2)	0.2 (0.1)	0.3 (0.1)	0.3 (0.2)	0.3 (0.2)	0.2 (0)	0.2 (0.1)
	10-20	0.2 (0)	0.1 (0)	0.3 (0.2)	0.2 (0.2)	0.4 (0.2)	0.2 (0)	0.3 (0.1)

Sampling points allocation

Sampling points, regularly distributed every 200m on the grid, were unequally distributed across the land-uses: 6 points were located in primary forest, 25 in secondary forest, 21 in multispecies plantations, 7 in 1994 and 2000-teak plantations, 8 in cocoa plantations, 11 in recurrent fallows and 9 in mixed-crop fields. Only 5 points were selected per land-use type for earthworm sampling, which was conducted during two different campaigns, i.e. July 2016 and August 2017, at the end of the small rainy season.

Land-use intensification

The land-use intensification index (LUI) calculated by Tondoh *et al.* (2007) was used as the index of forest disturbance. It was based on the agricultural intensification index calculated by Giller *et al.* (1997) and latter modified by Decaëns and Jiménez (2002).

Based on land-use intensification index (LUI), the eight land-use systems were ranked along land-use intensity gradients, going from the lowest to the highest. Primary forest (0) was considered as the system without intensification, while secondary forest (0.13) was the less managed ecosystem. Multispecies tree (0.26), cocoa (0.27), 1994-teak (0.28), 2000-teak (0.31) plantations and fallows (0.33) were considered as medium-intensification systems, whereas mixed-crop fields (0.38) were the most intensively managed systems.

Soil water content

The average soil water content in the top 20cm layer was estimated for each land-use type, using the Tropical Soil Biology and Fertility methods (Anderson and Ingram, 1993). The soil was sampled with a 5cm diameter metal cylinder, of constant volume, at each sampling point and the fresh weight (W1) was obtained. The sample was then dried at 105°C for 48 hrs and weighted again to get the dry weight (W2).

Earthworm sampling and identification

Earthworms were sampled from all plots in July 2016 and August 2017, using a modified method of the

Tropical Soil Biology and Fertility, consisting in the digging of soil monolith at 5m interval, along a transect (Anderson and Ingram, 1993). At each sampling point, a 20m long transect was delimited in such a way that the transect of 2017 was laid opposite direction from that of 2016.

At a distance of 10 m from the transect origin, 3 soil monoliths (50 x 50 x 20cm), spaced at 5m, were dug with a trench of 20 cm depth around. The earthworms species from each 10m layer of the monolith were then hand-sorted separately (Lavelle, 1978 ; Tondoh and Lavelle, 2005) and individuals were stored in a 4% formalin solution. They were then identified to species level, using the external morphology key of Lavelle (1978) and Csuzdi and Tondoh (2007).

Data analysis

The normality of distribution was first checked with the Shapiro–Wilk's test, before choosing the appropriate statistical test. The Mann–Whitney's test was used to compare earthworm abundance and species richness between the years 2016 and 2017, whereas the Student's test was used to analyse water content data, the Shannon index and cumulative species data. Land–use effects on the abundance and species richness were evaluated using the nonparametric test of Kruskal-Wallis.

The water content, the Shannon index and the cumulative species were run with the analysis of variance (ANOVA) with one factor. All statistical analyses were performed using the Statistica 7.0 software (Statsoft, Tulsa, USA).

The data were also analysed using a Principal Components Analysis (PCA). A general analysis was realised with the aim to extract the main pattern, consisting of a mixture of space–time effects, including interactions between these factors. A between-classes PCA was performed after the mixed analysis to examine between-classes multivariate variability, with the classes defined as land–use types or dates. The software ADE-4 (Thioulouse *et al.*, 1997) was used to perform these analyses.

Results

Changes in water content

Soil water content in 2016 (12.3%) was higher than in 2017 (11%), but this difference was not statistically significant. The water content variation was not significant across the land-use types in 2016.

In primary forest, the value was 14.7%, whereas it dropped to 13.5% in secondary forest. In multispecies, 1994-teak, 2000-teak, cocoa plantations and fallows, the values were 15.7, 11, 11.6, 11.1 and 12.4%, respectively.

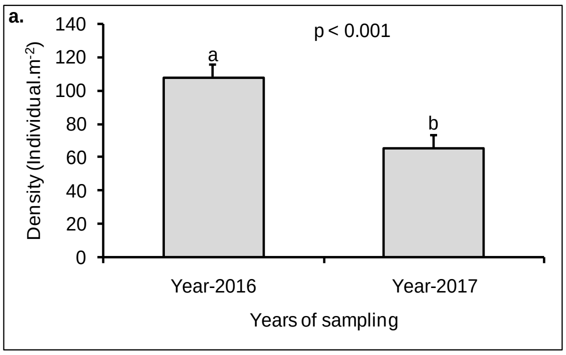
The mixed- crop fields (8.7%) had the lowest value. However, in 2017, water contents decreased significantly ($p < 0{,}001$) across the 8 land-use types. The highest values were recorded in the primary forest (15.7%), secondary forest (14%), multispecies (13.9%) and cocoa (15.1%) plantations, whereas fallows (5.5%) and mixed-crop fields (6.5%) exhibited the lowest water contents. The 1994-teak (9.3%) and 2000-teak (8.1%) plantations presented medium values.

Changes in earthworm communities

Abundance

The global abundance significantly decreased from 2016 to 2017 (Fig. 1a & b). Both earthworm density and biomass were 108.0±7.8 ind.m^{-2} and 21.6±2g.m^{-2} in 2016, respectively.

These values were significantly different from those observed in 2017, which were 65.4±7.6 ind.m^{-2} and 10.5±1.1g.m^{-2}. *Stuhlmannia zielae* (27.9-38.6%), *Dichogaster baeri* (25.5-24.6%), *D. terraenigrae* (7.3-10 %), *Millsonia omodeoi* (6.5-9.1%), and *Hyperiodrilus africanus* (9-5.3%) were prominent in terms of density during all the two years.



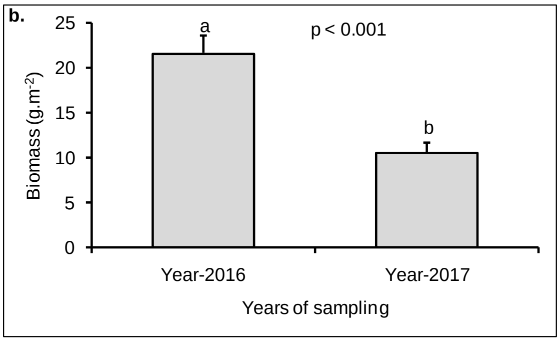


Fig. 1. Inter-annual variations in earthworm abundance: (a) Density and (b) Biomass. Values followed by different letters indicate a significant difference (Mann–Whitney's test).

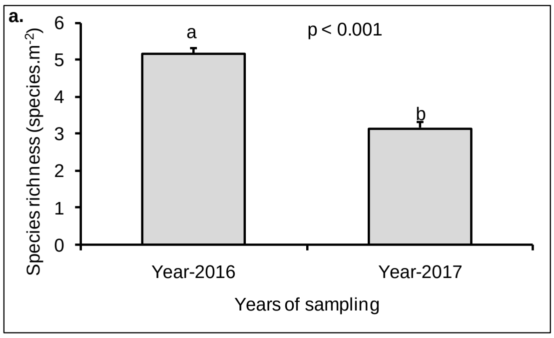
The responses of earthworms, in terms of abundance, to forest perturbations were similar in 2016 and 2017. Population density significantly increased by 81.2% ($p < 0.001$) from the primary forest to the mixed-crop fields in 2016 and 88.2% ($p < 0.001$) in 2017.

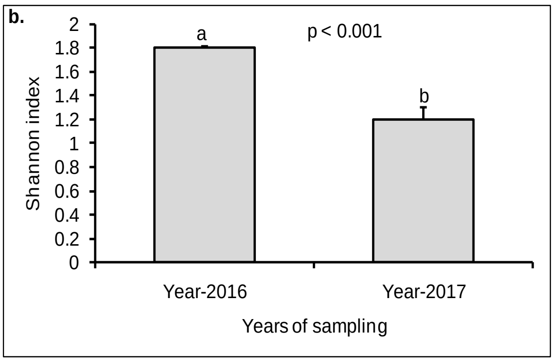
The populations of *H. africanus* were most prominent in the mixed-crop fields: 52.3±12.6 ind.m^{-2} and 19.2±4.1 ind.m^{-2}, in 2016 and 2017, respectively. The trend in *H. africanus* biomass was similar: 3.7±1g.m^{-2} and 1.1±0.5g.m^{-2} for the same periods respectively.

Diversity

Except for the cumulative species (11 species in 2016 and 12 species in 2017), which did not significantly change (Fig. 2c), the number of earthworm species and the Shannon index significantly decreased from 2016 to 2017.

Species richness varied from 5.2±0.2 species.m^{-2} to 3.2±0.2 species.m^{-2}, in 2016 and 2017, respectively (Fig. 2a) and the Shannon index changed from 1.8±0.0 to 1.2±0.1 (Fig. 2b).





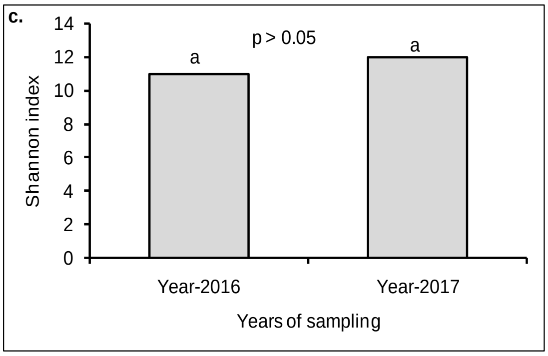
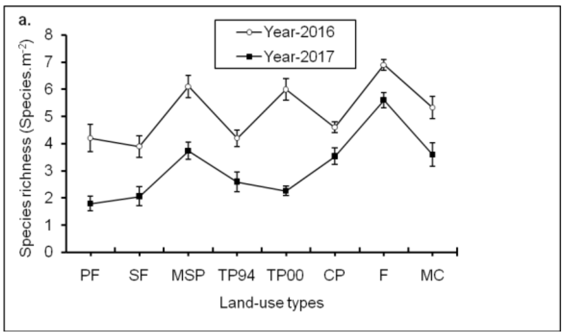


Fig. 2. Inter-annual variations in earthworm diversity: (a) Species richness, (b) Shannon index and (c) Cumulative species. Values followed by different letters indicate a significant difference (Mann–Whitney's test).

Earthworm diversity increased from natural ecosystems to the most disturbed ones in 2016. Species richness increased to 43.5% ($p < 0.01$) (Fig. 3a), the Shannon index increased to 27.3% ($p < 0.01$) (Fig. 3b) and cumulative species to 53% ($p < 0.001$). A similar trend was observed in 2017: 67.9% ($p < 0.001$) for species richness (Fig. 3a), 68.4% ($p < 0.001$) for the Shannon index (Fig. 3b) and 72.4% ($p < 0.001$) in cumulative species. The same pattern was observed each year, with the forest systems exhibiting lowest diversities, whereas multispecies plantations, mixed-crop fields and fallows presented the highest diversities.



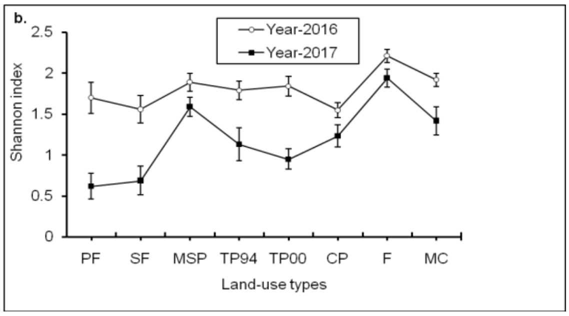


Fig. 3. Changes in earthworm (a) species richness and (b) Shannon index as a function of land-use types. PF primary forest, SF secondary forest, MSP multi-specific plantations, TP94 1994-teak plantations, TP00 2000-teak plantations, CP cocoa plantations, F fallows, MC mixed-crop fields.

General Principal Component Analysis

The distribution of the inertia indicated that axes 1 and 2 accounted for 52.2% and 13.5% of the total variance, respectively. Earthworm density, species richness, the Shannon index and cumulated species were negatively correlated to the first axis, whereas, only soil water content was negatively correlated to axis 2 (Fig. 4a). Sample ordination, along the first axis was mainly explained by a "size effect": it was likely that the first axis corresponds to land-use effect on earthworm communities. This effect was highly significant ($p < 0.0001$; Discriminant Analysis). Axis 2 separated objects as a function of dates. Date effect was significant ($p < 0.0001$; Discriminant Analysis) but was poorly separated by the general PCA (principal component analysis) (axis 2: 13.5%; Fig. 4b and 4c). The latter revealed that land management affected both earthworm density and diversity. Their communities were lower in both primary and secondary forest ecosystems, but higher in fallows, mixed-crop fields and multi-specific plantations. Date mainly affected the soil water content, which decreased from July 2016 to August 2017.

Between land-use Principal Component Analysis

The first two axes accounted for 91.5% of total inertia. The between land-use PCA correlation circle (Fig. 5a) was very similar to the general PCA. Correlations between the variables and the axes were particularly close to those obtained with the general PCA, which confirmed that the between land-use variability represented the main source of data variability. The ordination of land-use types, along axis 1, was highly significant ($p < 0.0001$; Monte Carlo test). Axis 1 (74%) separated land-use types as the pattern yielded by the general PCA (Fig. 5b). The dates were poorly separated by the between land-use PCA (axis 2:17, 9%).

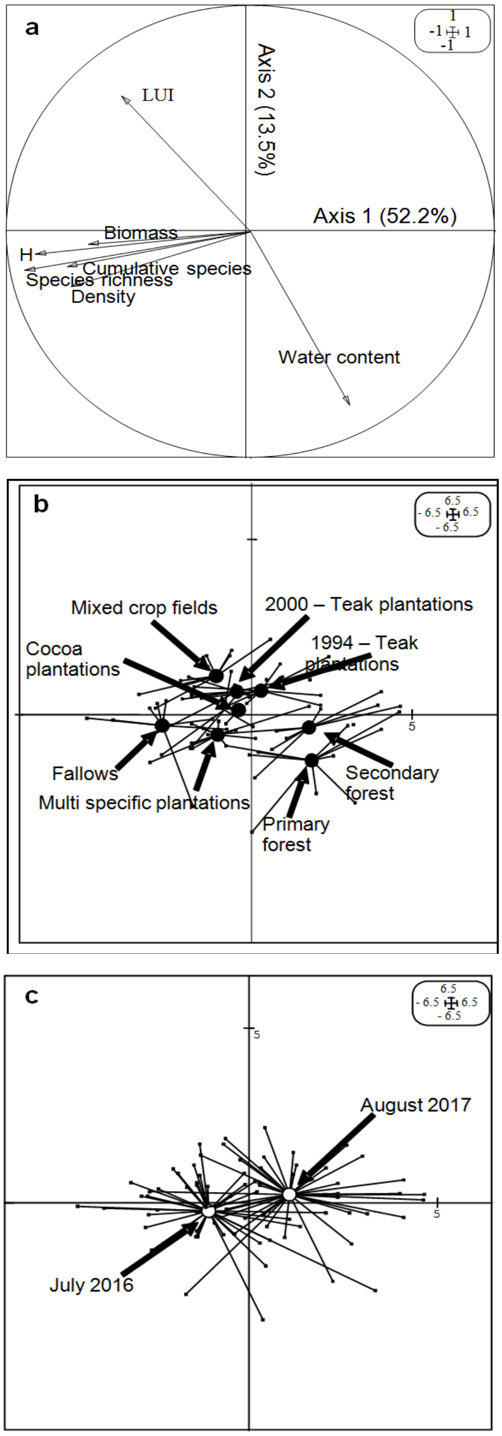


Fig. 4. General PCA on earthworm communities and abiotic parameters: (a) correlation circle, (b) variability of score among land-use types and (c) variability of score among dates.

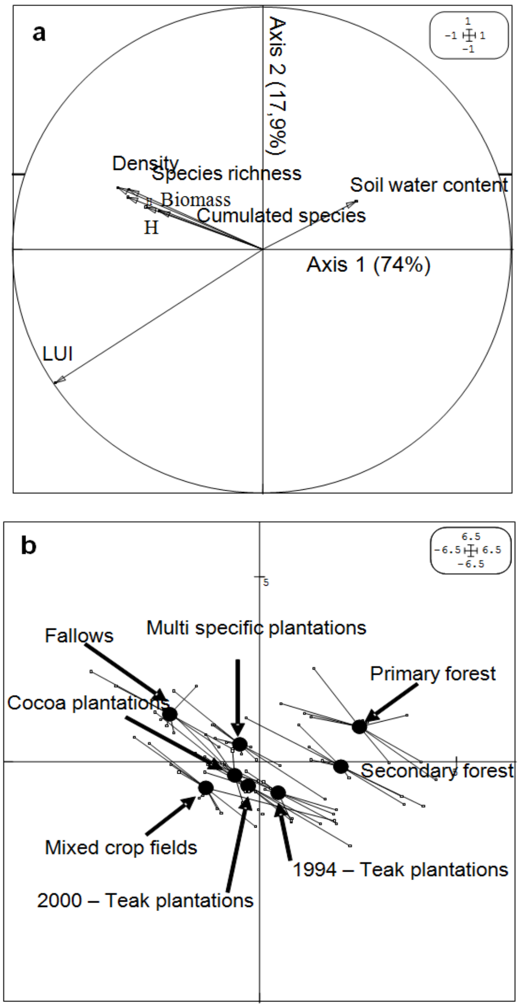


Fig. 5. Between land-use PCA on earthworm communities and abiotic parameters: (a) correlation circle and (b) variability of score among land-use types.

Between dates Principal Component Analysis

The effect of dates was highly significant ($p < 0.0001$) at the 5% confidence level. The distribution of the inertia indicated that all informations were revealed by axis 1. The between dates PCA represented 16.3%, whereas, the between land-use PCA revealed 39.5% of total inertia (Table 2).

Table 2. Total inertia of the PCA composing the between land-use and dates analysis in Goulikao (Oumé)

General PCA	Total inertia	Inertia ratio (%)*
	8	
Between land-use PCA	3.16	39.5
Between dates PCA	1.305	16.3

* Indicates the proportion of the variability that is explained by the between classes effect.

Discussion

Earthworm communities annual changes

Earthworm communities increased each year from natural ecosystems to the most intensively managed systems. These results contrasted, with previous works, which reported that both earthworm population and diversity were negatively affected when natural ecosystems were substituted for more disturbed agroecosystems (Curry *et al.*, 2002 ; Decaëns *et al.*, 2003 ; Dlamini and Haynes, 2004; N'Dri and N'Guessan; 2018). The increase in earthworm abundance was largely attributed to the growth of *Millsonia omodeoi*, *Dichogaster terraenigrae* and *Dichogaster saliens* individuals in disturbed systems (Tondoh *et al.*, 2007) and probably to the availability of soil organic matter sources suitable for reproduction. Gillot-Villenave (1994) observed that *M. omodeoi* had the best growing abilities in soil from agrosystems, as compared with forest soils. This was due to the efficiency of micro-organisms in transforming organic matter into assimilable fractions.

Hyperiodrilus africanus was the most common earthworm in annual cropping systems (degraded ecosystem), as supported by previous studies (Tondoh *et al.*, 2007; Guéi and Tondoh, 2012). The colonization abilities of *H. africanus* in degraded ecosystem may be related to its very good aptitude to withstand soil disturbance and scarcity of organic matter and to colonize opened areas by a exhibiting a high reproductive capacity and ability to recover population after the drought (Tondoh and Lavelle, 2005). Marichal *et al.* (2010) found the same behaviour for the pantropical species *Pontoscolex corethrurus* (Glossocolecidae) which populations replaced native earthworms after forest conversion to pastures.

The land-use types can be distributed into 3 groups, according to earthworm diversity: the first group was concerned with primary and secondary forests, which were characterised by low diversities; teaks and cocoa plantations constituted the second group (medium diversities) and the third group, with high earthworm diversities, was represented by multispecies plantations, mixed-crop and fallow fields.

The low diversity of earthworms in primary and secondary forests can be explained by the poor quality of litter (rich in lignin). As litter is the main source of food for earthworms, its quality could be a factor in the abundance of species. The high level of diversity in the fallow system can be explained by the intermediate disturbance hypothesis (IDH), which is diversity peaks at intermediate rate of disturbance (Huston, 1994; Roxburgh *et al.*, 2004). The fallow system favoured the reconstitution of earthworm communities, because of medium agricultural intensification and spatial variability in resources. So, in this ecosystem, the best competitor and disperser species could coexist indefinitely.

Factors drive earthworm communities changes

Earthworm global abundance and diversity decreased significantly from 2016 to 2017. The annual decrease was linked to a change in soil water content, as showed by the general PCA. Water is considered to be an important parameter in litter decomposition (Priming effects). It facilitates the production of enzymes involved in organic matter mineralization (Lavelle *et al.*, 1994; Sanabria *et al.*, 2016). Thus, low humidity leads to a drop in earthworm food resources, which, in turn, could result in a decrease in abundance and diversity. Several studies (Lavelle, 1979; Holmstrup, 2001; Tondoh, 2006) showed that earthworm populations increased because of growth of individuals when soil water potential was high. Results obtained with the general PCA showed that earthworm density and diversity changes were mainly driven by land-use effect, whereas soil water content appears to be greatly affected by date (Fig. 4). Land-use impact (39.5% of total inertia) was twice more important than the temporal effect (16.3% of total inertia) (Table 2). This result was supported by Rossi and Blanchart (2005), who reported that land management and temporal variability induced significant changes in soil macrofauna, but land-use impact prevailed upon temporal variability.

Conclusion

Earthworm density, biomass and diversity decreased significantly from 2016 to 2017. Interannual variation of the earthworm population along the land use gradient could be attributed to changes in soil water content. This study also showed an increase in the abundance and diversity of earthworms in the forest environment disturbed by human activities. In addition, the present study showed that the earthworm communities can be used as a bioindicator of tropical forest disturbance. The earthworm species, such as *H. africanus*, was the most common in annual crop fields, making this species a good indicator of disturbed ecosystems.

Acknowledgements

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