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ORIGINAL PAPER

Can earthworms be used as bio-indicators of land-use perturbations in semi-deciduous forest?

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Abstract The potential of tropical earthworms as bio-indicators of forest degradation by human-induced activities was assessed at a landscape level in the Ivory Coast. The study site covered 400 ha and was characterized by a set of land-use types along a gradient of perturbation from semi-deciduous forest, through reforestation, fallow systems to cultivated annual crops. Samples were taken on a grid at each sampling point and earthworms were hand-sorted from a 25×25×30-cm soil monolith. Results showed a potential increase in relative populations (number: +53.1%, biomass: +94.8%) of species in the earthworm communities following forest conversion. Furthermore, the impact of land-use change was higher in relation to land-use intensification in terms of earthworm populations and diversity in intermediate-disturbed systems (Multispecies plantations, old fallows). Earthworm diversity was the most sensitive response to land-use change. The species *Dichogaster saliens* Beddard 1893, *Hyperiodrilus africanus* Beddard 1891, *Millsonia omodeoi* Sims 1986, *Dichogaster baeri* Sciacchitano 1952, *Dichogaster ehrhardti* Michaelsen 1898, *Agastrodrilus* sp., *Stuhlmannia palustris* Omodeo and Vaillaud 1967 and, to some extent, *Millsonia* sp. appeared to be most sensitive to land-use change. More field and laboratory investigations are needed to find out the most efficient species to be used in bio-monitoring programmes aimed at preventing ecosystem degradation due to anthropogenic activities in the forest areas of Ivory Coast.

Keywords Tropical earthworms · Land-use intensification · Bio-indicators · Landscape

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Introduction

The continued loss of biological diversity in terrestrial ecosystems is alarming despite initiatives at the international level through the Rio-Convention on biodiversity to overcome this permanent threat. Even more disturbing is the neglect of soil organismal biodiversity, which deserves more protection because it is a major component of biodiversity in any ecological system (Hagvar 1998). This situation would benefit from the identification of bio-indicators of human activities because there is a need to assess the state of ecosystem health before systems are compromised functionally.

Earthworms comprise 40–90% of the soil macrofaunal biomass in most ecosystems, except under intensively cultivated annual crops (Fragoso et al. 1999) and are sensitive to ecosystem perturbations (Decaëns and Jiménez 2002; Fragoso et al. 1997, 1999) and rehabilitation (Hole et al. 2005; Ortiz-Ceballos and Fragoso 2004; Schmidt et al. 2003; Sepp et al. 2005). From these studies, it was concluded that earthworms can be used as potential indicators of changes in terrestrial ecosystems in a context of increasing land degradation and pollution.

Palearctic earthworms are suitable indicators of the effects of human activities because of their limited mobility and relative ease of sampling and identification (Paoletti 1999). Except for an interesting study by Fragoso et al.

(1999) on factors that influence earthworm communities at regional and global scales, few investigations have focused on tropical earthworms as soil bio-indicators.

This study deals with the response of earthworm populations to land-use change along a gradient of land-use systems in the semi-deciduous forest areas of Centre-West Ivory Coast at landscape scale. The potential of earthworms as bio-indicators of forest disturbance was also examined.

Materials and methods

Study site

The study was in the Oumé Region (6°37′N, 4°40′W) located in Centre-West Ivory Coast characterized by semi-deciduous degraded forests (Chatelain et al. 2003). Altitude ranged from 100 to 180 m above sea level, and the average rainfall over 27 years (1976–2003) ranged from 849 to 1764 mm. The annual rainfall in 2004 was about 1541 mm, whereas the average monthly temperature was about 26°C. The study area, which is a landscape mosaic of land-use types covering 400 ha, comprised 11 main land-use types, with specific vegetation structure along a gradient of land degradation from natural forest to crop-based systems: primary forest (41.8 ha), secondary forest (111.2 ha), multispecies plantations (84.4 ha), 20-year-old teak (22.7 ha), 10-year-old teak (27.9 ha), 4-year-old teak (36.1 ha) plantations, cocoa plantations (16.5 ha), coffee plantations (0.9 ha), old fallows (12.4 ha), recurrent fallows (25.7 ha) and mixed crop fields (20.5 ha).

The soils of the area are ferrasols (FAO-Unesco 1989) of homogeneous distribution across the landscape, with, however, differences related to topography (Angui, unpublished data). The surface organic layer is thin (20–30 cm) and friable (resistance to penetration varies between 200 and 1,000 kPa) and well mineralized. Water pH values ranged from 5.7 to 5.0 under primary forest and mixed crop fields, respectively. Soil cation exchange capacity varied significantly along the gradient of land-use intensification: 15.4 and 11.5 cmol kg^{-1} under primary forest and mixed crops, respectively.

Sampling points

Using satellite imageries, 100 sampling points were allocated in a 400-ha area using a regular grid. The points were distributed at 200-m intervals. From the 100 points obtained, 7 more were added specifically to land-use types when the number of replicates was below 5: cocoa plantation and mixed crop fields. The points were spaced within the grid at 100-m distances from the existing sample points, making a total of 107 sampling points. The geographic coordinates of these sampling points were determined using a Global Positioning System (GPS). Each sampling point was marked by a central post. There was an unequal number of sampling points across the land-use types: primary forest (6), secondary forest (25), multispecies plantations (21), 20-year-old teak (8), 10-year old teak (7), 4-year-old teak (7) plantations, cocoa (8), coffee plantation (0), old fallows (5), recurrent fallows (11) and mixed crop fields (9).

The primary forest is a semi-deciduous type characteristic of the humid zone. The multispecies plantations are part of the reforested areas of the SODEFOR (State Forest Agency). The vegetation is composed mainly of native (*Terminalia ivoriensis*, *Terminalia superba*, *Gmelina arborea*) and the exotic (*Tectona grandis*) plant species. The 20-year-old teak plantations were established in 1984. The fallows were 20-year-old and represented the unused burned and logged areas. In contrast, the younger 2- to 5-year-old fallows were used frequently for crop production. The mixed crop fields were a mixture of annual and perennial food crops: cassava, yam, plantain, maize and vegetables.

Land-use intensification

The combination of cultural practices and agro-ecological observations at each sampling point allowed calculating land-use intensification index (LUI). This index modified from that of Decäens and Jiménez (2002) integrates a set of patterns of land managements:

$$LUI = \frac{D + F + I + P}{N}$$

where D is length (year) of land utilization, F is fire use in land preparation, I is inorganic fertilizer option, P is pesticide use option and N is number of factors or subindex used for the calculation of the LUI.

Except for D, each subindex is a binary function: it assumes a value of 1 when the event happened and 0 when the option was not used. The respective values of factors were divided by the corresponding higher value (D). The minimum value thus corresponds to unmanaged systems, whereas the maximum value corresponds to the more intensively used systems.

Earthworm sampling protocol

Earthworms were sampled based on the Tropical Soil Biology and Fertility methods (Anderson and Ingam 1993). At each sampling point, a soil monolith with 25-cm side and 30-cm depth was extracted after digging a trench 30 cm deep. The monolith was sampled at three depths (0–10, 10–20 and 20–30 cm); earthworms were hand sorted and stored in 4% formaldehyde for later taxonomic identifications. A total of 107 soil monoliths were sampled from the landscape unit.

Data analysis

The diversity of earthworms at each sampling point (α diversity) was estimated using three expressions of species richness: (1) the average α diversity, expressed as the mean number of species per land-use type; (2) the Shannon–Wiener index of diversity (Pielou 1966) and (3) the cumulative α diversity defined as the total number of species recorded per land-use type.

The turnover of earthworm species between two land-use types or β diversity was estimated using the complementarity index of Colwell and Coddington (1994):

$$C = \frac{Species\ exclusive\ to\ one\ land-use\ type}{Combined\ richness} \times 100$$

C has a minimum value of 0 when the two habitats are identical and a maximum value of 100 when the habitats are completely different.

The γ diversity of earthworms was estimated at landscape scale through earthworm species accumulation curves across the 107 soil monoliths independent of land-use types.

A principal component analysis (PCA) was done to analyse the effects of land-use type on the earthworm communities, as well as the relationships between earthworm communities and land-use intensification. These analyses used the module ‘PCA’ of the software ADE-4 (Thioulouse et al. 1997). The EstimateS 6.0b1 software (Colwell 2000) was used to estimate the average species accumulation from 500 randomly ordered sequence of monoliths. The estimate number corresponds to species observed in the pooled samples (Colwell and Coddington 1994).

Results

Land-use intensification index

The land-use intensification index (LUI) reflects the recurrence of human intervention in a given system. The values of LUI ranged from 0 to 0.4 across the landscape unit, which indicated a gradient from the primary forest (0) to the mixed crop fields (0.4) through the secondary forest (0.1) and multispecies, teak, cocoa and plantations. The value of LUI was 0.3 under fallow fields. Tree-based systems and fallows were considered to be medium-intensification systems, whereas mixed crop fields were the most intensively managed systems (0.4).

Effect of land management on earthworm populations

Thirteen earthworm species were recorded across the landscape unit. Four belong to the Eudrilidea family: *Hyperiodrilus africanus* Beddard 1891, *Scolecillus compositus* Omodeo 1958, *Stuhlmannia palustris* Omodeo and Vaillaud 1967 and *Stuhlmannia zielae* Omodeo 1963. The remaining species (*Millsonia omodeoi* Sims 1986, *Millsonia lamtoiana* Omodeo and Vaillaud 1967, *Millsonia* sp., *Dichogaster baeri* Sciacchitano 1952, *Dichogaster ehrhardti* Michaelsen 1898, *Dichogaster saliens* Beddard 1893, *Dichogaster* sp. 1, *Dichogaster* sp. 2 and *Agastrodrilus* sp.) belong to the Acanthodrilidae family.

Overall, except for the 10-year-old teak plantations (number of individuals) and the 10-year-old teak plantations/cocoa plantations in terms of biomass, the derived forest systems were characterized by larger values in earthworm populations (Fig. 1). Total numbers of earthworm varied between 66.7±23.9 (primary forest) and 272.0±51.3 ind m^{-2} (old fallows) and mean earthworm biomass between 3.4±1.5 and 142.6±49.8 g m^{-2}, respectively. Earthworm communities comprised five main species as far as proportional density across the sampling grid is concerned: *M. omodeoi*

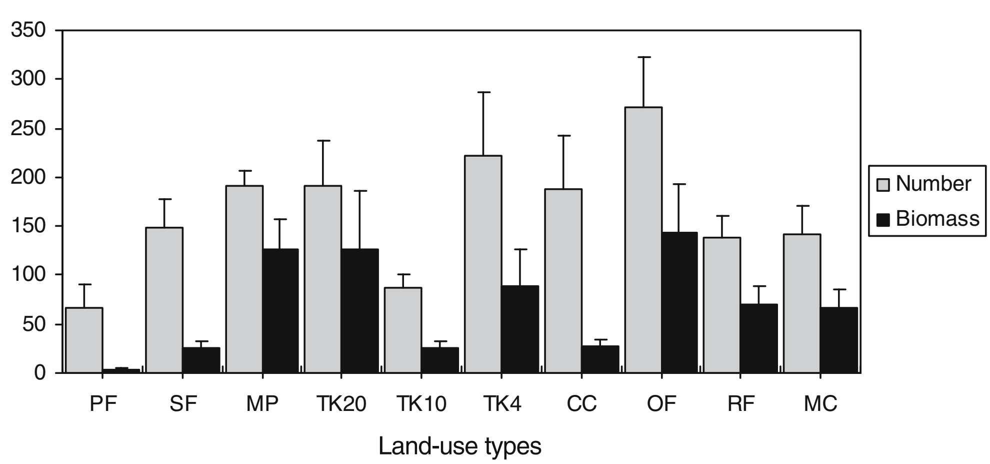

Fig. 1 Number (ind m^{-2}±SE) and biomass (g±SE) of earthworm populations along the gradient of land-use intensification. *PF* primary forest, *SF* secondary forest, *MP* multispecies plantations, *TK20* 20-year-old teak plantations, *TK10* 10-year-old teak plantations, *TK4* 4-year-old teak plantations, *CC* cocoa plantations, *OF* old fallows, *RF* recurrent fallows, *MC* mixed crop fields

(1.6–44.7%), *Millsonia* sp. (6.4–34.4%), *D. baeri* (2.1–48%), *H. africanus* (0.4–27.5%) and *S. zielae* (1.9–46.8%). In terms of biomass, *M. omodeoi* (1.7–75.5%), *M. lamtoiana* (4.8–34.6%), *Millsonia* sp. (20.9–71.2%) and *D. baeri* (0.1–89.7%) were the dominant species. In the primary forest, *D. baeri* was dominant in terms of numbers (89%) and biomass (48%), whereas in the secondary forest, with a biomass of 65.8%, populations of *M. omodeoi* were the most prominent.

Patterns of earthworm assemblages across the landscape

A PCA on correlation matrix was done on the data consisting of 13 variables (i.e. earthworm species) and 10 objects (i.e. land-use types). The correlation circle (Fig. 2a) showed an assemblage pattern of earthworm species within the landscape with the first two axes accounting for 70% of the total inertia. The first axis (55.2%) indicated clear differences in species composition since the variables were either positively or negatively correlated (Fig. 2a). Accordingly, three main groups emerged: the group of *D. saliens*, *H. africanus*, *M. omodeoi*, *D. baeri*, *D. ehrhardti*, *Agastrodrilus* sp. and *S. palustris*, with a high negative correlation; a second group consisting exclusively of *Millsonia* sp. with a medium negative correlation, whereas the third group comprising the remaining species was correlated negatively with the first axis. All the earthworm species except *D. saliens* and *H. africanus* were correlated positively to the second axis (14.8%). Land-use types were separated on the basis of species density.

The ordination of land-use types across the landscape revealed the effects of two main land-use factors (Fig. 2b). Along the first axis, the recurrent fallows were contrasted with other land-uses, indicating that ‘the effect of land-use’ consisted of changes in earthworm community structures. The second factor dealt with the disturbance state of the forest since axis 2 separated intermediate-disturbed habitats from undisturbed, low and highly disturbed systems. Forest perturbation affected mostly the density of species like *M. lamtoiana*, *Dichogaster* sp., *Millsonia* sp. and *S. compositus*.

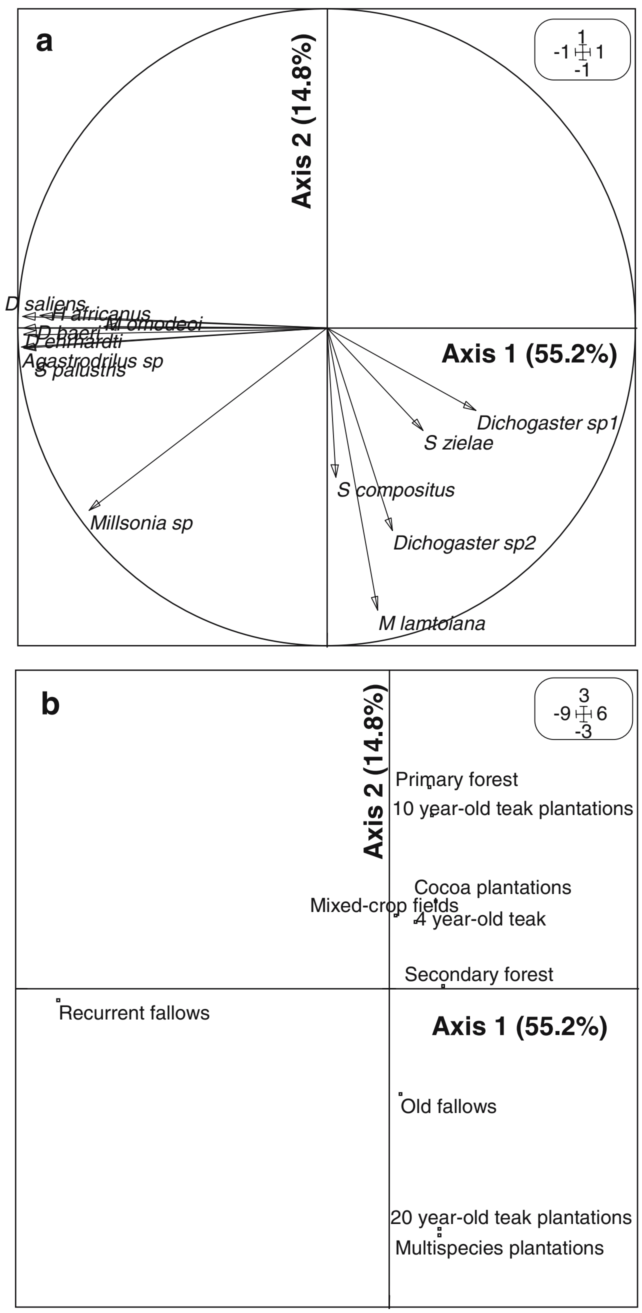

Fig. 2 **a** Correlation circle of the PCA showing the general pattern of distribution in earthworm species across land-use types. **b** Projection of land-use types on the factorial planes 1–2

Diversity of earthworm communities

The average number of species per square meter varied sharply from 2.2±0.5 (Primary forest) to 4.5±0.2 (Multispecies plantations) (Table 1). The same pattern was true with the Shannon index, which was in the range between 0.8±0.3 for primary forest and 1.9±0.1 for multispecies plantations.

Cumulative α diversity varied from 7 species (Primary forest, 4- and 10-year-old teak plantations) to 13 species in multispecies plantations (Table 1). Recurrent fallows, secondary forest and 20-year-old teak plantations had similar species richness (11–12) with multispecies plantations. Cocoa plantations, old fallows and mixed crop fields were included within the class of intermediate-earthworm diversity systems with 8 and 9 species.

The values of β diversity were generally low and varied from 4% to 41.2% (Table 2). The turnover of earthworm species between the secondary forest and the multispecies plantations was 4%, whereas cocoa plantations and mixed

Table 1 Diversity parameters of earthworm populations across the land-use types

	H (mean±SE)	S (mean±SE)	S_{cum} (mean±SE)
Primary forest	0.8±0.3	2.2±0.5	7±2
Secondary forest	1.4±0.1	3.5±0.3	12±1.5
Multispecies plantations	1.9±0.1	4.5±0.2	13±0.7
20-year-old teak plantations	1.3±0.3	3.4±0.6	11±2.1
10-year-old teak plantations	1.0±0.3	2.6±0.5	7±1.8
4-year-old teak plantations	1.4±0.3	3.3±0.6	7±1.9
Cocoa plantations	1.4±0.5	3.4±1.2	8±1.8
Old fallows	1.6±0.3	4.4±0.8	9±1.9
Recurrent fallows	1.7±0.1	4.0±0.3	12±1.8
Mixed crop fields	1.2±0.3	3.2±0.6	9±1.8

H=Shannon–Wiever index, S=average number of earthworm species m^{-2}, S_{cum}=cumulative number of earthworm species richness

crop fields displayed the highest turnover rate (41.2%) of species.

The estimated number of earthworm species in the whole landscape was 13 for a cumulative number of 1,093 individuals. The number of species was similar to the highest cumulative α species richness (13 species) found under multispecies plantations.

Relationships between earthworm communities and forest perturbation

When making a PCA on 7 variables (i.e. community parameters and disturbance index) and 10 objects (i.e. land-use types), the corresponding correlation circle (Fig. 3a) showed that all the variables were correlated negatively with the first axis (65.7%). This pattern explains the 'magnitude effect' of the measured parameters. Along the second axis (17.8%), the variables were either positively (earthworm species accumulated richness) or negatively (earthworm populations and LUI) correlated. As a result, they can be classified into three groups: (1) earthworm species richness accumulation, (2) earthworm species richness and diversity and (3) earthworm populations and LUI. The first two axes accounted for 84.5% of the total inertia.

The distribution of land-use types along the first axis revealed the existence of three main groups (Fig. 3b): the first group comprised the primary forest and the 10-year-old

Table 2 Index of complementarity between pairs of land-use types

	PF	SF	MP	TK20	TK10	TK4	CC	OF	RF	MC
PF		26.3	30.0	33.3	28.6	14.3	33.3	25.0	26.3	31.3
SF			4.0	13.0	26.3	26.3	20.0	14.3	0.0	19.0
MP				8.3	30.0	30.0	23.8	18.2	4.0	18.2
TK20					22.2	37.5	10.5	20.0	13.0	20.0
TK10						14.3	20.0	18.8	21.1	37.5
TK4							33.3	25.0	26.3	37.5
CC								29.4	20.0	41.2
OF									14.3	5.9
RF										23.8
MC										

PF primary forest, *SF* secondary forest, *MP* multispecies plantations, *TK20* 20-year-old teak plantations, *TK10* 10-year-old teak plantations, *TK4* 4-year-old teak plantations, *CC* cocoa plantations, *OF* old fallows, *RF* recurrent fallows, *MC* mixed crop fields teak plantations; the second group comprised the secondary forest, cocoa plantations, mixed crop fields, 4- and 20-year-old teak plantations and recurrent fallows; and the third group was mainly composed of multispecies plantations and old fallows. Land-use types were roughly ranked along the second axis according to the amount of forest disturbance in contrast to natural systems, multispecies plantations and human-influenced systems.

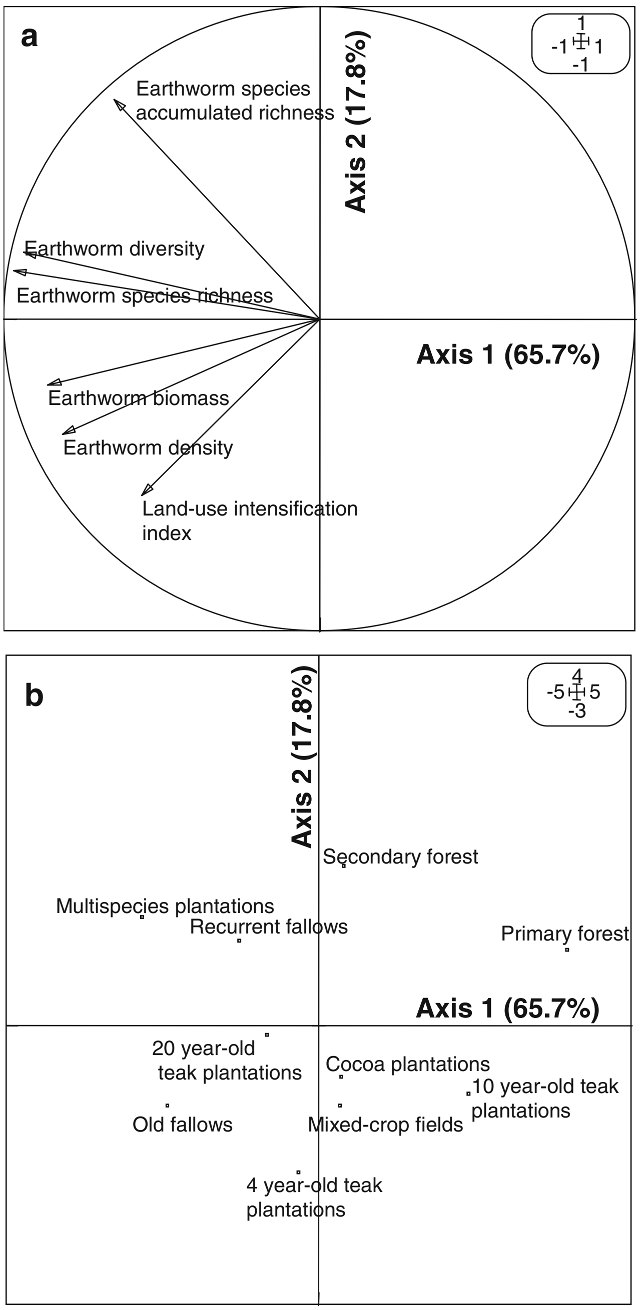

Fig. 3 **a** Correlation circle of the PCA showing the distribution of earthworm community parameters and the land-use intensification index across the landscape. **b** Ordination of the land-use types on the first and second factorial planes

Discussion

Effects of land management on earthworm populations

The numbers of earthworm species in the landscape unit fell in the typical range of tropical and temperate forests (between 13 and 15) reported by Lavelle (1983). Land-use change along the gradient of disturbance resulted in increases in earthworm populations and biomass. The earthworm populations in old fallows represented 16.5% and 20.3% of the overall populations and biomass of the earthworm community. Populations and biomass in the primary forest were low compared to the values of 120±39.6 ind m^{-2} and 28.2±8.9 g m^{-2} recorded from a Peruvian primary forest (Lavelle and Pashanasi 1989). The numbers in the secondary forest were close to those (150.4±33.7 ind m^{-2}) reported from the Central Region of Ivory Coast (Tondoh 1992). In total, the increases, in relative abundance (number: +53.1%, biomass: +94.8%) of the earthworm communities following human perturbations (from primary forest to annual crops), are a sound finding compared with general predictions in the literature (Fragoso et al. 1999). A decrease in earthworm populations (number: −89.20%, biomass: −83%) in Peru (Lavelle and Pashanasi 1989) and Central Ivory Coast was reported. Numbers and biomass in Ivory Coast were reduced to 73.9% and 4.6%, respectively. The numbers of earthworms in degraded areas could be attributed to the persistence of native species (*M. omodeoi*, *Millsonia* sp., *D. baeri*, *C. zielae*) in degraded systems and the availability of soil organic matter fractions and microclimatic conditions, suitable for individual earthworm growth, reproduction and population increase.

The sensitivity of the size of earthworm biomass to land-use intensification has been reported in Carimagua (Colombia) by Decaën and Jiménez (2002). Our results revealed a gradual increase in endogeic worm populations toward a system with high levels of disturbance. This ecological category comprises the ecosystem engineers (Jones et al. 1994; Lavelle et al. 1997), which are active in soil bioturbation and function. Our study is the first to show the potential increases in earthworm populations at intermediate level of intensification in agricultural systems.

The PCA demonstrated the precedence of a ‘land-use type’ factor over a ‘land-use intensification’ one. The species *D. saliens*, *H. africanus*, *M. omodeoi*, *D. baeri*, *D. ehrhardti*, *Agastrodrilus* sp., *S. palustris* and, to some extent, *Millsonia* sp. were most sensitive to land-use changes. Previous studies have highlighted the possibility of using *M. omodeoi* and *H. africanus* as bio-indicators of forest perturbations. However, a low biomass of *M. omodeoi* in a forest was reported in populations from a secondary forest of central Ivory Coast and was attributed to the poor efficiency of micro-organisms from forest soils in assimilating soil organic matter (Gilot-Villenave 1994). The maximum populations under old fallows were larger (23.4±5.7 ind m^{-2} and 15.2±3.2 g m^{-2}) than those in 32-year-old protected shrub savanna (Tondoh and Lavelle 2005). Populations of *H. africanus* were low compared to protected savanna in central Ivory Coast (130.9±ind m^{-2} and 25.3 g m^{-2}) (Tondoh and Lavelle 2005). The persistence of *H. africanus* populations in degraded areas and agrosystems that is encountered throughout humid Africa has been stressed by several authors (Hauser 1993; Hauser et al. 1998; Kang and Ojo 1996). The possible reasons are its relatively small size and high reproductive potential based on a rich diet consisting of organic residues (Tondoh and Lavelle 2005).

Diversity of earthworm communities

The multispecies plantations and fallow systems contained the most diverse communities. The intermediate disturbance systems (LUI=0.3), the multispecies plantations and fallows involved regeneration processes characterized by a combination of earthworm species favoured by litter heterogeneity, a diversity of types of soil organic matter and the efficiency of micro-organisms in transforming soil organic matter into fractions assimilable by earthworms (Gilot-Villenave 1994; Lavelle et al. 1995). Hence, the persistence and growth of both native and peregrine (*H. africanus*, *D. saliens*) earthworm species are likely to be the cause of the increased earthworm diversity. The low value of β diversity across the landscape indicated that the turnover of species between the different land-use types was small. This is probably due to the dominance of native species in communities as opposed to Amazonian forests, where the replacement of forest by pasture produced a dominance of the exotic worm communities (Fragoso et al. 1999). The multispecies plantations, secondary forests and recurrent fallows were the main driving force responsible for earthworm diversity at a landscape scale because their cumulative α diversity (13, 12) was similar to the γ diversity (13).

Sensitivity of earthworm community to land-use change and intensification

The PCA on earthworm community parameters and the LUI across the landscape confirmed that the earthworms were most sensitive to 'land-use type' since this factor accounted for 65.7% of the total variance. Earthworm diversity was the most sensitive response to land-use change. This parameter was followed by earthworm biomass and populations. The LUI did not fluctuate greatly across the landscape. Consequently, it could not discriminate the different habitats efficiently.

The sensitivity of earthworm species like *D. saliens*, *H. africanus*, *M. omodeoi*, *D. baeri*, *D. ehrhardti*, *Agastrodrilus* sp. and *S. palustris* to forest degradation suggested their potential role as bio-indicators. More field and laboratory investigations are needed to find out the most efficient species to be used in bio-monitoring programmes aimed at preventing ecosystem degradation due to anthropogenic activities in the forest areas of Ivory Coast.

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