Global Ecology and Conservation 3 (2015) 575–595

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Original research article

Ecological changes induced by full-sun cocoa farming in Côte d'Ivoire

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HIGHLIGHTS

- Ecological impacts of sun-grown cocoa farming in Côte d'Ivoire were assessed.
- Biodiversity and soil properties were measured along a chronosequence.
- Plant species richness and diversity markedly decreased from forest to cocoa stands.
- Earthworm abundance and species richness increased due the appearance of species adapted to degraded lands.
- Full-sun cocoa farming significantly deteriorated soil quality.

ARTICLE INFO

Article history:
Received 1 November 2014
Received in revised form 13 February 2015
Accepted 14 February 2015
Available online 20 February 2015

Keywords:
Biodiversity
Cocoa plantations
Côte d'Ivoire
Soil quality

ABSTRACT

Full-sun cocoa farming is currently the most widespread cocoa cultivation system in humid and sub-humid Côte d'Ivoire. Higher short-term yields from increasing surfaces under cultivation in this farming system have contributed to the country being ranked as top cocoa producer in the world. However the negative consequences including biodiversity loss, soil fertility depletion and soil quality degradation associated with this system, have incredibly received so less attention that the type and magnitude of such agro-ecological consequences within the current context of climate change are worth investigating. The present study was undertaken in the former cocoa belt of Central-Western Côte d'Ivoire, precisely in the Oumé Department. The main objective was to assess the impact of forest conversion to full-sun cocoa plantations on above and below-ground biodiversity along with soil quality by measuring chemical, physical and biological parameters along a chronosequence of different ages (5, 10 and 20 years). The results are summarized as follows: (i) the conversion of semi-deciduous forests to cocoa plantations resulted in plant diversity and species richness loss due to the disappearance of a huge number of native species while earthworm abundance and species richness increased due to the appearance of species adapted to degraded lands, (ii) soil quality was severely impaired by cocoa farming with the worse scenario being found under the 10-year-old cocoa plantations,

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http://dx.doi.org/10.1016/j.gecco.2015.02.007

where SOC, total N, CEC contributed mostly to soil quality degradation. The contribution of these findings to devise options for sustainable tree-based cocoa farming is discussed.

1. Introduction

Cocoa farming is the most widespread land use system in the Guinean rain forest (GRF) of West Africa (Gockowski and Sonwa, 2011), an area stretching from Guinea to Cameroon that has been identified 20 years ago as a global biodiversity hotspot (Myers et al., 2000). Cocoa production in Côte d'Ivoire expanded rapidly in the 1980's, becoming for the last 20 years, the largest cocoa producer in output and number of producers in the world currently holding more than 40% of the world market followed by Ghana, Nigeria and Cameroon (Gockowski and Sonwa, 2011; Hartemink, 2005). In humid and sub-humid areas of the country, these plantations are estimated to cover 1,924,056 ha with a global annual production amounting to 1,337,161 Mg (data from 2000–2006, Anonymous, 2006). The increase in area under cocoa plantations has been at the expense of forest cover as it is estimated that over 2.3 millions ha of deforestation and forest degradation in the GRF is associated with this most widespread land use system (Gockowski and Sonwa, 2011). Moreover, the significant reduction of forest cover ranging from 12 to 2.2 million ha between 1955 and 1993 in Côte d'Ivoire has been found to coincide with the strong increases in cocoa and coffee production (Leonard and Oswald, 1996; Brou et al., 1998), which corresponded to a deforestation rate of 7.6% per year (Balac, 1999).

In West Africa, cocoa farms are mostly established following a similar model referred to as short-term "boom-and-bust cycles" (Tscharntke et al., 2011): primary or secondary forests are selectively cleared, burned and cocoa is planted along with understory food crops (Isaac et al., 2005). After 20 and 25 years of cropping, the production decreases significantly and plantations are abandoned (Ruf and Zadi, 1988), and the centre of cocoa production typically moves to other areas. In Côte d'Ivoire, this resulted in the emergence of three major cocoa production zones over time (Balac, 1999): (i) the east and central-east (1955–1965), the central-west (1965–1975), and the southwest region (since 1975). In addition, the degree of shade in cocoa stands ranges from 24.5 to 48.1% showing the predominance of full-sun cocoa farming systems in the country with 28.2 to 37.5% of shade in the centre-west region hosting the present study (Gockowski and Sonwa, 2011).

Thus, the long-term conversion of forest to full-sun cocoa plantations might result in agro-ecological drawbacks such as forest degradation, biodiversity loss, soil quality disruption associated with low yield and food insecurity; and greenhouse gas emission as pointed out by several authors (Zapfack et al., 2002; Asase et al., 2009; Lal, 2009; Gockowski and Sonwa, 2011; Tscharntke et al., 2011). However the impacts of such an unsustainable land use change practice, which is widespread in the country with devastating environmental impacts in the long run, have rarely been assessed to provide necessary baseline figures relevant for future rehabilitation actions.

Although information about agro-ecological consequences in current and old main cocoa production zones in Côte d'Ivoire is limited, signs of land degradation such as low cocoa production, drop in economic activities, soil fertility depletion, food insecurity and decrease in cocoa-cultivated surfaces in former "cocoa belts" are clearly visible. Assessing changes in agro-ecological environments along a chronosequence of sun-grown cocoa plantations in one of the former cocoa belt, seems to be the most relevant approach to find out the magnitude of impact over time, as reported recently in Ghana (Dawoe et al., 2014). It also the first step towards identification of efficient options to reverse land degradation associated with full-sun cocoa farming.

The current study was designed to fill in this gap by gathering empirical data on biodiversity loss and soil quality degradation as a consequence of sun-grown cocoa farming in Côte d'Ivoire. The objective was to assess the impact of these cocoa plantations on biodiversity and soil quality along a chronosequence of cocoa plantations from those recently established after conversion to old growth stands of 20 years. This study is a first attempt to assess soil health deterioration due to sun-grown cocoa cropping in Côte d'Ivoire. We tested the general hypothesis that full-sun cocoa farming in Côte d'Ivoire results in biodiversity loss and soil quality deterioration leading to short-term abandonment of plantations. Finally, in light of results generated, options for sustainable cocoa farming will be outlined based on previous works.

2. Material and methods

2.1. Study site

The study area is located in a semi-deciduous forest area in the Central-West Region of Côte d'Ivoire (Latitude $6^\circ 30' $N and Longitude $5^\circ 31'$W). Twenty years ago, this area was part of the "cocoa belts", that is one of the main cocoa producing areas, characterized by a high rate of deforestation. Consequently the landscape is at the present time highly fragmented with a mosaic of land-uses including forests, cocoa plantations, fallows and food crops spread around three settlements, namely Petit Bouaké (PB), Djekoffikro (DK) and Nkroadjo (NK) each located at least 5 km away from the main village Goulikaho (Fig. 1). Ivorian farmers from savanna areas seeking arable lands for cocoa farming exclusively occupy these settlements.

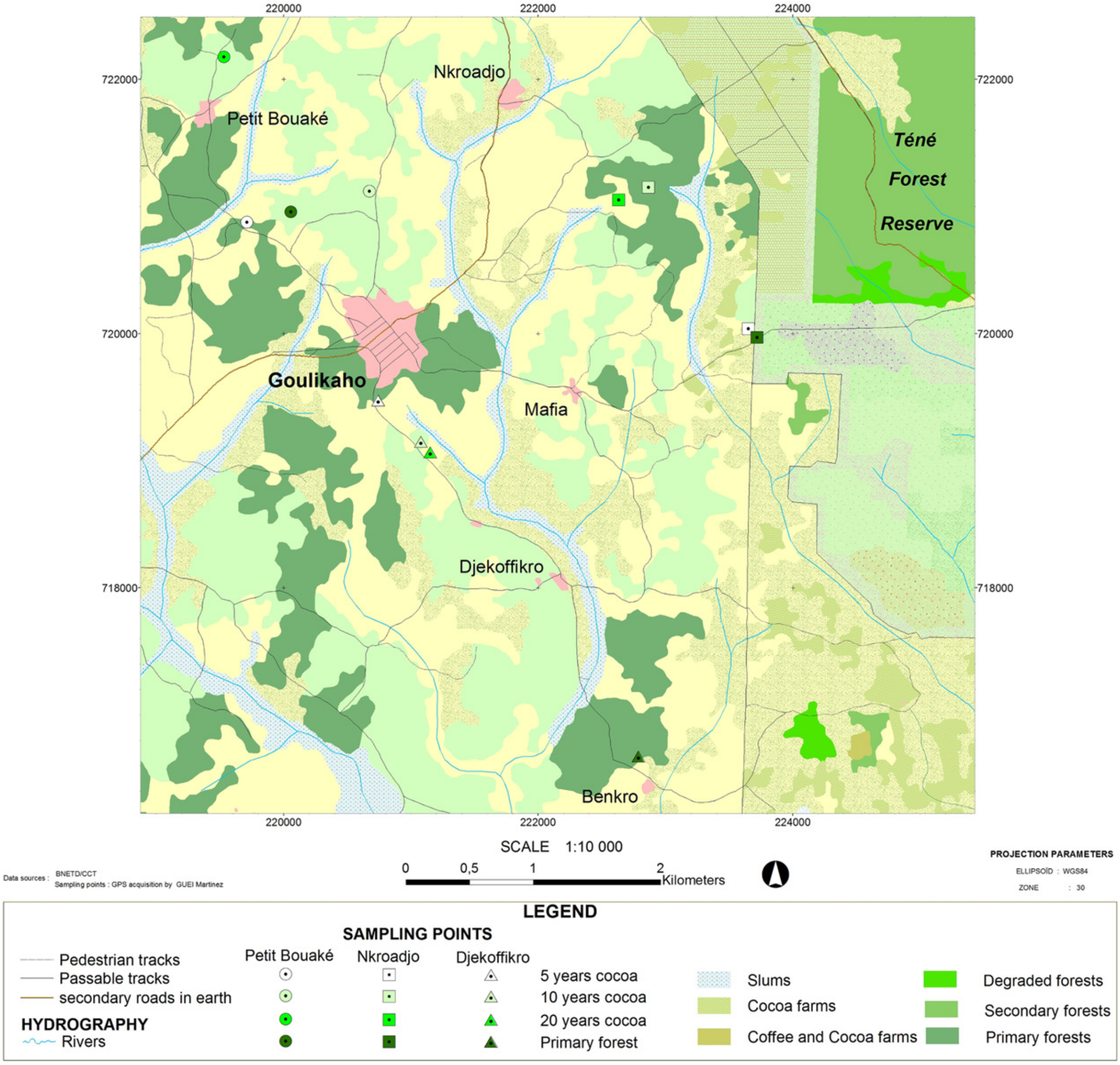

Fig. 1. Map of the landscape showing sampling sites spread around the village Goulikaho.

The land-use system consists of a mixture of perennial and food crops, including fallows as intermediary steps for soil regeneration. Cocoa is the main cash crop and forest patches initially converted to food crops are progressively transformed into cocoa plantations within 5 years, after which the production starts until 20 years or more after clearance, covering up to 2.3 ha (Table 1). Part of the incomes derived from the plantations is used for their maintenance, which consists mainly in weeding. It is generally done three times per year meaning is June (fruiting period), from November to February (harvest period), and April (onset of rain season), depending on the availability of manpower (Yao, 2008). Afterwards, pesticides spraying sessions of aged cocoa plantations might follow. It is estimated that about 41% of farmers do not use pesticides or use them once, whereas 47% used pesticides twice (February and April) per year and none of them apply the third treatment. However relatively wealthier farmers representing approximately 23% regularly use pesticides; at least three times in the year. Generally, farmers seem to prefer the use of pesticides that are affordable and crucial for good cocoa production to inorganic fertilizers that are rather expensive.

The climate of the area is sub-equatorial 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. Annual rainfall for the study year was about 1626.7 mm. The average monthly temperature was about 26 °C with low monthly variability of 1.6 °C. Soils are Ferralsols (World Soil Reference, 2006), acid in the top 20 cm (pHwater < 6.5) with a sandy-loam texture along with low nutrient contents that decrease rapidly from the upper soil layer to 20 cm depth (Assié et al., 2008).

Table 1
Land-use types in the sampling area.

Sites	Land-use types	Surface (ha)
Petit Bouaké	Secondary forest	2
	5 year-old cocoa plantation	1.5
	10 year-old cocoa plantation	2
	20 year-old cocoa plantation	2
Djekoffikro	Secondary forest	2.5
	5-year-old cocoa plantation	2
	10-year-old cocoa plantation	2
	20-year-old cocoa plantation	2
Nkroadjo	Primary forest	5.8
	5-year-old cocoa plantation	2
	10-year-old cocoa plantation	2.5
	20-year-old cocoa plantation	2.3

2.2. *Sampling design and data collection*

Sampling was designed following a hierarchical stratified scheme, where land uses were chosen randomly. In practice, three main settlements of cocoa farmers spread in the landscape and referred to as sampling sites (Sites), namely Petit Bouaké, Djekoffikro and Nkroadjo (Fig. 1) were selected. Within each site, a range of cocoa stands of 5, 10 and 20 years (respectively, since site clearance) along with a forest baseline referred to as land-use types (LUT) were selected. From each LUT, five sampling plots of 225 m^2 each, separated by at least 30 m in a contiguous stand were randomly selected and used as replicates. Thus, each sampling site was composed of 20 sampling points from which 5 are allocated randomly per LUT along the chronosequence, yielding a total of 60 sampling plots for the whole landscape. Apart from plant communities, which measurement was done in the two settlements – Nkroadjo and Djekoffikro –, sampling of earthworm communities, soil and litter characteristics collection were undertaken at the same sites and sampling plots. The sampling campaign took place from June to October 2008, a period of low to medium raining events.

2.2.1. *Plant species*

Plant species are recognized as indicators of biodiversity at local or regional scale (Rocchini et al., 2005; Pereira and Cooper, 2006). With the help of a slightly modified transect method for a rapid appraisal protocol of Gillison et al. (2013) for measuring plant biodiversity, qualitative plant inventory was performed at the same sampling points together with other measurements. At each sampling plot, randomly assigned transects of 50 m length and 10 m width covering 500 m^2, were divided into five 10 × 10 cm quadrats in which samples, namely flowering or fruiting branches and, if possible sterile branches of all plants were collected and used to make a herbarium gathered at the Centre for Ecological Research of the University of Nangui Abrogoua.

Plant samples were identified using the work of Aubréville (1959), Hutchinson and Dalziel (1954, 1958, 1963, 1968, 1972), Hawthorne and Jongkind (2006). The confirmation of these determinations was made with herbaria of the Swiss Centre for Scientific Research and the National Flotistic Center the of University Félix Houphouët-Boigny. The basic nomenclature used is that of Hutchinson and Dalziel (1954, 1958, 1963, 1972). The scientific names of plants were updated based on Lebrun and Stork (1991, 1992, 1995, 1997) and Aké Assi (2001, 2002) criteria.

2.2.2. *Litter mass and characteristics determination*

Standing leaf litter stocks in forest and cocoa plantations were collected with a 1 − m^2 quadrat, from 5 plots chosen randomly in each of the land use type (LUT). Litter collected was oven-dried at 60 °C for 72 h and weighed. A 20 g subsample of leaves was finely ground and stored in plastic bags for further chemical analyses.

Organic carbon (C) was determined after mineralization of plant residues using a sulfochromic solution (Walkley and Black, 1934), while total nitrogen (N) was determined using the standard Kjeldahl digestion method. Phosphorus (P) was measured by colorimetry following nitriperchloric acid digestion and subsequent molybdenum-blue colour development (Olsen and Sommers, 1982). Major cations (Ca, K, Mg) were extracted using ammonium acetate buffer (pH 7) and determined by means of atomic absorption spectrophotometry techniques (Anderson and Ingram, 1993).

2.2.3. *Earthworm populations*

Within the soil macro-invertebrates communities, earthworms are considered are indicators of land use change in semi-deciduous forest areas (Tondoh et al., 2007, 2011; Guéi and Tondoh, 2012). They were sampled in each LUT using a modified method recommended for tropical soils (Moreira et al., 2008), consisting in digging out 3 soil monoliths (50 cm × 50 cm × 30 cm) spaced by 5 m interval along a transect at each sampling point (Tondoh et al., 2011). Each monolith was used as replicates in each land-use, which comprised 15 replicates in total per LUT and thus 60 per sampling site. The monolith was surrounded by a trench of 30 cm depth preventing the escape of individuals and allowing for subdivision by trenches of 10 cm for hand sorting in trays (Tondoh and Lavelle, 2005). Specimens collected were preserved in 4% formaldehyde solution, identified to species level (Csuzdi and Tondoh, 2007), counted and weighed.

2.2.4. Soil physical and chemical characteristics measurements

Prior to earthworms sampling, nine soil cores distributed around sampling points were collected in the first 10 cm top soil known to be sensitive to land use change in the study area (Tondoh et al., 2011), air-dried, sieved and mixed thoroughly to form a composite sample. Soil bulk density was estimated using the cylinder method as per Assié et al. (2008). Soil total nitrogen (total N) was extracted according to Nelson and Sommers (1980) and determined using Technicon autoanalyzer (Technicon Industrial Systems, 1977). Soil Organic Carbon (SOC) was determined using a modified method of Anne (1945) based on a dichromate oxidation procedure. A correction factor of 1.72 was used to account for incomplete oxidation of organic carbon (Nelson and Sommers, 1982). Available phosphorus (avP) was extracted according to the Bray-1 procedure (Olsen and Sommers, 1982) and determined using a Technicon Auto Analyzer (Technicon Industrial Systems, 1977). Exchangeable bases namely K, Ca and Mg were extracted using the standard ammonium acetate (pH 7) buffer and measured by atomic absorption spectrometry (Thomas, 1982). Cation exchange capacity (CEC) was obtained using standard methods (Anderson and Ingram, 1993). Soil pH-H_20 (pH) was determined by means of a glass electrode in 1:2.5 soil:water ratio.

Carbon and Nitrogen stocks were calculated according to the following equation (De Rouw et al., 2010):

$$\text{C}\ \textit{stock} = \text{SOC} \times p \times \text{d}, \quad \text{where.}$$

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

SOC stock was further converted into Mg C ha^{-1}. The same calculation was applied for total N stock.

In order to account for differences in soil bulk densities between the forest and cocoa stands, we adjusted the thickness of soil layer beneath the cocoa fields by applying the following equation (Lemenih et al., 2005; Dawoe et al., 2014):

$$\text{d}\ \textit{corrected} = (p\ \text{forest} \mid p\ \text{cocoa fields}) \times \text{d}, \quad \text{where}$$

d *corrected* is the adjusted thickness of a sample soil layer under plantation of farmland, p forest the bulk density of the sampled soil layer under the natural forest, p cocoa fields the bulk density of the sampled soil layer under cocoa land use and d the thickness of soil layer used during field sampling.

2.3. Data processing and statistical analysis

Biodiversity of plant and earthworm species was assessed through species richness and Shannon–Wiener diversity index (Legendre and Legendre, 1984):

$$H = \sum_{i=1}^{s} pi \ln pi$$

where, s is the total number of species pi: the proportion of individual in the ith species.

In this study, soil quality was defined as its capacity to support plant production and sustain the deliverance of ecosystem services (Kibblewhite et al., 2008). The impact of cocoa farming on soil quality was assessed using degradation indices (DIs). Soil quality degradation indices for each soil property, which reflects the percent change (positive or negative) under a specific management from the baseline values under the adjacent natural forest (Adejuwon and Ekanade, 1988; Islam and Weil, 2000; Lemenih et al., 2005; Dawoe et al., 2014), were calculated by estimating the relative deviations of each soil parameter under a specific management from values under the adjacent natural forest. As an index of soil quality responses (either degradation or improvement) to the establishment of cocoa plantations, the cumulative DI was obtained by summing up the resultant positive and negative DI's of the individual soil properties for each LUT. Data for pH and C:N ratio were not included in this calculation because the criteria of "more is better" does not apply to these parameters within the ranges observed for this study area (Islam and Weil, 2000). According to Wang et al. (2001) the magnitude of degradation is commensurate with ranges of DIs as follows: (i) $0 < \text{DIs} \leq 5\%$ indicate no deterioration; (ii) $-5 < \text{DIs} \leq 5\%$, light degradation, (iii) $-10 < \text{DIs} \leq -20\%$, moderate deterioration, and (iv) $\text{DIs} > -20\%$, serious deterioration.

Prior to statistical analysis, the distribution of soil variables was tested for normality, and when necessary, the data were subjected to logarithmic transformations. Data on litter mass and characteristics were analysed using a one-way ANOVA, with Tukey HSD multicomparison test. Linear mixed models were used to explore changes in plant communities, soil biological, physical and chemical parameters along cocoa chronosequence converted from forest. Land-use type (LUT) namely forest, 5-, 10-, and 20-year-old cocoa plantations and sampling sites including Petit Bouaké, Nkroadjo and Djekoffikro and interaction between LUT and Sites were referred to as fixed effects while plots were considered as random effects. Residuals of linear model models were tested for normality. In order to study relationships between biotic data (earthworm and plant communities) and soil parameters, a co-inertia analysis (COI) was performed. COI is a multivariate method that characterizes a global measure of the co-structure between biological and environmental data (Dray et al., 2003). This method is based on coupling above mentioned data sets by comparing the structures revealed in each principal component

Table 2
Anova table of general linear mixed effect models on plant biodiversity parameters across Sites and LUT. *F*-values and the corresponding *p*-values are displayed.

	df	Species richness	Shannon index (H)
		F	*F*
Site	2	26.1***	21.6***
LUT	3	17.5***	16.9***
Site × LUT	6	3.3*	1.9

* $p < 0.05$.
*** $p < 0.001$.

Table 3
Descriptive statistics of plant biodiversity parameters along the chronosequence.

	Minimum	Maximum	Mean	Standard deviation
Species richness				
Forest	24	60	42	13.4
5 year-old cocoa	10	41	23.7	11.2
10 year-old cocoa	12	51	20.8	13.7
20 year-old cocoa	13	29	19.2	4.7
Shannon–Wiener index (H)				
Forest	4.6	5.9	5.3	0.5
5 year-old cocoa	3.3	5.4	4.4	0.7
10 year-old cocoa	3.6	5.7	4.2	0.8
20 year-old cocoa	3.7	5.4	4.4	0.4

analysis (PCA) to show whether the co-structures described by the major axes is similar to the structures described by the analysis performed for each data matrix (Dolédec and Chessel, 1994). The overall correlation of the two data sets is expressed by a multivariate extension of the Pearson correlation coefficient called the RV-coefficient (Robert and Escoufier, 1976). RV-coefficient varies between 0 and 1 where a high value indicates a high degree of co-structure. The statistical significance of this coefficient is determined using a Monte Carlo permutation test with 1000 permutations (Thioulouse et al., 1997). Statistical tests were made using the R software (R Development Core Team, 2013) and the package nlme for mixed effect models along with the ADE-4 package (Chessel et al., 2004).

3. Results

3.1. Diversity of plants and earthworms

3.1.1. Plant diversity

In total, 1057 individuals of plants belonging to 237 species in 70 families were identified in this study. Families with the greatest number of species were Euphorbiaceae (14), Rubiaceae (14), Apocynaceae (12) and Sterculiaceae (11). Both LUT and Site have significant impact on plant species richness and diversity across the landscape as forest conversion into cocoa plantations significantly reduced plant diversity and species richness that vary markedly across sampling sites (Table 2). However, only the interaction between LUT and Site slightly affect species richness. Average species richness significantly ($p < 0.001$) decreased from forest (42 ± 13.4) to the 20-year-old cocoa stands (19.2 ± 4.7), showing the negative impact of cocoa farming (Tables 2 and 3). Also, Shannon–Weaver diversity index showed significant variation between LUTs with the highest value being found in the forest (5.3 ± 0.5) and the lowest, in the 10-year-old cocoa plantations (Tables 2 and 3). On the other hand, there was a significant drop in tree percentage from forest (64.9 ± 6.1%) to cocoa plantations (47 ± 9.7%) compared to lianas and herbaceous, which showed very little changes along the chronosequence (Table 4, Fig. 2). More importantly, the establishment of full-sun cocoa plantations was followed by a significant ($p < 0.001$) reduction in forest species (86.1 ± 4.4 to 30 ± 7.6%) along with a significant rise in pioneer (12.7 ± 4.4 to 54 ± 6.6%) and exotics (1.2 ± 1.4 to 17.5 ± 6.7%) species along the chronosequence (Table 5, Fig. 3). Pioneer trees in cocoa fields were mostly from natural regeneration among which those with agroforestry potential commonly included *Acacia kamerunensis*, *Albizia adianthifolia*, *Albizia zygia*, *Ricinodendron heudelotii, Alstonia boonei*, *Ficus exasperata*, *Terminalia ivorensis*, *Terminalia superba*, *Spathodea campanulata*, *Newbouldia laevis*, *Triplochiton scleroxylon* (Appendix B). The most common exotic plant species found in the plantations (Appendix C) were *Albizia lebbeck*, *Anacardium occidentale*, *Ananas comosus*, *Canna indica*, *Cedrela odorata*, *Citrus sinensis*, *Musa sapientum*, *Persea americana*, *Psidium guajava.*

3.1.2. Earthworm density, biomass and diversity

In total, 20 species composed of three families, namely Acanthodrilidae, Eudrilidae and Ocnerodrilidae were collected and species richness broadly ranged from 16 to 17 species across LUT (Table 6). Total density falls in the ranges between

Table 4
Anova table of general linear mixed effect models on the percentage of plant morphology of across Sites and LUT. F-values and the corresponding p-values are displayed.

	df	Tree	Liana	Herbaceous
		F	F	F
Site	2	5*	0.09	4.8
LUT	3	13.9***	2.8	4.3*
Site × LUT	6	1.6*	2.2	2.7

* $p < 0.05$.
*** $p < 0.001$.

Table 5
Anova table of general linear mixed effect models on the percentage of plant ecological type across Sites and LUT. F-values and the corresponding p-values are displayed.

	df	Native	Pioneer	Exotic
		F	F	F
Site	1	0.14	3.87	16.8
LUT	3	153***	90.4***	26***
Site × LUT	3	0.69	0.84	2

*** $p < 0.001$.

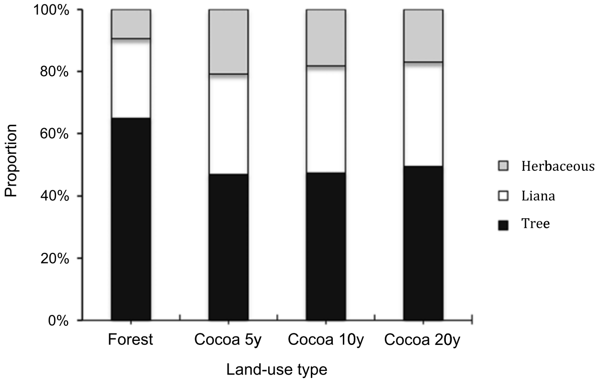

Fig. 2. Change in morphological types in the vegetation along the chronosequence of cocoa fields in a semi-deciduous forest of Côte d'Ivoire. Cocoa5, cocoa10 and cocoa20 correspond to 5-, 10-, and 20-year-old cocoa plantations, respectively.

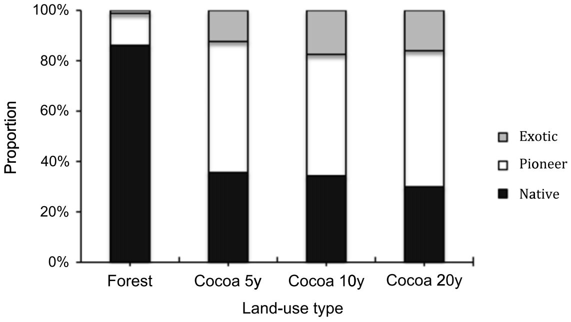

Fig. 3. Change in plant ecological categories in the vegetation along the chronosequence of cocoa fields in a semi-deciduous forest of Côte d'Ivoire. Cocoa5, cocoa10 and cocoa20 correspond to 5-, 10-, and 20-year-old cocoa plantations, respectively.

the forest (86 ± 19.7 ind m^{-2}) and the 5-year-old cocoa plantation (53.9 ± 8.2 ind m^{-2}) while biomass values varied between the forest (16.7 ± 4.2 g m^{-2}) and the 10-year-old plantation (12.3 ± 2.2 g m^{-2}). The four more common species in terms of density are *Stuhlmania zieale* (17.9 ± 7.4 ind m^{-2}), *Dichogaster eburnean* (17.4 ± 5 ind m^{-2}), *Dichogaster baeri* (14.6 ± 4 ind m^{-2}) and *Dichogaster erhrhardti* (13.7 ± 3.6 ind m^{-2}). On the other hand, three species namely *Dichogaster*

Table 6
Average Density (individual m^{-2}) and biomass ($g\ m^{-2}$) of earthworms along the chronosequence of cocoa plantations. Values in brackets are standard errors and N = 15.

	Forest		Cocoa 5 y		Cocoa 10 y		Cocoa 20 y	
	Density	Biomass	Density	Biomass	Density	Biomass	Density	Biomass
M. lamtoiana	0.5(0.2)	2.46(1.37)	0.3(0.2)	2.46(1.44)	–	–	0.0(0.0)	0.65(0.68)
M. omodeoi	1.4(0.9)	0.66(0.39)	6.1(2.0)	3.91(1.36)	7.1(2.8)	3.21(1.24)	8.3(2.8)	4.56(1.64)
M. nilesi	0.2(0.2)	0.04(0.04)	0.0(0.0)	–	–	–	0.5(0.3)	0.10(0.10)
D. baeri	14.5(4.0)	4.11(1.04)	6.0(1.1)	3.78(0.68)	5.4(1.2)	2.69(0.70)	6.5(1.5)	3.41(0.99)
D. terraenigrae	6.3(2.0)	7.00(2.77)	2.6(0.8)	5.00(1.49)	3.0(0.7)	3.01(0.86)	3.0(0.9)	4.18(0.96)
D. saliens	3.4(1.1)	0.04(0.01)	0.5(0.2)	0.01(0.00)	1.2(0.6)	0.02(0.01)	1.8(0.9)	0.03(0.01)
D. erhrhardti	13.6(3.6)	0.94(0.25)	3.8(1.4)	0.45(0.14)	2.8(0.9)	0.30(0.10)	4.5(1.3)	0.54(0.20)
D. lamottei	0.2(0.2)	0.02(0.02)	–	–	0.0(0.0)	0.01(0.01)	–	–
D. papillosa	0.4(0.2)	0.01(0.01)	4.4(2.8)	0.10(0.06)	12.1(4.3)	0.35(0.14)	5.9(1.4)	0.15(0.04)
D. eburnea	17.4(5.0)	0.35(0.09)	4.1(1.1)	0.13(0.03)	4.1(2.0)	0.20(0.12)	2.1(1.1)	0.05(0.02)
D. mamillata	2.9(2.4)	0.12(0.10)	–	–	0.1(0.1)	0.01(0.01)	0.0(0.0)	–
D. affinis	1.2(0.4)	0.06(0.03)	0.5(0.3)	–	0.1(0.1)	0.02(0.01)	–	–
Dichogaster sp.	2.2(1.9)	0.09(0.07)	1.3(1.3)	0.26(0.27)	–	–	0.4(0.4)	0.36(0.37)
H. africanus	–	–	4.2(1.0)	1.14(0.32)	0.8(0.5)	0.29(0.21)	0.8(0.3)	0.36(0.17)
S. compositus	0.2(0.2)	–	0.1(0.1)	0.02(0.02)	0.0(0.0)	0.00	–	–
S. zielae	17.8(7.4)	0.77(0.34)	13.3(3.6)	0.80(0.21)	36.3(7.6)	2.20(0.43)	34.0(4.2)	1.97(0.25)
S. palustris	2.1(1.2)	0.02(0.01)	–	–	0.1(0.1)	0.00	0.7(0.4)	0.01(0.01)
A. multivesiculatus	–	–	0.2(0.1)	0.02(0.01)	0.0(0.0)	0.02(0.02)	0.9(0.5)	0.15(0.10)
A. opisthogynus	–	–	0.0(0.0)	0.13(0.13)	–	–	–	–
G. paski	0.8(0.5)	0.01(0.01)	5.6(2.6)	0.10(0.04)	0.1(0.1)	0.01(0.00)	0.1(0.1)	–
Total	85.9(19.7)	16.70(4.20)	53.8(8.2)	18.30(2.80)	74.1(12.6)	12.30(2.20)	70.3(7.9)	16.50(3.20)

Table 7
Anova table of general linear mixed effect models on log-transformed earthworm characteristics across Sites and LUT. F-values and the corresponding p-values are displayed.

	df	Density	Biomass	Species richness
		F	F	F
Site	2	18***	7.9**	1.7
LUT	3	1.6	1.2	2.9*
Site × LUT	6	2.7*	3.5**	1.4

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

terreanigrae (6.3 ± 2 ind m^{-2}), *D. baeri* (4.1 ± 1 ind m^{-2}) and *Millsonia lamtoiana* (2.5 ± 1.4 ind m^{-2}) were the dominant as far as biomass was concerned. Density and biomass of earthworms varied significantly ($p < 0.01$) across sites but not throughout land-uses, although variation was less significant when land-use and site were combined as an interaction (Table 7). Species richness showed a significant ($p < 0.05$) drop in the 10-year old plantation, which brought along an overall significant variation with a decreasing trend along the chronosequence. Values ranged from 7.5 ± 1.9 species m^{-2} (5 years cocoa) to 6.1 ± 1.5 species m^{-2} (10 years cocoa).

3.2. Standing litter stock and nutrients sequestered

The standing litter values were significantly higher in the cocoa system with reference to 10-year-old (6.3 ± 0.4 Mg ha^{-1}) and 20-year-old (7.7 ± 1.1 Mg ha^{-1}) plantations, compared with the forest (Table 8). Carbon (C) sequestered in surface litter ranged from 1.4 ± 0.1 to 2.8 ± 0.4 Mg C ha^{-1} for 5 and 20-year-old plots, respectively (Table 8). Nutrients sequestered in surface leaf litter showed significantly higher values in the two oldest cocoa stands and are ranked in the order Ca > N > Mg > K > P in all land uses. Furthermore, the C:N ratio was significantly lower in the forest (22.3 ± 1.4) compared with the plantations where values were similar and ranged between 32.1 ± 1.5 and 33.1 ± 2.9 (Table 8).

3.3. Soil physical and chemical parameters

Soil bulk density showed significant rise from 1.23 ± 0.05 (forest) to 1.42 ± 0.04 (20-year-old cocoa plantations) along the chronosequence (Tables 9 and 10). Except for available P, all chemical variables were significantly affected by cocoa farming, which brought about decreasing trends with SOC and total N being chiefly affected (Tables 9 and 10). Additionally, the interaction between LUT and Site showed significant but less marked impact on SOC, total N, bulk density, exchangeable Mg,

Table 8
Average standing leaf litter stocks (Mg DM ha^{-1} ± SE, N = 5) and nutrients sequestered (kg ha^{-1}) in the forest and cocoa ecosystems. For a given row values with the same(s) letter(s) are not significantly different (Anova, $p = 0.05$).

	Forest	Cocoa plantations		
		5 year-old	10 year-old	20 year-old
Litter mass (Mg ha^{-1})	4.95 ± 0.6a	3.9 ± 0.3a	6.3 ± 0.4ab	7.7 ± 1.1ab
C (kg ha^{-1})	1.8 ± 0.2a	1.4 ± 0.1a	2.3 ± 0.1ab	2.8 ± 0.4ab
N (kg ha^{-1})	66.4 ± 8.7a	52.0 ± 4.2a	84.8 ± 4.8ab	102.8 ± 14.4ab
C:N	22.3 ± 1.4a	32.7 ± 1.2b	32.1 ± 1.5b	33.1 ± 2.9b
P (kg ha^{-1})	3.3 ± 0.4a	2.6 ± 0.2a	4.2 ± 0.2ab	5.1 ± 0.7ab
Ca (kg ha^{-1})	140.8 ± 18.5a	110.2 ± 9.0a	179.9 ± 10.2ab	218.1 ± 30.6ab
Mg (kg ha^{-1})	16.0 ± 2.1a	12.5 ± 1.0a	20.4 ± 1.2ab	24.8 ± 3.5ab
K (kg ha^{-1})	12.2 ± 1.6a	9.5 ± 0.8a	15.6 ± 0.9ab	18.9 ± 2.6ab

Table 9
Anova table of general linear mixed effect models on log-transformed soil chemical characteristics across Sites and LUT. *F*-values and the corresponding *p*-values are displayed.

	df	pH	SOC	Total N	C:N	Av. P	CEC	Ca	Mg	K	Bd	SOC stock	Total N stock
		F	*F*	*F*	*F*	*F*	*F*	*F*	*F*	*F*		*F*	*F*
Site	2	0.8	18.4***	1.9	5.0**	0.8	11.2**	3.5	5.4*	256.2***	3.8	15.9***	0.8
LUT	3	6.0**	52.2***	26.8***	1.2	2.0	7.6***	5.0**	9.5***	6.6***	17.1***	35.2***	14.2***
Site × LUT	6	0.5	21.6***	17.5***	3.9**	2.6	3.0*	3.2*	6.8***	0.7	7.1***	15.7***	9.8***

[*] $p < 0.05$.
[**] $p < 0.01$.
[***] $p < 0.001$.

Table 10
Soil physico-chemical characteristics (mean ± standard error, N = 15) along cocoa plantations chronosequence converted from semi-deciduous forest.

	Forest	Cocoa plantations		
		5-year-old	10-year-old	20-year-old
Bulk density	1.2 ± 0.1	1.5 ± 0.04	1.3 ± 0.03	1.4 ± 0.04
pH-H20	6.1 ± 0.1	6.2 ± 0.2	6 ± 0.2	6.8 ± 0.2
C (g kg^{-1})	20.3 ± 2	10.6 ± 0.7	10.1 ± 0.5	14.5 ± 1.6
Total N (g kg^{-1})	1.7 ± 0.2	1 ± 0.1	0.9 ± 0.1	1.3 ± 0.1
C:N	11.7 ± 0.5	10.9 ± 0.5	11.1 ± 0.6	11.7 ± 0.5
Available P (mg kg^{-1})	46.1 ± 3.4	52.3 ± 5.5	61 ± 7.9	58.6 ± 4.6
CEC (cmolc kg^{-1})	13 ± 1.0	9.6 ± 0.5	9.7 ± 0.5	11 ± 0.7
Ca (cmolc kg^{-1})	3 ± 0.5	1.5 ± 0.2	1.5 ± 0.2	2.3 ± 0.4
Mg (cmolc kg^{-1})	0.7 ± 0.08	0.5 ± 0.03	0.4 ± 0.02	0.6 ± 0.1
K (cmolc kg^{-1})	0.5 ± 0.06	0.4 ± 0.1	0.3 ± 0.03	0.39 ± 0.1
C stock (Mg ha^{-1})	24 ± 1.8	17.1 ± 1.5	12.6 ± 1.0	12.8 ± 1
Total N (Mg ha^{-1})	2.1 ± 0.2	1.5 ± 0.1	1.2 ± 0.1	1.3 ± 0.2

C:N ratio, exchangeable Ca and CEC (Table 9). Also, SOC and total N stocks in the topsoil (10 cm) significantly decreased across LUTs ($p < 0.001$) with forest values reducing at the rates of 46.7% and 38.1% respectively at the end of the chronosequence (Table 10).

3.4. Soil quality degradation

Table 11 depicted a steady deterioration in soil quality starting 5 years (DI = −46) after conversion to full-sun cocoa, followed by severe degradation 10 years (−137.3) and 20 years (−94.3) later. In general, SOC, total N, CEC and exchangeable cations were markedly deteriorated and thereby contributed negatively to the cumulative DI under cocoa plantations with the worse situation being found under the 10-year-old stand. We can therefore talk about a steady degradation of soil quality over time in full-sun cocoa stands, though the value is a bit lower in the 20-year-old plantation.

3.5. Relationship between soil parameters and earthworms plant communities

The COI analysis showed a significant correlation between the combined biotic group (earthworm and plant characteristics) and soil parameters (RV coefficient = 0.74; $p = 0.029$). The first two axes explained 97.4% of the variance in data with the first axis accounting for most (75.5%) of the information while the second axis holds 21.7% (Fig. 4). A part from

Table 11
Degradation indices (%) in the 0–10 cm soil layer under cocoa plantations considering soil physical and chemical parameters.

	Cocoa plantations		
	5-year-old	10-year-old	20-year-old
Bulk density	+18.2	+8.7	+22.0
C (g kg^{-1})	−28.9	−43.5	−39.1
Total N (g kg^{-1})	−27.7	−40.0	−31.0
Available P (mg kg^{-1})	+38.4	+41.4	+22.4
CEC (cmolc kg^{-1})	−13.3	−21.0	−21.0
Ca (cmolc kg^{-1})	−15.2	−23.2	−09.1
Mg (cmolc kg^{-1})	−5.3	−34.9	−24.5
K (cmolc kg^{-1})	−12.1	−24.8	−14.1
Cumulative DI	−46	−137.3	−94.3

10-year-old cocoa stands (10 CPDK and 10 CPNK) where biotic and soil data are most likely unrelated due to their lengthy line, the remaining sites are characterized by a close relationship between the two data sets. The first axis distinguished between forests, 5- and 20-year-old cocoa stands while LUT from Djekoffikro and Nkroadjo are opposed along the second axis. In terms of characteristics, forest plots were associated with enhanced biotic indicators (plant species richness and diversity, earthworm diversity) and high content of SOC, Total N, Mg, Ca and CEC. Young cocoa plantations were established on soil showing moderate values of C:N ratio and pH while the 20-year-old-cocoa plantations were associated with a significant increase in the abundance of earthworm populations, bulk density and avP (Fig. 4). The correlation between the biotic component (earthworms, plants) and soil properties was better revealed by Fig. 5 that emphasized positive links between biodiversity metrics (earthworms and plants) and most soil properties except C:N ratio, pH and avP. On the other hand, the abundance and species richness of earthworms are positively correlated with bulk density and avP.

4. Discussion

4.1. Plant community and diversity

In central western Côte d'Ivoire, full-sun cocoa farming resulted in a drastic loss of forest plant species that are replaced by pioneer and exotic species. Similar trends were found in shaded cocoa farmlands of Ghana (Asase et al., 2009), Nigeria (Oke and Odebiyi, 2007), Cameroon (Zapfack et al., 2002; Sonwa et al., 2007) and recently southwestern Côte d'Ivoire (Dumont et al., 2014). The list of all plant species found in the forest along with cocoa systems is shown in Appendices A–C. As pointed out by Asase et al. (2009) in Ghana, cocoa farming resulted in a significant recruitment of non-forest plants namely pioneers and exotics, which represent 64.4% to 70% of the community. Among the recruited plants (Appendix C) some as orange (*C. sinensis*), avocado (*Persea americana*), guava (*Psidium guayava*), mango (*Anacardium occidentale)*, are fruit trees planted by farmers as recently pointed out by Dumont et al. (2014) in south-West Côte d'Ivoire. Koko et al. (2013) went a bit further talking about innovation system devised by farmers in central Cote d'Ivoire (Bouaflé Region), made up by a system combining cocoa and fruit trees of orange and avocado due to their ecological (shade trees) and economic (cash crop) services. A number of pioneer tree species collected in cocoa plantations namely *Acacia kamerunensis*, *Albizia adianthifolia*, *A. zygia*, *Ricinodendron heudelotii*, *Alstonia boonei*, *Ficus exasperata*, *Terminalia ivorensis*, *T. superba*, *Spathodea campanulata*, *Newbouldia laevis*, *Triplochiton scleroxylon* has been reported as shade tree species with multiple functions including food, fruit, medicine, construction and arts (Herzog, 1994; Anim-Kwapong and Teklehaimanot, 1995; Oke and Odebiyi, 2007; Anim-Kwapong and Osei-Bonsu, 2009; Asase et al., 2009; Somarriba and Beer, 2011; Koko et al., 2013). Of these species, *Spathodea campanulata*, *Terminalia ivorensis*, *Terminalia superba*, *Ricinodendron heudelotii*, planted together as fallows, have shown potential to conserve biodiversity, manage efficiently shade, improve soil fertility and therefore rehabilitate degraded lands from full-sun cocoa cultivation in Ghana (Anim-Kwapong and Osei-Bonsu, 2009). The same trees were cited by the vast majority of Ivorian farmers from the current cocoa-belt (southwestern area) as most compatible trees with cocoa (Dumont et al., 2014). On the other hand, the presence in cocoa stands of indigenous shade trees derived from natural regeneration with high potential for reclamation of degraded cocoa lands in West Africa, has significant implications in setting up intensive and improved cocoa farming in order to sustain the cocoa industry and halt further deforestation.

4.2. Earthworm community and diversity

The earthworm community was made up of populations of *S. zielae*, *D. baeri*, *D. eburnea*, *D. erharhadti* and *M. omodeoi*, which account for up to 75.6% of earthworms collected. The geophaguous polyhumic *S. zielae* along with the mesohumic *M. omodei* showed an increasing trend from forest to cocoa plantation while the proportion of *D. eburnea*, *D. baeri* and D. *erharhadti* decreased along the chronosequence. These results agree with recent findings identifying *D. eburnean* and *D. baeri* as species linked to SOM-rich ecosystems whereas *M. omodeo* is considered as indicator of disturbed ecosystems (Guéi

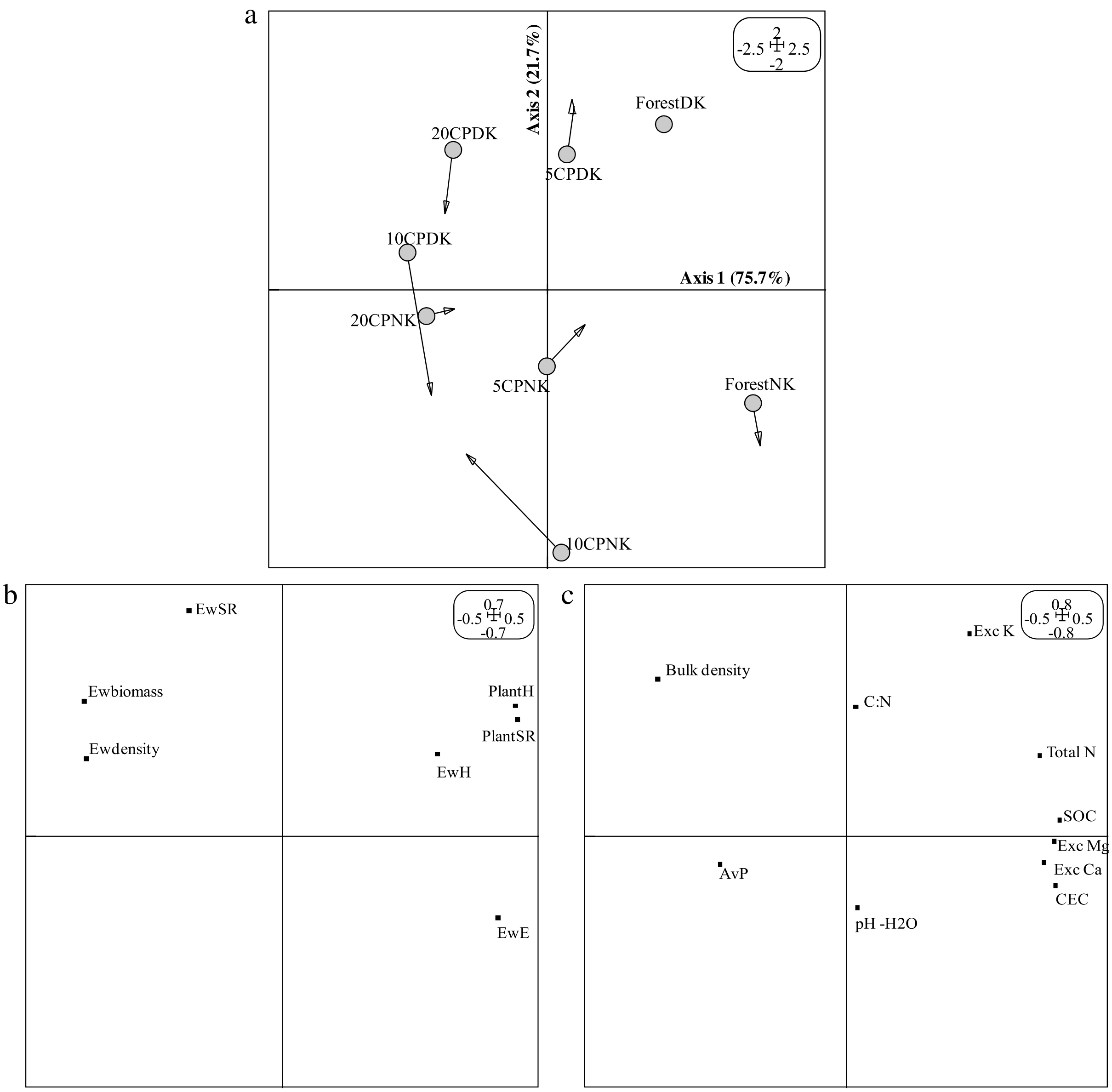

Fig. 4. Co-inertia analysis combining biotic (earthworms and plants) characteristics and soil parameters across LUTs (a) Ordination of sampling sites in the factorial plan described by axes 1 and 2 of co-inertia; circles and arrows represent the projected coordinates of each data set (physico-chemical variables and biotic characteristics), and these are joined by a line, which length is proportional to the divergence between the data sets; ForestNK: Nkroadjo forest; ForestDK: Djèkoffikro forest; (5, 10, 25) CPNK: 5, 10-, 25-year-old cocoa plantations (Nkroadjo); (5,10, 25) CPDK: 5, 10, 25- year-old cocoa plantations (Djekoffikro). (b) Ordination of biotic and soil variables described the COI along axes 1 and 2; EwSR: earthworm species richness; Ewbiomass: earthworm biomass; Ewdensity: earthworm density; EwH: earthworm diversity; PlantH: plant diversity; EwE: earthworm eveness; C:N: CN ratio.

and Tondoh, 2012). Unlike density and biomass, earthworm species richness significantly varied along the chronosequence because of the drop in the 10-year-old plantations due to the disappearance of forest species, namely *M. lamtoiana*, *M. nilesi* and *Dichogaster* sp. The low quality of litter in cocoa plantations as shown by high values of C:N ratio ranging from 32.7 ± 1.2 to 33.1 ± 2.9 coupled with low N content is likely to explain the negative impact on earthworm diversity. Indeed it was recently reported in Brazil that litter quality under different cocoa agroforestry systems is accountable for variation in the diversity of litter and soil fauna (Moço et al., 2010). On the other hand, earthworm density and biomass varied significantly across sampling sites showing the existence of an intensification gradient from the protected Téné Reserve Forest that locates by Nkroadjo, to agricultural-intensified sites of Djekoffikro and Petit Bouaké. This finding confirms observations about the sensitiveness of earthworms to agricultural activities across landscapes (Tondoh et al., 2011).

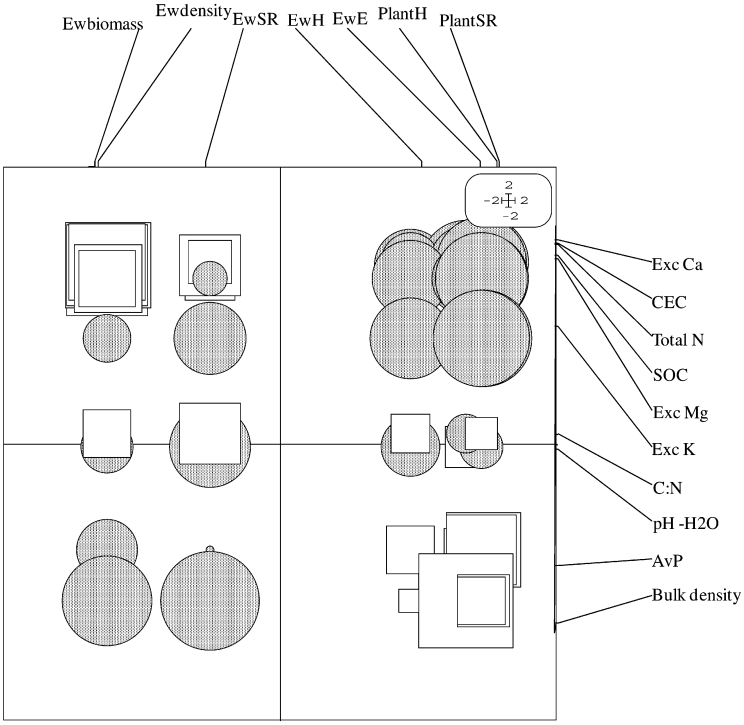

Fig. 5. Cross table summarizing the relationship between biotic and edaphic parameters in the factorial plan (1–2) of the COI. Circles and squares represent positive and negative scores, respectively and the size is proportional to the corresponding value.

4.3. Soil bulk density, nutrient content, soil organic matter pool and stocks

Soil bulk density, the only physical property measured, significantly increased under cocoa plantations indicating a tendency of soil compaction likely due to human traffic associated with cocoa management operation such as harvesting, weeding and replanting activities as observed in Ghana by Dawoe et al. (2014). It also likely that the huge standing litter in cocoa systems with low decomposition rates might have contributed to harden the floor and therefore increasing the bulk density. Significant losses of SOM over the first 10 years are likely due to increasing mineralization coupled with soils acidification, which led to significant decrease in retention and availability of cations. This could have also been magnified by runoff and erosion (Roose and Barthes, 2001). Similar trends have been found in shaded cocoa systems in Ghana (Isaac et al., 2005; Dawoe et al., 2014) under the assumption that carbon breakdown through land clearing is the root cause. The continuous decrease in the soil organic carbon (SOC) pool and total N over time is indicative of the unsustainability of the full-sun cocoa system as reported by Lal (2009) in a recent review. In the same way, other soil properties such as CEC, declined and remained largely unmitigated, while exchangeable Ca, Mg and K showed a moderate reduction within the first 10 years of cocoa cropping. Similar observations were made in the Ashanti region in Ghana, where these cations remained stable up to 15 years or showed an increasing tendency at 30 years (Dawoe et al., 2014). According to the same authors, this result can be attributed to trade-off between nutrients export through cocoa bean harvest and "the nutrient pumping" effect of deep rooting cocoa trees. Unfortunately, trends in the variation of nutrients sequestered in the leaf litter along the chronosequence are not clear enough to allow speculations on the relationship between standing litter stock and soil properties. However, the marked but not significance increase of nutrient stocks in the 20-year-old plantations is indicative of the contribution of leaf litter in the re-accumulation of nutrient content over time. It is noteworthy that changes in soil parameters varied strongly across sampling sites, showing marked differences in SOC, total N, CEC and SOM stocks. This is likely explained by spatial variation in soil parameters as SOM, CEC and the C:N ratio from Nkroadjo to Petit Bouaké. Indeed Nkroadjo, the less agricultural-intensified site is located by to the Forest Reserve of Téné, where conservation efforts have drastically reduced human footprints. Consequently the high values of SOC, total N, CEC and SOM stocks at Nkroadjo, decreased at Djekoffikro and Petit Bouaké, which are respectively moderately and highly degraded sites.

In general, SOC and total N stocks were impaired by cocoa cropping as up to 47.5% and 42.9%, respectively was removed over the first 10 years. However, the drop in SOC stock stabilized from 10 (−47.5%) to 20 years (−46.7%), while a decrease (−42,9% to −38.1%) was observed for total N stock over the same period. This revealed the beginning of re-accumulation in the system. Hence, the loss of SOC (−28.8% to −46.7%) and total N (−28.6% to −42.9%) stocks in cocoa stands showed the crucial role that might have played diverse shade trees left out at the very beginning of the system in building up SOM as revealed by Chiti et al. (2013) in South-western Ghana.

The apparent rise in avP content can be explained by the hold-up exerted by available P levels relative to other nutrients after forest conversion. It can therefore be presumed that avP levels did not decrease over due to return through litter fall as external addition of mineral P barely happened in such systems. Moreover, it is hypothesized that accumulation of huge cocoa leaf litter of low quality (C:N ratio ranging from 32.1 to 32.7, see Table 2) implying low decomposition capability and high soil moisture has reduced the loss of avP. Another strong possibility is the immobilization of P by iron (Fe) and aluminium (Al) anions as it is common in acid soils (Colding et al., 2000; Thanh et al., 2001; Arias et al., 2006; Pizzeghello et al., 2011).

4.4. Effect of cocoa farming on soil properties, earthworm and plant communities

The Monte Carlo test of COI revealed a strong relationship between biotic components (earthworm and plant communities) and soil parameters with a "chronosequence effect" along the first axis while a "site effect" was found throughout the second. This co-structure mainly involved the forests, the 5- and the 20-year-old plantations. These findings mainly showed the effect of land conversion in cocoa plantations as high values of biodiversity and soil chemical parameters (SOC, Total N, Mg, Ca, CEC) associated with forests, which are progressively replaced by moderate values of C:N ratio and pH-H_2O (5-year-old cocoa stands) and in the end, high values of earthworm abundance, species richness, bulk density and avP took over. In Costa Rica, Rousseau et al. (2012) found similar results in old-growth forests that were referred to as functionally viable ecosystem unlike old cocoa stand plots where high bulk density were associated with enhanced phosphorus availability. Soil compaction indicated by high bulk density are likely explained by the overwhelming presence of geophageous earthworm such as *M. omodeoi* and *D. terraenigrae* that were found responsible for the production of massive globular casts in tree-based systems (Tondoh et al., 2011; Guéi and Tondoh, 2012) and might have positively influenced phosphorus availability (Lavelle and Martin, 1992; Kuczak et al., 2006). Therefore the apparent rise in avP beneath old cocoa plantations should also be accountable for the massive presence of earthworm populations through huge casting activity. These findings underscored the idea that sun-grown cocoa farming has a devastating impact on soil chemical characteristics over time with surprisingly beneficial effect on earthworm abundance, species richness and phosphorus availability.

4.5. Change in soil quality

In general, most soil parameters have decreased significantly along the chronosequence, with soil quality being continuously deteriorated over time in cocoa stands after initial forest clearance. Most DIs were above −20 highlighting the potential impact of full-sun cocoa farming on soil quality degradation (Wang et al., 2001). This observation is consistent with previous studies that considered sun-grown cocoa cropping systems as a threat to food security and environmental sustainability (Siebert, 2002; Schroth and Harvey, 2007). The COI analysis revealed the association of high content of soil chemical variables with plant and earthworm diversity in the forest, confirming the assumption that soil quality in tropical ecosystems depends to a large extent on plant residue inputs (Tian et al., 2007) and litter residence times (Hairiah et al., 2006) that provide soil protection and food for soil organisms. Apart from avP, the decrease in soil parameters is in line with previous studies in Nigeria, Bangladesh and Ethiopia (Adejuwon and Ekanade, 1988; Islam and Weil, 2000; Lemenih et al., 2005). Moreover, the significant drop in soil parameters beneath the plantations of 10 years might suggest the occurrence of a marked degradation in soil quality about 10 years after initial forest clearance. This period appeared therefore as a threshold of degradation, which is close to the period of 8 years found by Lal (1996) under various cropping systems in West Africa where the use of fertilizers was recommended. Conversely in Ghana, the reverse trend obtained in shaded-cocoa systems in Kumasi areas, where soil quality (0–20 cm) seriously deteriorated 3 years after forest clearing and thereafter, improved in 15 and 30-year-old plantations (Dawoe et al., 2014), highlights the potential beneficial impact of shaded-cocoa systems on soil quality. As a result, tree-based cocoa cropping systems in between which crops and trees are planted as recommended by several studies for rapid soil carbon build-up, biodiversity conservation and sustainable cocoa production (Herzog, 1994; Rice and Greenberg, 2000; Siebert, 2002; Franzen and Mulder, 2007; Schroth and Harvey, 2007; Sonwa et al., 2007; Bisseleua et al., 2009; Gama-Rodrigues et al., 2010; An et al., 2013), should be vowed as an alternative to the current cropping system.

4.6. Options for sustainable shaded-cocoa plantations

Despite the positive impact of cocoa agroforests in terms of environmental protection, ecological services and income diversification as stressed by a number of studies (Rice and Greenberg, 2000; Siebert, 2002; Franzen and Mulder, 2007; Bisseleua et al., 2009; Gama-Rodrigues et al., 2010; An et al., 2013; Sonwa et al., 2007; Schroth and Harvey, 2007), the vast majority of Ivorian cocoa smallholders have moved towards full-sun plantations for the past 20–40 years (Ruf, 2011; Gockowski and Sonwa, 2011). A field survey realized among cocoa planters in Ghana pointed out three main reasons that might explain the decline of cocoa agroforests in West Africa (Ruf, 2011): (i) for 41% of farmers the main cause is the introduction of plant hybrid material with higher yield and profitability in a short period of time, (ii) the negative perception of ecological services of agroforests as according to 23% of farmers, shade trees may harbour squirrels and insects causing damage to cocoa pods, increase humidity and lead to black pods and finally bring about competition of cocoa trees for light and, as a result, lead to taller trees that make harvesting more difficult, (iii) the exclusion of farmers from the timber market as stressed out by 9% of farmers, is likely due to the fact that West African legislation supports loggers against farmers. Based on these constraints and together with the main findings of this study, the followings alternative cocoa systems are recommended:

- The cocoa–fruit tree intercropping system that uses fruit trees at a reasonable density for shading purposes as farmers will not promote trees that provide them with little or no returns (Ruf, 2011; Koko et al., 2013): this systems is currently in use in degraded areas of Côte d'Ivoire (Koko et al., 2013) and widespread in the southwestern part of the country where fruit trees are dominant in cocoa fields (Dumont et al., 2014);
- Given the fact that the current cocoa belt located in south-western Côte d'Ivoire is the last frontier in the expansion of cocoa areas, it seems urgent and timely to start thinking of the rehabilitation of former degraded cocoa landscapes mostly situated in the centre-west and east regions of the country to establish new cocoa stands. To this end, native legume (*Albizia zygia*, *A. adianthifolia*) and non-legumes (*Spathodea campanulata*, *Ricinodendron heudelotti*, *Terminalia ivorensis*, *T. superba*) shade trees found across cocoa stands in the current study, might be planted as multispecies fallow to rehabilitate degraded cocoa lands. This option was successfully tested in Ghana, where the role of above trees in soil fertility improvement, weed control and shade provision has been demonstrated (Anim-Kwapong and Osei-Bonsu, 2009). Chances of success of this option may be high if we consider findings of a recent study in the current cocoa belt in the Soubré area in Côte d'Ivoire, where farmers overwhelmingly want to plant trees on their farms, both to sustain their cocoa production and to diversify their livelihood (Dumont et al., 2014; Gyau et al., 2014). The success of this option is commensurate with adoption of laws by the Government acknowledging the ownership of farmers over timbers in the cocoa plantations.

4.7. Conclusion and recommendation

General results from the current study, which can be grouped into two categories, may be extrapolated to former degraded cocoa landscapes in the Central-Western and Eastern Côte d'Ivoire: (i) the conversion of semi-deciduous forests into cocoa plantations resulted in plant diversity and species richness loss due to the disappearance of a huge number of native species while earthworm abundance and species richness increased due to the appearance of species adapted to degraded lands, (ii) soil quality was severely impaired by cocoa farming with the worse scenario being found under the 10-year-old cocoa plantations and the decline in SOC, total N and CEC contributing mostly to soil quality degradation.

One of the weaknesses of this study lies in the focus on the topsoil that overlooks physical constraints such as water infiltration capacity, root depth restriction and soil compaction, which might have occurred over time beneath cocoa plantations as highlighted recently in the study area by Assié et al. (2008). Further actions to undertake will include the assessment of land degradation risks due to cocoa farming using appropriate landscape methodological approaches such as the Land Degradation Surveillance Framework (LDSF) as recommended by Vågen et al. (2013). This landscape-related method will help assessing soil health chemical and physical constraints, biodiversity loss, aboveground and belowground carbon sequestration leading to evidence-based recommendations for land rehabilitation along with sustainable intensification options of cocoa farming.

Acknowledgement

The authors gratefully acknowledge the financial support of UNEP-GEF through the project No GF/2715-2 untitled "Conservation and Sustainable management of Below-Ground Biodiversity (CSM-BGBD)", which made this study possible.

Appendix A. Forest native tree species collected across the landscape.

Family	Species
Acanthaceae	*Lankesteria elegans* (P.Beauv.) T.Anders.
Acanthaceae	*Pseuderanthemum tunicatum* (Afzel) Milne-Redh.
Adiantaceae	*Pteris burtonii* Baker
Annonaceae	*Isolona campanulata* Engl. & Diels
Annonaceae	*Monodora tenuifolia* Benth.
Annonaceae	*Uvaria tortilis* A.Chev. ex Hutch. & Dalz.
Annonaceae	*Uvariastrum pierreanum* Engl.
Annonaceae	*Uvariodendron occidentale* Le Thomas
Apocynaceae	*Alafia barteri* Oliv.
Apocynaceae	*Funtumia africana* (Benth.) Stapf
Apocynaceae	*Landolphia micrantha* (A.Chev.) Pichon
Apocynaceae	*Motandra guineensis* (Thonn.) A.DC.

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Family	Species
Apocynaceae	*Voacanga africana* Stapf
Araceae	*Anchomanes difformis* (Blume) Engl.
Araceae	*Nephthytis afzelii* Schott
Balanophoraceae	*Thonningia sanguinea* Vahl
Bombacaceae	*Bombax buonopozense* P.Beauv.
Capparidaceae	*Euadenia eminens* Hook.f.
Celastraceae	*Bequaertia mucronata* (Exell) Wilcz.
Celastraceae	*Reissantia indica* (Willd.) N.Hallé
Celastraceae	*Salacia baumannii* Loes.
Celastraceae	*Salacia erecta* (G.Don) Walp.
Celastraceae	*Salacia nitida* (Benth.) N.E.Br.
Celastraceae	*Salacia owabiensis* Hoyle
Convolvulaceae	*Calycobolus africanus* (G.Don) Heine
Convolvulaceae	*Calycobolus heudelotii* (Bak. ex Oliv.) Heine
Convolvulaceae	*Neuropeltis acuminata* (P.Beauv.) Benth.
Convolvulaceae	*Neuropeltis prevosteoides* Mangenot
Davalliaceae	*Nephrolepis biserrata* (Sw.) Schott
Dichapetalacae	*Dichapetalum toxicarium* (G.Don) Baill.
Dioscoreceae	*Dioscorea burkilliana* Miège
Dioscoreceae	*Dioscorea cayenensis* Lam.
Dioscoreceae	*Dioscorea multiflora* Mart. ex Griseb.
Dioscoreceae	*Dioscorea smilacifolia* De Wild.
Dracaenaceae	*Dracaena aubryana* Brongn. ex C.J.Morren
Dracaenaceae	*Dracaena ovata* Ker-Gawl.
Dracaenaceae	*Dracaena surculosa* Lindl.
Ebenaceae	*Diospyros canaliculata* De Wild.
Ebenaceae	*Diospyros gabunensis* Gürke
Ebenaceae	*Diospyros soubreana* F.White
Ebenaceae	*Diospyros vignei* F.White
Ebenaceae	*Diospyros viridicans* Hiern
Euphorbiaceae	*Drypetes gilgiana* (Pax) Pax & Hoffm.
Euphorbiaceae	*Drypetes singroboensis* Aké Assi
Euphorbiaceae	*Mallotus oppositifolius* (Geisel.) Müll.Arg.
Euphorbiaceae	*Mareya micrantha* (Benth.) Müll.Arg.
Euphorbiaceae	*Martretia quadricornis* Beille
Flacourtiaceae	*Scottellia klaineana* Pierre
Hoplestigmataceae	*Hoplestigma klaineanum* Pierre
Leguminseae-Papilionoideae	*Aganope gabonica* (Baill.) Polhill
Leguminseae-Papilionoideae	*Baphia nitida* Lodd.
Leguminseae-Papilionoideae	*Dalbergia albiflora* Hutch. & Dalz.
Leguminseae-Papilionoideae	*Dalbergia bignonae* Berh.
Leguminseae-Caesalpinioideae	*Bussea occidentalis* Hutch.
Leguminseae-Caesalpinioideae	*Daniellia thurifera* Benn.
Leguminseae-Caesalpinioideae	*Dialium guineense* Willd.
Leguminseae-Caesalpinioideae	*Hymenostegia afzelii* (Oliv.) Harms
Leguminseae-Caesalpinioideae	*Griffonia simplicifolia* (Vahl ex DC.) Baill.
Loganiaceae	*Strychnos splendens* Gilg
Lomariopsidaceae	*Lomariopsis guineensis* (Undrew.) Alston
Marantaceae	*Sarcophrynium brachystachyum* (Benth.) Schumann
Marantaceae	*Thaumatococcus daniellii* (Bennet) Benth.
Menispermaceae	*Penianthus patulinervis* Hutch. & Dalz.
Menispermaceae	*Sphenocentrum jollyanum* Pierre
Menispermaceae	*Tiliacora dinklagei* Engl.
Menispermaceae	*Triclisia patens* Oliv.
Meliaceae	*Entandrophragma angolense* (Welw.) C.DC.
Meliaceae	*Trichilia monadelpha* (Thonn.) J.J.De Wild.
Meliaceae	*Trichilia prieureana* A.Juss.
Meliaceae	*Turraea heterophylla* Sm.

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Family	Species
Moraceae	*Milicia excelsa* (Welw.) Berg
Moraceae	*Morus mesozygia* Stapf ex A.Chev.
Moraceae	*Streblus usambarensis* (Engl.) Berg
Moraceae	*Trilepisium madagascariense* DC.
Myrtaceae	*Eugenia salacioides* Laws. ex Hutch. & Dalz.
Napoleonaeaceae	*Napoleonaea vogelii* Hook. & Planch.
Olacaceae	*Olax gambecola* Baill.
Olacaceae	*Olax subscorpioidea* Oliv.
Olacaceae	*Strombosia pustulata* Oliv. var. *lucida* (J.Léonard) Villiers
Orchidaceae	*Bulbophyllum sp*
Orchidaceae	*Oeceoclades saundersiana* Garay & Taylor
Pandaceae	*Microdesmis keayana* J.Léonard
Polygalaceae	*Carpolobia lutea* G.Don
Rubiaceae	*Aidia genipiflora* (DC.) Dandy
Rubiaceae	*Chassalia kolly* (Schumach.) Hepper
Rubiaceae	*Coffea liberica* Bull. ex Hiern
Rubiaceae	*Corynanthe pachyceras* Schumann
Rubiaceae	*Morinda longiflora* G.Don
Rubiaceae	*Morinda lucida* Benth.
Rubiaceae	*Oxyanthus formosus* Hook.f. ex Planch.
Rubiaceae	*Pavetta corymbosa* (DC.) Williams
Rubiaceae	*Psilanthus mannii* Hook.f.
Rubiaceae	*Psychotria peduncularis* (Salisb.) Steyerm.
Rubiaceae	*Rothmannia longiflora* Salisb.
Rubiaceae	*Sacosperma paniculatum* (Benth.) G.Taylor
Rutaceae	*Vepris verdoorniana* (Exell & Mendonça) W.Mziray
Sapindaceae	*Blighia sapida* Koenig
Sapindaceae	*Blighia unijugata* Bak.
Sapindaceae	*Chytranthus carneus* Radlk.
Sapindaceae	*Deinbollia pinnata* (Poir.) Schum. & Thonn.
Sapindaceae	*Lecaniodiscus cupanioides* Planch.
Sapindaceae	*Majidea fosteri* (Sprague) Radlk.
Sapindaceae	*Paullinia pinnata* L.
Sapotaceae	*Chrysophyllum albidum* G.Don
Sapotaceae	*Chrysophyllum giganteum* A.Chev.
Sapotaceae	*Chrysophyllum subnudum* Bak.
Sapotaceae	*Englerophytum oblanceolatum* (S. Moore) T.Pennington
Sapotaceae	*Omphalocarpum pachysteloides* Hutch. & Dalz.
Sapotaceae	*Pouteria altissima* (A.Chev.) Baehni
Sterculiaceae	*Cola caricaefolia* (G.Don) Schumann
Sterculiaceae	*Cola gigantea* A.Chev. var. *glabrescens* Brenan & Keay
Sterculiaceae	*Cola reticulata* A.Chev.
Sterculiaceae	*Eribroma oblongum* (Mast.) Pierre ex Germain
Sterculiaceae	*Nesogordonia papaverifera* (A.Chev.) Cap.
Sterculiaceae	*Pterygota macrocarpa* Schumann
Ulmacaeae	*Celtis adolfi-fridericii* Engl.
Ulmacaeae	*Celtis mildbraedii* Engl.
Ulmacaeae	*Holoptelea grandis* (Hutch.) Mildbr.
Violaceae	*Rinorea ilicifolia* (Welw. ex Oliv.) O.kuntze
Violaceae	*Rinorea oblongifolia* (C.H.Wright) Chipp
Violaceae	*Rinorea yaundensis* Engl.
Vitaceae	*Cissus aralioides* (Welw. ex Bak.) Planch.

Appendix B. Pioneer tree species collected across the landscape.

Famille	Species
Acanthaceae	*Phaulopsis ciliata* (Willd.) Hepper
Acanthaceae	*Rhinacanthus virens* (Nees) Milne-Redh.

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Famille	Species
Acanthaceae	*Ruellia praetermissa* Schweinf. ex Lindau
Amaranthaceae	*Celosia trigyna* L.
Amaranthaceae	*Cyathula prostrata* (L.) Blume
Anacardiaceae	*Spondias mombin* L.
Apocynaceae	*Alstonia boonei* De Wild.
Apocynaceae	*Baissea baillonii* Hua
Apocynaceae	*Baissea zygodioides* (Schumann) Stapf
Apocynaceae	*Hunteria umbellata* (Schumann) Hall.f.
Apocynaceae	*Landolphia incerta* (Schumann) Pers.
Apocynaceae	*Rauvolfia vomitoria* Afzel.
Apocynaceae	*Strophanthus hispidus* DC.
Apocynaceae	*Strophanthus sarmentosus* DC.
Apocynaceae	*Tabernaemontana glandulosa* (Stapf) Pichon
Arecaceae	*Elaeis guineensis* Jacq.
Asclepiadaceae	*Gongronema angolense* (N.E.Br.) Bull.
Asclepiadaceae	*Gongronema latifolium* Benth.
Asclepiadaceae	*Pergularia daemia* (Forssk.) Chiov.
Asclepiadaceae	*Secamone afzelii* (Schult.) Schumann
Asteraceae	*Ageratum conyzoides* L.
Asteraceae	*Conyza sumatrensis* (Retz.) E.H.Walker
Asteraceae	*Chromolaena odorata* (L.) R.King & H.Robyns.
Asteraceae	*Synedrella nodiflora* Gaertn.
Asteraceae	*Tridax procumbens* L.
Bignoniaceae	*Newbouldia laevis* (P.Beauv.) Seem. ex Bureau
Bignoniaceae	*Spathodea campanulata* P.Beauv.
Bombacaceae	*Ceiba pentandra* (L.) Gaertn.
Burseraceae	*Canarium schweinfurthii* Engl.
Caricaceae	*Carica papaya* L.
Colchicaceae	*Gloriosa superba* L.
Combretaceae	*Combretum hispidum* Laws.
Combretaceae	*Combretum mucronatum* Schum. & Thonn.
Combretaceae	*Combretum paniculatum* Vent.
Combretaceae	*Combretum racemosum* P.Beauv.
Combretaceae	*Terminalia ivorensis* A.Chev.
Combretaceae	*Terminalia superba* Engl. & Diels
Commelinaceae	*Commelina diffusa* Burm.f.
Commelinaceae	*Commelina erecta* L.
Connaraceae	*Cnestis ferruginea* Vahl ex DC.
Convolvulaceae	*Ipomoea mauritiana* Jacq.
Cucurbitaceae	*Ruthalicia longipes* (Hook.f.) C.Jeffrey
Euphorbiaceae	*Alchornea cordifolia* (Schum. & Thonn.) Müll.Arg.
Euphorbiaceae	*Croton hirtus* L'Hér.
Euphorbiaceae	*Euphorbia heteropylla* L.
Euphorbiaceae	*Euphorbia hirta* L.
Euphorbiaceae	*Phyllanthus amarus* Schum. & Thonn.
Euphorbiaceae	*Phyllanthus muellerianus* (O.Kuntze) Exell
Euphorbiaceae	*Ricinodendron heudelotii* (Baill.) Pierre ex Heckel
Euphorbiaceae	*Tragia benthamii* Bak.
Icacinaceae	*Pyrenacantha vogeliana* Baill.
Lamiaceae	*Hoslundia opposita* Vahl
Leguminseae-Mimosoideae	*Acacia kamerunensis* Gandoger
Leguminseae-Mimosoideae	*Albizia adianthifolia* (Schum.) W.F.Wight
Leguminseae-Mimosoideae	*Albizia zygia* (DC.) J.F.Macbr.
Leguminseae-Mimosoideae	*Mimosa pudica* L.
Leguminseae-Caesalpinioideae	*Anthonotha macrophylla* P.Beauv.
Leguminseae-Caesalpinioideae	*Cassia hirsuta* L.
Leguminseae-Caesalpinioideae	*Dialium dinklagei* Harms
Leguminseae-Caesalpinioideae	*Mezoneuron benthamianum* Baill.

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Famille	Species
Leguminseae-Papilionoideae	*Indigofera macrophylla* Schum.
Leguminseae-Papilionoideae	*Leptoderris brachyptera* (Benth.) Dunn
Leguminseae-Papilionoideae	*Leptoderris fasciculata* (Benth.) Dunn
Leguminseae-Papilionoideae	*Leptoderris sp*
Leguminseae-Papilionoideae	*Millettia zechiana* Harms
Leguminseae-Papilionoideae	*Mucuna pruriens* (L.) DC.
Linaceae	*Hugonia afzelii* R.Br. ex Planch.
Loganiaceae	*Spigelia anthelmia* L.
Malvaceae	*Abutilon mauritianum* (Jacq.) Medik.
Malvaceae	*Sida acuta* Burm.f.
Marantaceae	*Hypselodelphys violacea* (Ridl.) Milne-Redh.
Marantaceae	*Marantochloa leucantha* (Schumann) Milne-Redh.
Menispermaceae	*Cissampelos owariensis* P.Beauv. ex DC.
Menispermaceae	*Rhigiocarya racemifera* Miers
Nyctaginaceae	*Boerhavia diffusa* L.
Passifloraceae	*Adenia lobata* (Jacq.) Engl.
Passifloraceae	*Passiflora foetida* L.
Periplocaceae	*Periploca nigrescens* Afzel.
Poaceae	*Panicum brevifolium* L.
Poaceae	*Panicum laxum* Sw.
Poaceae	*Sporobolus pyramidalis* P.Beauv.
Portulacaceae	*Talinum triangulare* (Jacq.) Willd.
Rhamnaceae	*Gouania longipetala* Hemsl.
Simaroubaceae	*Harrisonia abyssinica* Oliv.
Solanaceae	*Physalis angulata* L.
Solanaceae	*Solanum erianthum* D.Don
Solanaceae	*Solanum rugosum* Dunal
Sterculiaceae	*Leptonychia pubescens* Keay
Sterculiaceae	*Mansonia altissima* (A.Chev.) A.Chev.
Sterculiaceae	*Sterculia tragacantha* Lindl.
Sterculiaceae	*Triplochiton scleroxylon* Schumann
Tiliaceae	*Glyphaea brevis* (Spreng.) Monachino
Tiliaceae	*Triumfetta rhomboidea* Jacq.
Ulmaceae	*Trema orientalis* (L.) Blume
Verbenaceae	*Clerodendrum umbellatum* Poir.
Verbenaceae	*Clerodendrum verticillatum* G.Don
Verbenaceae	*Clerodendrum volubile* P.Beauv.
Verbenaceae	*Lantana camara* L.

Appendix C. Exotic plant species collected across the landscape.

Family	Species
Anacardiaceae	*Anacardium occidentale* L.
Araceae	*Xanthosoma maffafa* Schott
Bromeliaceae	*Ananas comosus* (L.) Merr.
Cannaceae	*Canna indica* L.
Euphorbiaceae	*Manihot esculenta* Crantz
Leguminseae-Mimosoideae	*Albizia lebbeck* (L.) Benth.
Lauraceae	*Persea americana* Mill.
Meliaceae	*Cedrela odorata L.*
Musaceae	*Musa sapientum* L.
Myrtaceae	*Psidium guajava* L.
Poaceae	*Zea mays* L.
Rutaceae	*Citrus sinensis* L.

Appendix D. Occurrence of earthworm species under cocoa plantations chronosequence converted from semi-deciduous forest.

Family	Species	Ecological category	Forest	Cocoa plantations		
				5-year-old	10-year-old	20-year-old
Acanthodrilidae	*Millsonia lamtoiana* (Omodeo and Vaillaud, 1967)	Detritivore	+	+		+
	Millsonia omodeo (Sims, 1986)	Geophageous mesohumic	+	+	+	+
	Millsonia nilesi (Sims, 1986)	Geophageous	+	+		+
	Dichogaster baeri (Sciacchitano, 1952)	Detritivore	+	+	+	+
	Dichogaster terraenigrae (Omodeo and Vaillaud, 1967)	Geophageous oligohumic	+	+	+	+
	Dichogaster saliens (Beddard, 1893)	Geophageous polyhumic	+	+	+	+
	Dichogaster erhrhardti (Michaelsen, 1898)	Geophageous mesohumic	+	+	+	+
	Dichogaster lamottei (Omodeo, 1958)	Detritivore	+		+	
	Dichogaster papillosa (Omodeo, 1958)	Detritivore	+	+	+	+
	Dichogaster eburnea (Csuzdi and Tondoh, 2007)	Detritivore	+	+	+	+
	Dichogaster mamillata (Csuzdi and Tondoh, 2007)	Detritivore	+		+	+
	Dichogaster affinis (Sims, 1986)	Detritivore	+	+	+	
	Dichogaster sp.	Detritivore	+	+		+
	Agastrodrilus multivesiculatus (Omodeo and Vaillaud, 1967)	Geophageous oligohumic		+	+	+
	Agastrodrilus opisthogynus (Omodeo and Vaillaud, 1967)	Geophageous oligohumic		+		
Eudrilidae	*Hyperiodrilus africanus* (Beddard, 1891)	Geophageous polyhumic		+	+	+
	Scolecillus compositus (Omodeo, 1958)	Geophageous polyhumic	+	+	+	
	Stuhlmannia zielae (Omodeo, 1958)	Geophageous polyhumic	+	+	+	+
	Stuhlmannia palustris (Omodeo and Vaillaud, 1967)	Geophageous polyhumic	+		+	+
Ocnerodrilidae	*Gordiodrilus paski* (Stephenson, 1928)	Geophageous	+	+	+	+

Appendix E. Soil physico-chemical (mean ± standard error, N = 15) variables across sampling sites.

	Petit Bouaké	Djekoffikro	Nkroadjo
Bulk density	1.3 ± 0.0	1.4 ± 0.0	1.2 ± 0.0
pH-H_20	6.2 ± 0.1	6.4 ± 0.1	6.1 ± 0.1
C (g kg^{-1})	10.9 ± 0.5	13.2 ± 1.2	17.4 ± 1.9
Total N (g kg^{-1})	1.1 ± 0.0	1.1 ± 0.1	1.4 ± 0.15
C:N	10.2 ± 0.3	11.6 ± 0.4	12.2 ± 0.4
Available P (mg kg^{-1})	45.9 ± 2.0	60.1 ± 5.2	57.4 ± 5.9
CEC (cmolc kg^{-1})	9.3 ± 0.4	10.7 ± 0.5	12.4 ± 0.8
Ca (cmolc kg^{-1})	1.4 ± 0.1	2.3 ± 0.3	2.4 ± 0.4
Mg (cmolc kg^{-1})	0.4 ± 0.0	0.6 ± 0.0	0.5 ± 0.0
K (cmolc kg^{-1})	0.1 ± 0.0	0.5 ± 0.0	0.4 ± 0.0
C stock (Mg ha^{-1})	14.4 ± 0.7	18 ± 1.6	17.4 ± 1.9
Total N (Mg ha^{-1})	1.5 ± 0.1	1.6 ± 0.2	1.4 ± 0.1

References

Adejuwon, O.J., Ekanade, O., 1988. A comparison of soil properties under different land use types in a part of the Nigerian Cocoa belt. Catena 15, 319–331.

Aké Assi, L., 2001. Flore de la Côte d'Ivoire. Catalogue Systématique, Biogéographie et écologie. Tome I, Boissiera 57. Conservatoire et Jardin Botanique de Genève, Genève, Suisse, p. 396.

Aké Assi, L., 2002. Flore de la Côte d'Ivoire. Catalogue Systématique, Biogéographie et écologie, Tome II, Boissiera 58. Conservatoire et Jardin Botanique de Genève, Genève, Suisse, p. 401.

An, S.-S., Darboux, F., Cheng, M., 2013. Revegetation as an efficient means of increasing soil aggregate stability on the Loess Plateau (China). Geoderma 209–210, 75–85.

Anderson, J.M., Ingram, J.S.I., 1993. Tropical Soil Biology and Fertility, A Handbook of Methods, second ed. CAB Int, New York.

Anim-Kwapong, G.J., Osei-Bonsu, K., 2009. Potential of natural and improved fallow using indigenous trees to facilitate cacao replanting in Ghana. Agrofor. Syst. 76, 533–542.

Anim-Kwapong, G.J., Teklehaimanot, Z., 1995. Reclamation of degraded cocoa lands using *Albizia zygia*. Land Degrad. Rehabil. 6, 109–123.

Anne, P., 1945. Carbone organique (total) du sol et de l'humus. Ann. Agron. 15, 161–172.

Anonymous, 2006. Recensement National de l'Agriculture. Ministère d'Etat. Ministère de l'Agriculture, Abidjan, p. 38.

Arias, M., Da Silva-Carballal, J., García-Rio, L., Mejuto, J., Núñez, A., 2006. Retention of phosphorus by iron and aluminium-oxides-coaled quartz particles. J. Colloid Interface Sci. 295, 65–70.

Asase, A., Ofori-Frimpong, K., Ekpe, K.P., 2009. Impact of cocoa farming on vegetation in an agricultural landscape in Ghana. Afr. J. Ecol. 48, 338–346.

Assié, K.H., Angui, K.T.P., Tamia, A.J., 2008. Effet de la mise en culture et des contraintes naturelles sur quelques propriétés physiques ferralitiques au Centre-Ouest de la Côte d'Ivoire: conséquences sur la dégradation des sols. Eur. J. Sci. Res. 23, 149–166.

Aubréville, A., 1959. Flore forestière de la Côte d'Ivoire, Vol. 15, second ed. Centre Technique Forestier Tropical, Nogent-sur-Marne, France, 3 tomes: p 372, p 342, p 334.

Balac, R., 1999. Les économies pionnière prédatrices du milieu forestier: le cas de l'économie de plantation en Côte d'Ivoire. In: Bahuchet, S., Bley, D., Pagezy, H., Vernazza-Licht, N. (Eds.), L'homme et la Foret Tropicale. pp. 429–437.

Bisseleua, D.H.B., Missoup, A.D., Vidal, S., 2009. Biodiversity conservation, ecosystem functioning, and economic incentives under cocoa agroforestry intensification. Conserv. Biol. 23, 1176–1184.

Brou, Y.T., Servat, E., Paturel, J.-M., 1998. Contribution à l'analyse des inter-relations entre activités humaines et variabilités climatiques: cas du Sud forestier ivoirien. C. R. Acad. Sci. II. 327, 833–838.

Chessel, D., Dufour, A.B., Thioulouse, J., 2004. The ADE 4 package-1. One-table methods. R News 4, 5–10.

Chiti, T., Grieco, E., Perugini, L., Rey, A., Valentini, R., 2013. Effect of the replacement of tropical forests with tree plantations on soil organic carbon levels in the Jomoro district, Ghana. Plant Soil http://dx.doi.org/10.1007/s11104-013-1928-1.

Colding, E.E., Chaney, R.L., Mulchi, C.L., 2000. Use of aluminium-and iron-rich residues to immobilize phosphorus in poultry litter and litter-amended soils. J. Environ. Qual. 29, 1924–1931.

Csuzdi, C., Tondoh, E.J., 2007. New and little-known earthworm species from the Côte d'Ivoire (Oligochaeta: Acanthodrilidae: Benhamiinia-Eudrilidae). J. Nat. Hist. 41, 2551–2567.

Dawoe, K.E., Quashie-Sam, J., Opong, K.S., 2014. Effect of land-use conversion from frorest to cocoa agroforest on soil characteristics and quality of a Ferric Lixisol in lowland humid Ghana. Agrofor. Syst. 88, 87–99.

De Rouw, A., Huon, S., Soulileuth, B., Jouquet, P., Pierrot, A., Ribolzi, O., Valentin, C., Bourdoun, B., 2010. Possibilities of carbon and nitrogen sequestration under conventional tillage and no-till cover crop farming (Mekong valeley, Laos). Agricult. Ecosys. Environ. 136, 148–161.

Dolédec, S., Chessel, D., 1994. Co-inertia analysis: an alternative method for studying species–environment relationships. Freshw. Biol. 31, 277–294.

Dray, S., Chessel, D., Thioulouse, J., 2003. Co-inertia analysis and linking of ecological data tables. Ecology 84, 3074–3089.

Dumont, S.E., Gnahoua, M.G., Ohouo, L., Sinclair, L.F., Vaast, P., 2014. Farmers in Côte d'Ivoire value integrating tree diversity in cocoa for the provision of ecosystem services. Agrofor. Syst. http://dx.doi.org/10.1007/s10457-014-9679-4.

Franzen, M., Mulder, M.B., 2007. Ecological, economic and social perspectives on cocoa production worldwide. Biodivers. Conserv. 16, 3835–3849.

Gama-Rodrigues, F.E., Nair, R.K.P., Nair, D.V., Gama-Rodrigues, C.A., Baligar, C.V., Machado, R.C.R., 2010. Carbon storage in soil size fraction under two cacao agroforestry systems in Bahia, Brazil. Environ. Manag. 45, 274–283.

Gillison, N.A., Bignell, E.D., Brewer, W.R.K., Fernandes, M.C.E., Jones, T.D., Sheil, D., May, H.P., Watt, D.A., Constantino, E., Couto, G.E., Hairiah, K., Jepson, P., Kartono, P.A., Maryanto, I., Neto, G.G., van Noordwijk, M., Silveira, A.E., Susilo, F.X., Vosti, A., Nunes, C.P., 2013. Plant functional types and traits as biodiversity indicators for tropical forests: two biogeographically separated case studies including birds, mammals and termites. Biodivers. Conserv. 22, 1909–1930.

Gockowski, J., Sonwa, D., 2011. Cocoa intensification scenarios and their predicted impact on CO_2 emissions, biodiversity conservation, and rural livelihoods in the Guinea Rain Forest of West Africa. Environ. Manag. 48, 307–321.

Guéi, A.M., Tondoh, E.J., 2012. Ecological preferences of earthworms for land-use types in semi-deciduous forest areas, Côte d'Ivoire. Ecol. Indic. 18, 644–651.

Gyau, A., Smoot, K., Kouamé, C., Diby, L., Kahia, J., Ofori, D., 2014. Farmer attitudes and intentions towards trees in cocoa (Theobroma cocoa L.) farms in Côte d'Ivoire. Agrofor. Syst. http://dx.doi.org/10.1007/s10457-014-9677-6.

Hairiah, K., Sulistyani, H., Suprayogo, D., Widiento, , Purnomosidhi, P., Widodo, H.R., van Noordwijk, M., 2006. Litter layer residence time in forest and coffee agroforestry systems in Sumberjaya, West Lampung. For. Ecol. Manag. 224, 45–57.

Hartemink, A.E., 2005. Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: a review. Adv. Agron. 86, 227–253.

Hawthorne, W.D., Jongkind, C., 2006. Woody Plants of Western African Forests. A Guide to the Forest Trees, Shrubs and Lianes from Senegal to Ghana. Kew Publishing, Royal Botanic Gardens, Kew, UK, p. 1023.

Herzog, F., 1994. Multipurpose shade trees in coffee and cocoa plantations in Côte d'Ivoire. Agrofor. Syst. 27, 259–267.

Hutchinson, J., Dalziel, J.M., 1954. Flora of West Tropical Africa, Vol. 1 Part 1, second ed. Millbank, London, p. 295.

Hutchinson, J., Dalziel, J.M., 1958. Flora of West Tropical Africa, Vol. 1 Part 2, second ed. Millbank, London, pp. 296–828.

Hutchinson, J., Dalziel, J.M., 1963. Flora of West Tropical Africa, Vol. 2, second ed. Millbank, London, p. 544.

Hutchinson, J., Dalziel, J.M., 1968. Flora of West Tropical Africa, Vol. 3 Part 1, second ed. Millbank, London, p. 276.

Hutchinson, J., Dalziel, J.M., 1972. Flora of West Tropical Africa, Vol. 3 Part 2, second ed. Millbank, London, pp. 277–574.

Isaac, M.E., Gordon, A.M., Thevathasan, N., Oppong, S.K., Quashie-Sam, J., 2005. Temporal changes in soil carbon and nitrogen in West Africa multistrata agroforestry systems: a chronosequence of pools and fluxes. Agrofor. Syst. 65, 23–31.

Islam, K.R., Weil, R.R., 2000. Land use effect on soil quality in a tropical forest ecosystem of Bangladesh. Agricult. Ecosys. Environ. 79, 9–16.

Kibblewhite, G.M., Ritz, K., Swift, J.M., 2008. Soil health in agricultural systems. Philos. Trans. R. Soc. B 3363, 685–701.

Koko, K.L., Snoeck, D., Lekadou, T.T., Assiri, A.A., 2013. Cocoa-fruit tree intercropping effects on cocoa yield, plant vigour and light interception in Côte d'Ivoire. Agrofor. Syst. 87, 1043–1052.

Kuczak, N.C., Fernandes, C.M.E., Lehmann, J., Rondon, A.M., Flavio, J., Luizão, J.F., 2006. Inorganic and organic phosphorus pools in earthworm casts (Glossoscolecidae) and a Brazilian rainforest Oxisol. Soil Biol. Biochem. 38, 553–560.

Lal, R., 1996. Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria. II. Soil chemical properties. Land Degrad. Dev. 7, 87–98.

Lal, R., 2009. Soil degradation as a reason for inadequate human nutrition. Food Secur. 1, 45–57.

Lavelle, P., Martin, A., 1992. Small-scale and large-scale effects of endogeic earthworms on soil organic matter dynamics in soil of the humid tropics. Soil Biol. Biochem. 24, 1491–1498.

Lebrun, J.-P., Stork, A.L., 1991. Enumération des Plantes à Fleurs d'Afrique Tropicale: Généralités et Annonaceae à Pandaceae. Vol. I. C. J. B, Genève, p. 249.

Lebrun, J.-P., Stork, A.L., 1992. Enumération des Plantes à Fleurs d'Afrique Tropicale: Chrysobalanaceae à Apiaceae, Vol. II. C. J. B, Genève, p. 257.

Lebrun, J.-P., Stork, A.L., 1995. Énumération des Plantes à Fleurs d'Afrique Tropicale. Monocotylédones: Limnocharitaceae à Poaceae, Vol. III. C. J. B, Genève, p. 341.

Lebrun, J.-P., Stork, A.L., 1997. Enumération des Plantes à Fleurs d'Afrique Tropicale. Gamopétales: Ericaceae à Lamiaceae, Vol. IV. C. J. B., Genève, p. 712.

Legendre, L., Legendre, P., 1984. Ecologie Numérique. Tome 1: le Traitement Multiple des Données Écologiques. Masson, Paris, p. 260.

Lemenih, M., Karltun, E., Olsson, M., 2005. Assessing soil chemical and physical property responses to deforestation and subsequent cultivation in smallholders farming system in Ethiopia. Agricult. Ecosys. Environ. 105, 373–386.

Leonard, E., Oswald, M., 1996. Une agriculture forestière sans forêt. Changements agro-écologiques et innovations paysannes en Côte d'Ivoire. Nat. Sci. Soc. 4, 202–216.

Moço, S.K.M., Gama-Rodrigues, F.E., Gama-Rodrigues, C.A., Machado, R.C.R., Baligar, C.,V., 2010. Relationships between invertebrate communities, litter quality and soil attributes under different cacao agroforestry systems in the south of Bahia, Brazil. Appl. Soil Ecol. 46, 347–354.

Moreira, M.S.F., Huising, E.J., Bignell, D., 2008. A handbook of Tropical Soil Biology. Sampling and Characterization of Belowground Biodiversity. Earthscan, London.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858.

Nelson, D.W., Sommers, L.E., 1980. Total nitrogen analysis for soil and plant tissues. J. Assoc. Off. Anal. Chem. 63, 770–778.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter, part 2. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, second ed. Am. Soc. Agron, Madison, Wisconsin, pp. 539–579.

Oke, O.D., Odebiyi, A.K., 2007. Traditional cocoa-based agroforestry and forest species conservation in Ondo State, Nigeria. Agricult. Ecosys. Environ. 122, 305–311.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Page, A.L., et al. (Eds.), Methods of Soil Snalysis, Part 2, second ed. In: Agron. Mongr., vol. 9. ASA and SSSA, Madison, WI, pp. 403–430.

Pereira, H.M., Cooper, D.H., 2006. Towards the global monitoring of biodiversity change. Trends Ecol. Evol. 21, 123–129.

Pizzeghello, D., Berti, A., Nardi, S., Moreria, F., 2011. Phosphorus forms and P-sorption properties in three alkaline soils after long-term mineral and manure applications in northeastern Italy. Agricult. Ecosys. Environ. 141, 58–66.

R Development Core Team, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN: 3-900051-07-0, URL: http://www.R-project.org/.

Rice, R.,A., Greenberg, R., 2000. Cacao cultivation and the conservation of biological biodiversity. Ambio 29, 167–173.

Robert, P., Escoufier, Y., 1976. A unifying tool for linear multivariate statistical methods: the RV-coefficient. Appl. Stat. 25, 257.

Rocchini, D., Butini, S.A., Chiarucci, A., 2005. Maximizing plant species inventory efficiency by means of remotely sensed spectral distances. Glob. Ecol. Biogeogr. 14, 437–437.

Roose, E., Barthes, B., 2001. Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. Nutr. Cycl. Agroecosyst. 61, 159–170.

Rousseau, G.X., Deheuvels, O., Arias, I.R., Somarriba, E., 2012. Indicating soil quality in cacao-based agroforestry systems and old-growth forests: The potential of soil macrofauna assemblage. Ecol. Indic. 23, 535–543.

Ruf, O.F., 2011. The myth of complex cocoa agroforests: the case of Ghana. Hum. Ecol. 39, 373–388.

Ruf, O.F., Zadi, H., 1988. Cocoa: from deforestation to reforestation. First International Workshop on sustainable cocoa growing. Smithsonian Institute, Panama.

Schroth, G., Harvey, C.A., 2007. Biodiversity conservation in cocoa production landscapes—an overview. Biodivers. Conserv. 16, 2237–2244.

Siebert, S.,F., 2002. From shade- to sun-grown perennial crops in Sulawesi, Indonesia: implications for biodiversity conservation and soil fertility. Biodivers. Conserv. 11, 1889–1902.

Somarriba, E., Beer, J., 2011. Productivity of Theobroma cacao agroforestry systems with timber or legume service shade trees. Agrofor. Syst. 81, 109–121.

Sonwa, D.J., Nkongmeneck, B.A., Weise, S.F., Tchatat, M., Adesina, A.A., Janssens, M.J.J., 2007. Diversity of plants in cocoa agroforests in the humid forest zone of Southern Cameroon. Biodivers. Conserv. 16, 2385–2400.

Technicon Industrial Systems 1977. Individual/simultaneous determination of nitrogen and/or phosphorus in BD acid digests. Technicon Industrial Systems, Tarrytown, New York.

Thanh, H.D., Sikora, J.L., Hamasaki, A., Chaney, R.L., 2001. Manure phosphorus extractability as affected by aluminium- and iron by-product and aerobic composting. J. Environ. Qual. 5, 1633–1698.

Thioulouse, J., Chessel, D., Dolédec, S., Olivier, J.M., 1997. ADE-4: a multivariate analysis and graphical display software. Stat. Comput. 7, 75–83.

Thomas, G.W., 1982. Exchangeable cations. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, Part 2. In: Agronomy monograph, ASA/SSSA, Madison, pp. 159–164. vol. 9.

Tian, G., Bajedo, M.A., Okoh, A.J., Ishida, F., Kolawole, G.O., Hayashi, Y., Salako, F.K., 2007. Effects of residue quality and climate on plant residue decomposition and nutrient release along the transect from humid to Sahel of West Africa. Biogeochemistry 86, 217–229.

Tondoh, E.J., Lavelle, P., 2005. Population dynamics of *Hyperiodrilus africanus* (Oligochaeta, Eudrilidae) in Côte d'Ivoire. J. Trop. Ecol. 21, 1–8.

Tondoh, E.J., Monin, M.L., Tiho, S., Csuzdi, C., 2007. Can earthworms be used as bio-indicators of land-use perturbations in semi-deciduous forest? Biol. Fertil. Soils 43, 585–592.

Tondoh, E.J., Guéi, A.M., Csuzdi, C., Okoth, P., 2011. Effect of land-use on the earthworm assemblages in semi-deciduous forest of Central-West Ivory Coast. Biodivers. Conserv. 20, 169–184.

Tscharntke, T., Clough, Y., Shonil, A., Bhagwat, A.S., Buchori, D., Faust, H., Hertel, D., Hölscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., Scherber, C., Schroth, G., Veldkamp, E., Thomas, C., Wanger, C.T., 2011. Multifunctional shade-tree management in tropical agroforestry landscape—a review. J. Appl. Ecol. 48, 619–629.

Vågen, T.-G., Winowiecki, L., Desta, T.L., Tondoh, E.J., 2013. The Land degradation and Surveillance Framework (LDSF). Field Guide, p. 14. Agriculture (CIAT).

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 34, 29–38.

Wang, J., Fu, B., Qiu, Y., Chen, L., 2001. Soil nutrients in relation to land use and landscape position in the semi-arid small catchment on the loess plateau in China. J. Arid Environ. 48, 537–550.

World Soil Reference, 2006. A Framework for International Classification, Correlation and Communication. In: World Soil Resources reports, vol. 103. FAO, p. 127.

Yao, K.T., 2008. Typologie des systèmes d'utilisation des sols dans la périphérie de la forêt de Téné (Oumé): Diagnostique pour une gestion durable. Mémoire de DUT, Université de Bouaké, URES de Korhogo, p. 21.

Zapfack, L., Engwald, S., Sonke, B., Achoundong, G., Madong, B.A., 2002. The impact of land use conversion on plant biodiversity in the forest zone of Cameroon. Biodivers. Conserv. 11, 2047–2061.