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Potential storages and drivers of soil organic carbon and total nitrogen across river basin landscape: The case of Mo river basin (Togo) in West Africa

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ABSTRACT

Quantification of carbon and nitrogen in soils in relation to ecological, landform and management factors over river basins is essential to understand landscape ecosystem functions and efforts to manage land restoration and the reduction of greenhouse gases emissions. Therefore, this research aimed at providing distribution of the potential storage in soil organic carbon (SOC) and total nitrogen (TN) within the multifunctional landscapes of the Mo river basin in Togo. We (1) quantified the potential storages of SOC and TN under different land use/cover types, landscape positions, and land management regimes; and (2) highlighted the relationships among these soil chemical properties, *in-situ* ecological conditions, and other hypothesized controlling factors. We used soil data from 75 sample sites to determine the quantity of SOC and TN at two depths (0–10 cm and 10–30 cm). *In-situ* ecological variables were collected simultaneously during soil sampling. Spatial information on biophysical conditions of the study sites were obtained from satellite images and most updated global topographic and soil databases. The results showed that SOC and TN varied significantly according to land cover types, soil depths, topographical positions and land protection regime. Generally, forests and woodland contain highest SOC (4%) and TN (0.3%). Agricultural fields (fallowed and cultivating farms) exhibited the lowest values of SOC and TN, except in some selected farm sites where these chemicals are still high. Topsoil layer (0–10 cm) contribute up to 60% of the total nutrient contents in soils. The sequential multivariate statistical approach unpacked and quantified the effects of inter-dependent ecological, management and landform drivers on the two important soil chemical properties (SOC and TN). The findings from this study could contribute to the improvement of national programme for assessing of greenhouse gases induced by land conversions. Based on this case-based finding in contextualization with related studies, we discussed on its implications for sustainable landscape restoration and climate change mitigation.

1. Introduction

Except water and other biosphere components, lands (comprising soil, vegetation, landscape, climate and intrinsic ecological processes) provide multiple direct and indirect functions and services to all living organisms (Costanza et al., 1997; De Beenhouwer et al., 2013; Munoz et al., 2013). Billions of people worldwide and about 60 to 70% of people in Africa directly rely on land resources to ensure their livelihoods throughout agriculture, and the collection of timber and non-timber forest products (Akanni, 2013; Ghosal, 2011; Melaku et al., 2014; Steele et al., 2015). Additionally, land is crucial for global climate mitigation, as they store and sequester elements involved in the biogeochemical cycles and greenhouse effects (Foley et al., 2005). Unfortunately, in Sub-Saharan Africa, land management approaches induce land degradation and soil

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quality loss through the poor resource allocation and use, inappropriate land-related policy development and inadequate planning and management strategies (Petter et al., 2012; Portman, 2013; Primdahl et al., 2013). Consequently, sustainable land management is facing inefficiency and failure due to the dearth of timely and accurate information.

As indicators of soil performance and productivity, soil nutrients, especially soil organic carbon (SOC) and total nitrogen (TN), provide information on land health (Vagen and Winowiecki, 2013; Wiesmeier et al., 2014a; Xiong et al., 2014; Zucca et al., 2013). Though SOC and TN are not the sole important elements for soil fertility and productivity measurement, they increasingly required interest because of their contribution to biogeochemical cycles and climate change mitigation processes. In this sense, it has been shown that soils represent one of the largest reservoirs of carbon interacting with the atmosphere, vegetation, climate and other carbon pools (Jobbágy and Jackson, 2000). Globally, soils are ranked as the third largest carbon pool after oceanic and fossil fuels, storing about 2157–2293 Pg C and 133–140 Pg N in the upper 100 cm (Batjes, 1996). However, this carbon pool is affected by numerous disturbances that affect its storage capacities. At any scale, land use/management (cropping, grazing, mining, etc.), and environmental factors (climatic, edaphic, *etc.*) have been targeted as major factors shaping soil system and its relationships with other subsystems of the biogeochemical cycle (Dorji et al., 2014; Gutiérrez-Girón et al., 2015; Vagen and Winowiecki, 2013; Villarino et al., 2014).

At any level, land management and land cover are of great importance as they play a key role in controlling soil chemical amounts and distribution (Biro et al., 2013; Houghton and Goodale, 2004). Land use land cover change that affect terrestrial ecosystems are responsive for carbon and nitrogen fluxes, in both soils and vegetation (Selassie et al., 2015; Touré et al., 2013; Wiesmeier et al., 2014c; Xue et al., 2013). Foremost of the concerns in land management is that the current traditional farming systems are fair-efficient and have been attributed the degradation of soil quality through organic matter depletion, productivity decline, and soil erosion (Sebastia et al., 2008; Touré et al., 2013; Vagen and Winowiecki, 2013). In response to climate change and human population growth, adaptation options usually tend to agricultural land expansion with acquisition and clearance of forested and other wooded vegetation stands. These practices affect land quality in terms of soil potential in carbon and nitrogen storage, its productivity, and other ecosystem service provision (Ciric et al., 2013; Kintché et al., 2010; Xue et al., 2013). In this regard, one of the research questions that should be answerless over time and space is how much SOC and TN are stored in soils undergoing perpetual and tremendous changes under the diverse options of adaptation and mitigation to climate change. The attempt in answering this question makes an insightful input in improving soil information through data update in order to reduce soil vulnerability and contribute to climate change mitigation (Conant, 2012; Wiesmeier et al., 2014a).

In Togo, published researches highlighted the adverse effects of charcoal production on soil biological properties (hypogea fauna) (Fontodji et al., 2009). At farm plot levels, studies carried out in the Northern Savannah area of Togo showed soil nutrient that long term farming induced nutrient loss while setting farm plots into fallows replenishes SOC amounts (Kintché et al., 2010; Sebastia et al., 2008). The latter authors mainly focused on the quality assessment for agricultural purposes to support farmers in building options to protect their lands. Meanwhile, available data on soils properties from The Global Assessment of Soil Degradation (GLASOD) (Oldeman et al., 1990) and Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008) are of poor resolution, especially when dealing with small landscapes. Additionally, soil potential in agricultural and wild landscapes are still unknown to be accounted for greenhouse gases (GHG) assessment

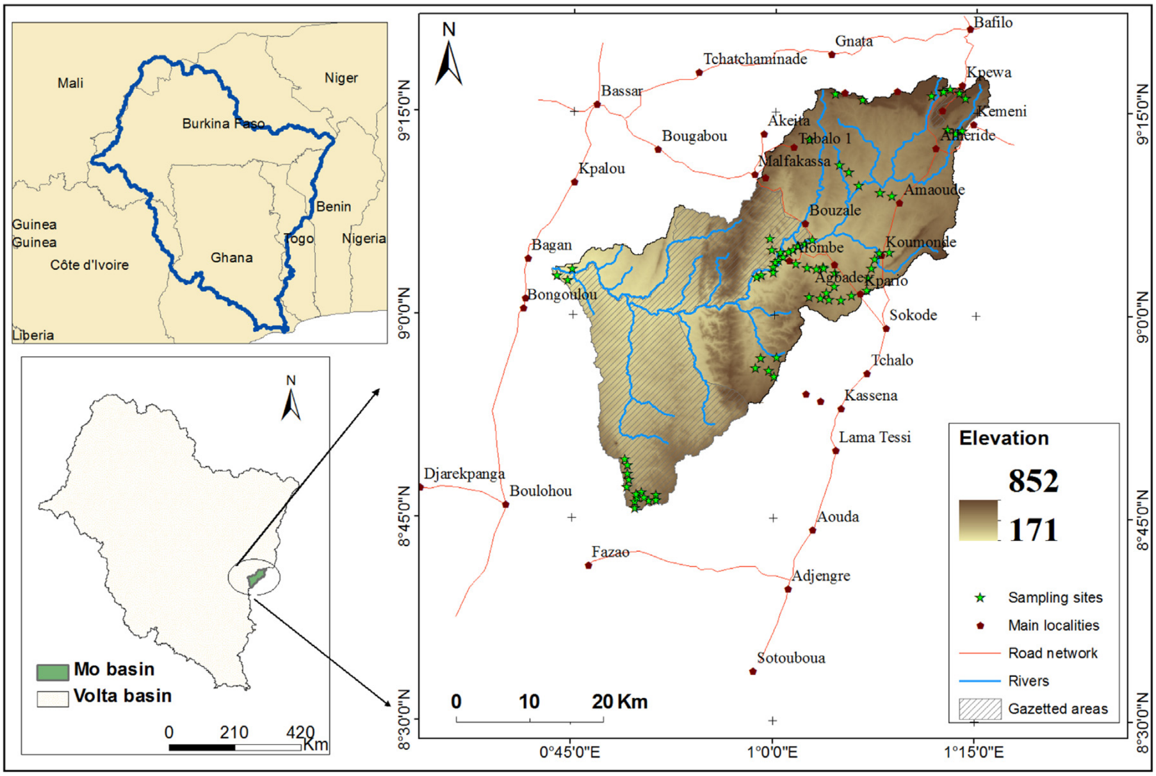

Fig. 1. Location of the study area with the sample sites.

and the contribution of Agriculture, Forestry and Other Land Uses (AFOLU) or Land Use Land Use Change and Forestry (LULUCF) sector to the national and global chemical cycles.

The knowledge on soil carbon and nutrient cycling in different ecosystems, especially mountainous lands is therefore crucial in order to understand their contribution to the viability of mitigation strategies. Accordingly, an assessment of SOC and TN potential amounts in soils would be of benefit to existing knowledge and the policy-making options regarding sustainable land management and global change mitigation. Consequently, this study was carried out in the multifunctional landscapes of Mo river basin (Togo). It focused on the soil contents in organic carbon and nitrogen to a depth of 30 cm. Specifically, the study aimed at (1) quantifying the potential storages of SOC and TN under different land use/cover types, landscape positions, and land management regimes; and (2) highlighting the relationships between soil chemical conditions, in situ ecological and biophysical conditions. It is assumed that soil concentrations in organic carbon and total nitrogen are still not sufficiently documented to support sustainable land management options in mountainous landscapes. Based on these case-based findings with related studies, we discussed on the implications for sustainable landscape management and climate change mitigation.

2. Methodology

2.1. Outline of the study area

The Mo river basin at Mo (Fig. 1), a sub-basin of Volta basin located in mountainous areas of the central region of Togo. The watershed covers about 148592 ha and is particularly sensitive as it contains a network of protected areas under human pressures (Wala et al., 2012; Woegan, 2007). The Mo basin lies within the ecological zone 2 of Togo and embeds a mosaic of ecosystems comprising dry forests, woodlands, savannahs and agro-ecosystems within human-transformed landscapes (non-protected zones) (Dourma et al., 2009; Woegan, 2007). Relief is very rugged made up of mounts with altitudes higher than 800 m above sea level, especially in Aledjo Mounts. The topography is steep, especially in the hilly areas, making inaccessible great parts of the basin. Climate is characterised by two seasons with a rainy season spanning from May to October or November. The Mo basin falls within one of the region in Togo with high rainfalls. The mean annual rainfall ranges between 1200 and 1500 mm, even 1600 mm in the highlands around Aledjo mounts. Mean minimal and maximal temperatures reach respectively 19 °C in January with the effects of Harmattan winds and 30 °C in April. A detailed soil information is lacking at local level with only Leptosols and Lithosols as dominant soil types based a broad national map (Lamouroux, 1969). According to the last census, the population of Mo river basin was about 17761 inhabitants dominated by *Tem* ethnic group (DGSCN, 2010). The same census revealed that the central region embedding Mo basin has the lowest density of population 47 persons/km^2 in 2010 compared to 109 person/km^2 on a national average. Foremost of the land uses are the small-scale farming, pasturelands, and protected areas. Thus, the main livelihood activities are crop farming, cattle grazing, firewood collection and charcoal production, and illegal gold mining, inducing land degradation especially in easily accessible areas.

2.2. Data collection and analyses

2.2.1. Sampling design and soil sample collection

Field campaigns were undertaken from March to May for soil sampling in the different land use/cover types occurring at different landscape positions. Since topography was the main constraint during the fieldwork, plots were installed randomly along a topographical gradient from valleys to top-hill or summits without any predefined plot number for each location (Diwediga et al., 2015). In addition to physical conditions (vegetation cover and accessibility), sampling was conducted following the land protection regime (protected or unprotected) to assess the effect on conservation on soil properties. Thus, we collected soil samples at different sites according to the accessibility and the vegetation homogeneity in such a way to represent the different vegetation types under different management regimes in the landscape. The collection of each sample was set in areas where vegetation features were homogeneous over a minimum surface of 1 ha (100 m × 100 m). The geographic coordinates of each core site was recorded from GPS handheld sensor. In total, seventy-five sampling sites were investigated in the different cover and management types including farmlands (both cultivating and fallow). The samples were collected at two depth levels: 0–10 cm and 10–30 cm, hereafter named as topsoil and subsoil, respectively. At each site and for each depth, a composite sample was collected from five (5) replicate samples scattered within a minimum surface of 20 × 20 m^2.

2.2.2. Laboratory analyses of soil samples

All the 150 samples were air-dried for one week before their oven drying for 24 h, in the Laboratory of Soil and Plant Analyses of the Agronomy School (University of Lomé). Chemical analyses consisted of determining soil organic carbon (SOC, in%) and soil organic matter (SOM, in%) contents, total nitrogen (N), and pH$_{\text{water}}$. SOC was determined using Walkley-Black method which consists of titration of excess potassium dichromate used with sulphuric acid to react with 3 g of dried soil. SOM was derived from the SOC using the Van Bemmelen conversion factor (1.724) commonly used for the estimation of organic matter content (Agboadoh, 2011; Fontodji et al., 2009; Sebastia et al., 2008). SOC (in g kg^{-1}) and SOM (in g kg^{-1}) were determined proportionally to prime 3 g of soil used. The total nitrogen was analyzed using Total Kjeldahl Nitrogen method. The potential of hydrogen (pH), which measures the acidity or alkalinity of a solution, was determined using the soil/water ratio of 1/2.5. The pH of the solution is electronically and directly measured using a glass electrode pH-meter.

2.2.3. Collection of in-situ ecological variables and other environmental parameters at the sampling sites

Ecological features and human disturbances were recorded at each sampling site. first, vegetation canopy cover, indicating the surface covered by the vertical projection of the all tree foliage present in a given plot, was recorded according to Braun-Blanquet method used in several studies (Diwediga et al., 2015; Folega et al., 2012; Okou et al., 2014). Then, based on the occurrence (presence/absence) without any intensity gradient, the footprints of tree logging, cattle grazing, and wildfire were recorded as human disturbances. Finally, soil submersion potential was recorded as presence/absence data. In farmlands and fallows, supplementary features such as crop type, fallow age were noted but were not considered in data interpretation. These records were not available for all sites since land users were not around to confirm our guesses. Soil and water conservation measures were not recorded since no technique was noticeable in the fields.

Other potential environmental parameters were extracted from SRTM Digital Elevation Model at 30 m resolution that is newly available from USGS (https://earthexplorer.usgs.gov.). These parameters included different terrain attributes such as slope, topographic position index (TPI), stream power index (SPI), topographic Wetness Index (TWI), mean altitude above channel level (Alt_a.c.l.), upslope contributing area (CA). TPI indicates the topographical slope position whereas TWI is a topographic indicator of spatial distribution of soil moisture conditions (Sørensen et al., 2006). SPI,

Table 1
Soil total nitrogen for different land use/cover types and soil depths.

	Deth	LUC	Mean ± StdDev	Min.	Max.	ANOVA	Tukey test	Fisher test
Total nitrogen (TN in%)	0–10 cm	Dry forests	0.16 ± 0.11	0.05	0.38	***(p = 0.000 at α = 0.05 CI)	AB ab	A ab
		Fallows	0.06 ± 0.03	0.04	0.1	***(p = 0.000 at α = 0.05 CI)	BC ab	B c
		Cultivating farms	0.06 ± 0.05	0.02	0.2		C b	C c
		Gallery forests	0.16 ± 0.08	0.05	0.3		A a	AC a
		Shrubs	0.08 ± 0.04	0.03	0.16		ABC ab	BC abc
		Woodlands	0.11 ± 0.05	0.05	0.24		ABC ab	AB abc
		Woody savannahs	0.08 ± 0.04	0.04	0.15		ABC ab	BC bc
10–30 cm	Dry forests	0.09 ± 0.06	0.04	0.19	***(p = 0.002) at 95 % CI ***(p = 0.002) at 99 % CI	A a	A a	
		Fallows	0.04 ± 0.02	0.03	0.08		AB a	B c
		Cultivating farms	0.05 ± 0.03	0.02	0.15		B a	B c
		Gallery forests	0.08 ± 0.03	0.05	0.12		A a	A ab
		Shrubs	0.05 ± 0.01	0.04	0.07		AB a	B abc
		Woodlands	0.07 ± 0.02	0.02	0.1		AB a	AB abc
		Woody savannahs	0.05 ± 0.03	0.02	0.09		AB a	AB bc
0–30 cm	Dry forests	0.25 ± 0.15	0.12	0.57	***(P = 0.000) at 95% CI ***(p = 0.000) at 99% CI	A a	A a	
		Fallows	0.10 ± 0.04	0.07	0.18		B b	BC b
		Cultivating farms	0.11 ± 0.07	0.04	0.28		B b	C c
		Gallery forests	0.24 ± 0.11	0.11	0.42		A a	A ac
		Shrubs	0.13 ± 0.05	0.07	0.23		AB ab	BC bc
		Woodlands	0.18 ± 0.06	0.12	0.33		AB ab	AB ab
		Woody savannahs	0.13 ± 0.06	0.06	0.24		AB ab	BC bc

Note: StdDev = Standard deviation; Min = minimum; Max = maximum; ANOVA = analysis of variance; Tukey and Fisher = post-hoc multiple comparison using Tukey and Fisher methods.

, ** = statistically significanti at $p < 0.01$ (99% CI), $p < 0.05$ (95% CI) respectively; **CI** = Confidence interval; ***p = probability value of the ANOVA tests ($p = 0.01$ and 0.05). Means that do not share a letter are significantly different; Capitalized letters stand for the outputs of Post hoc tests at 95% CI whereas minimal letters express comparison results from post hoc methods at 99% CI.

CA and Alt_a.c.l. are used to indicate the potential effect of channel network on water flow, as indicators of soil drainage and its influence on soil chemical contents. All these topographic are used as potential indicators of the influence of hydrological processes on soil chemical contents.

Accordingly, potential effects of soil erosion were analysed by integrating the factors of the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). In this study, the RUSLE-based factors used were the soil erodibility index (K factor), the rainfall erosivity of soil particles (R-factor), and the vegetation cover index (C-factor).

The R factor is derived based on Eq. (1) using the average annual precipitation data, covering 16 regular gridded weather stations, downloaded from the Global Weather Data (http://globalweather.tamu.edu/) (Dile and Srinivasan, 2014; Fuka et al., 2014). The equation 1 was successfully used in West African environments to calculate R-factor (Le et al., 2012; Tamene and Le, 2015).

$$R = 0.577\,Pa - 5.766 \qquad (1)$$

where R = annual rainfall erosivity ($\mathrm{MJ\,mm\,ha^{-1}h^{-1}y^{-1}}$), and Pa = average annual precipitation (mm) of nearby stations.

The values for the K factor were derived from Le et al. (2012) in accordance with the dominant soil types from the Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008). Accordingly, Mo basin is covered by two dominant types: Lixisols and Leptosols. The derived values for K factor were of 0.09 for Lixisols and 0.19 for Leptosols (Le et al., 2012). The lack of experimental data for Mo basin to calculate K factor (Angima et al., 2003; Renard et al., 1997) constrained to the usage of these limited values.

The surface cover (C factor) as a factor of soil erosion potential was estimated based on the usage of satellite image as good proxy of land cover. Therefore, the C factor values were computed using the normalised difference vegetation index (NDVI) data of the Landsat 8 image (http://www.earthexplorer.usgs.gov) using Eq. (2) (Le et al., 2012; Parveen and Kumar, 2012; Tamene et al., 2014).

$$C = \exp\left[-2.5 * \frac{\mathrm{NDVI}}{(1 - \mathrm{NDVI})}\right] \qquad (2)$$

All the spatial explicit variables potential controlling parameters of SOC and TN storages were extracted at 30 m-resolution. The various maps were then exported to a Geographical Information System for extracting values of the variables to GPS coordinates of the 75 sample sites.

2.2.4. *Statistical analyses*

All the investigated sites were described and compared using descriptive statistics. One-way analyses of variance (*ANOVA at* $p < 0.05$ and $p < 0.01$) were performed to evaluate the significance of the difference of SOC and TN according to the four main factors (land cover types, topography, soil depths and land protection status). The post-hoc comparison of Fisher-Tukey tests was used to detect least significance differences and support the ANOVA. Correlations between soil chemical properties and environmental variables were tested using pairwise correlation adjusted to Bonferroni significance level at 95% Confidence Interval (95% CI). Multivariate approaches were used to identify the different relationships between environmental conditions and soil chemical properties at landscape level. We performed a Canonical Correspondence Analysis (CCA) to detect the effects of environmental variables on soil chemical contents for all investigated sites. Another CCA was used to explore the relationships between the distribution of soil parameters and ecological variables prevailing in cultivated and fallowed sites. Among all ecological features and human disturbances used as explanatory variables, the fire occurrence, the farming or fallowing of the land, tree logging, soil submersion, protection status of lands, and cattle grazing were coded as dichotomous variables (0 = Absence and 1 = Presence). Data on topography, canopy cover and altitude above sea level were considered as simple variables at each site level. To reveal and extract the main factors explaining SOC and TN distribution, we used orthogonal rotated loadings of principal factor analyses with significance level of 95% CI. These supplementary statistics were carried to overcome the interrelationships between hypothesized environmental and topographical factors that control SOC and TN storage.

Table 2
Soil Organic Carbon (SOC) for different land use cover types and soil depths.

Variables	Depth	LULC	Mean	Min	Max	ANOVA	Tukey test	Fisher test
Soil organic carbon (SOC in%)	0–10 cm	Dry forests	3.58 ± 0.49	1.98	6.14	***(p = 0.026 at α=0.05 CI)	A a	A a
		Fallows	1.81 ± 0.79	0.82	3.03	***(p = 0.026 at α=0.01 CI)	AB a	AB ab
		Cultivating farms	2.26 ± 1.00	1.27	5.50		AB a	AB ab
		Gallery forests	2.86 ± 1.24	0.78	4.70		AB a	B ab
		Shrubs	2.12 ± 0.62	1.05	2.63		B a	B b
		Woodlands	2.71 ± 0.76	1.49	3.86		AB a	B b
		Woody savannahs	2.33 ± 1.03	1.03	4.72		AB a	B b
	10–30 cm	Dry forests	2.14 ± 0.49	1.33	2.80	*(p = 0.053 at α = 0.05 CI)		
		Fallows	2.20 ± 0.77	1.68	3.52	*(p = 0.053 at α = 0.01 CI)		
		Cultivating farms	1.52 ± 0.31	1.01	2.18			
		Gallery forests	1.93 ± 0.66	0.84	3.04			
		Shrubs	1.92 ± 0.92	1.18	3.87			
		Woodlands	2.23 ± 0.63	1.01	3.48			
		Woody savannahs	1.63 ± 0.89	0.69	3.19			
	0–30 cm	Dry forests	5.71 ± 1.44	4.34	7.96	***(p = 0.007 at α = 0.05 CI)	A a	A a
		Fallows	4.01 ± 0.62	3.43	4.88	***(p = 0.007 at α = 0.01 CI)	AB ab	AB ab
		Cultivating farms	3.78 ± 1.06	2.61	7.09		AB ab	AB ab
		Gallery forests	4.79 ± 1.38	2.91	7.65		AB ab	BC ab
		Shrubs	4.05 ± 1.20	2.69	6.47		AB ab	BC ab
		Woodlands	4.93 ± 0.93	3.47	6.36		AB ab	BC ab
		Woody savannahs	3.96 ± 1.75	1.81	7.71		B b	C b

Note: StdDev = Standard deviation; Min = minimum; Max = maximum; ANOVA = analysis of variance; Tukey and Fisher = post-hoc multiple comparison using Tukey and Fisher methods.
, ** = statistically significanti at $p < 0.01$ (99% CI), $p < 0.05$ (95% CI) respectively; **CI** = Confidence interval; ***p = probability value of the ANOVA tests ($p = 0.01$ and 0.05). Means that do not share a letter are significantly different; Capitalized letters stand for the outputs of Post hoc tests at 95% CI whereas minimal letters express comparison results from post hoc methods at 99% CI.

3. Results

3.1. Variations of SOC and TN under different land use/cover types

Total nitrogen contents in topsoil layer (0–10 cm) highly differed ($p < 0.01$) under different vegetation types, both natural and cultivated lands (Table 1). The mean TN varied from 0.06% in fallows to 0.16% in dry forests. The lowest TN record (0.02%) was found in farms whereas the highest (0.38%) was in dry forests. Agricultural landscapes exhibited the lowest TN stocks of 0.06 and 0.06% in fallows and farms, respectively. Similar to the TN contents in the topsoil, subsoil TN (10–30 cm) differed significantly according to LUC types ($p < 0.01$). The lowest (0.04%) and highest (0.09%) TN mean values occurred in the subsoil layers of woody savannahs and dry forests, respectively. At site level, records of TN ranged from 0.02% to 0.19% in the same cover types, respectively. Accordingly, the TN amounts (cumulative over 0–30 cm) varied significantly ($p = 0.01$) among the soil cover types. At this depth, the lowest mean value (0.10%) occurred in fallows whereas dry forests have the highest mean content (0.25%). In general, the results showed that TN contents are highly influenced by LUC types, with soils under moderate to high canopy cover being TN-richer. TN contents decreased with increasing soil depth, indicating that deeper soil layer contains less TN. At both depths, farm soils contain more TN than the soils in the fallows.

As far as soil organic carbon (SOC) is concerned, a significant difference was observed for the average values in the topsoil according to land cover types ($p < 0.05$) (Table 2). The average SOC contents ranged from 1.81% (fallows) to 3.58% (dry forests), which store by far the highest SOC. Dry forests, riparian forests, and woodlands were significantly richer in SOC contents whilst man-made ecosystems were poor ($p = 0.026$). The rank order was obtained: dry forests > riparian forests > woodlands > woody savannahs > farms > shrubs > fallows. In contrast, SOC in subsoil did not show significant differences in relation with the cover types (Table 2). However, the lowest (1.52%) and highest (2.23%) average contents of SOC occurred in farmlands and woodlands, respectively. The following rank order was observed: woodlands > fallows > dry forests > riparian forests > shrubs > woody savannahs > farms. The cumulative amount of SOC (0–30 cm) varied highly ($p = 0.007$) between the different LUC types. Lowest mean value (1.81%) occurred in woody savannahs whereas the dry forests stored the highest mean SOC content (7.96%). In general, the results showed that SOC are highly affected by land use in the topsoil layer whilst SOC variability in subsoil is not significantly related to land use and management. Soils under moderate to high canopy cover were richer in SOC. For all LUC types, SOC decreases with increasing soil depth. In the topsoil, cultivating farm soils contain more SOC than fallows, whereas the subsoil organic matter was lower in the fallows.

3.2. Distribution of SOC and TN according to topographical positions

Fig. 2a shows the significant variability of SOC in relation with topography in Mo landscapes. Mean SOC values showed highest records in inland valleys and low-hill. Flat terrain (1.89%) and riverbank (2.16%) are the landscape positions with less SOC whereas low-hills (2.63%) and mid-hills (3.53%) exhibited the highest SOC. The general trend of SOC values as follow: inland > low-hill > riverbank > mid-hill > summit > flat terrain. In the subsoil, there was no evidence of difference for SOC in subsoil at any topographical position. The river banks (2.06%) and top-hills (2.03%) contained more SOC. The following trend was observed: summit > riverbank > mid-hill > low-hill > inland > flat terrain. In aggregate, SOC of the overall layer (0–30 cm) is significantly affected by topography with mid-hill (5.42%) containing more SOC than riverbanks (4.22%), low-hill (4.10%), and flat terrain (3.84%). Topsoil exhibited the highest SOC stocks for all topographical positions while flat terrain showed the lowest mean records regardless to the depth.

On average, topsoil TN contents varied significantly from 0.05% on flat terrains to 0.15% on mid-hills (Fig. 2b). The lowest record (0.02%) was found in cultivating farms whereas the highest (0.38%) was on mid-hills. TN in this top 10 cm ranked in the following order: inland > low-hill > riverbank > summit

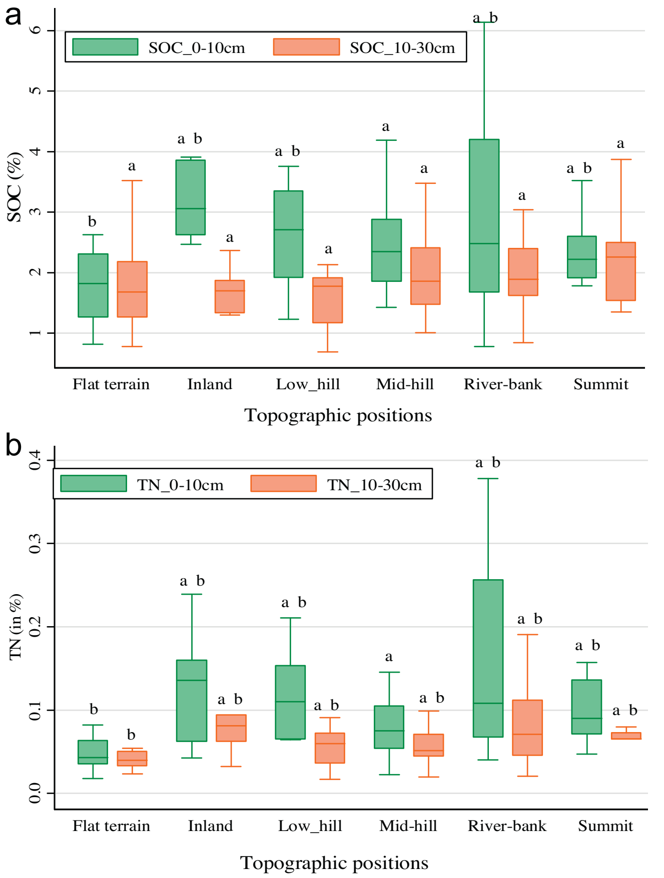

Fig. 2. a Daistribution of SOC according to landscape positions for different soil depths. Dbistribution of TN according to landscape positions for different soil depths.

> mid-hill > flat terrain. In the subsoil, significant variations were observed according to topographical locations ($p = 0.002$). The lowest (0.05%) and highest (0.08%) mean values of TN were obtained for flat terrains and mid-hills, respectively. The records ranged from 0.02% in flat terrain to 0.19% in mid-hills. In contrast to the topsoil, the rank order was inland valleys > riverbank > low-hill > summit > mid-hill > flat terrain. For the total depth (0–30 cm), TN contents varied significantly with lowest mean value (0.10%) occurring in flat terrains and the highest mean record (0.23%) on mid-hills. Meanwhile, the minimum and maximum of records were of 0.04% and 0.57% in the same topographical positions, respectively. The trend in TN contents in both soil depths showed that inland valleys, riverbanks, and low-hills are the landscape positions of highest TN stocks.

3.3. *Influence of land protection regime on soil chemical properties*

An analysis of protected versus unprotected areas showed that land protection status had significant effects on the amounts of SOC contents in the soils (Fig. 3). Regardless to the LUC types, mean SOC in topsoil is higher than its content in subsoil. Exception is observed in the riparian forests of the unprotected areas where subsoil was more concentrated in SOC than the topsoil. Dry forests of both protected and unprotected areas and protected riparian forests showed highest values (over 3%) of SOC in the top layer. In the topsoil layer of protected areas, the following ranking order was observed: riparian forests > dry forests> woodlands> tree savannahs whereas the land cover types ranked dry forests > woodlands > shrubs > tree savannahs > riparian forests in unprotected areas. In the subsoil, SOC ranked in the following order: woodlands > riparian forests > dry forests > tree savannahs within protected areas. Meanwhile the rank in unprotected lands was riparian forests > dry forests > woodlands > shrubs > tree savannahs.

Similar to the trends of SOC, TN exhibited high variability in the top soil layer in dry forests and riparian forests (Fig. 4). TN contents were low in the subsoil (less than 0.10%) for all LUC types. Meanwhile, protected riparian forests (more than 0.20%) and dry forests (more than 0.15%) showed highest values in upper 10 cm. TN contents in the topsoil were ranked as follows: riparian forests > dry forests > woodlands > tree savannahs, and dry forests > woodlands > riparian forests > shrubs > tree savannahs, for protected and unprotected lands, respectively. The trends of TN in the subsoil also differed according to the land protection status. In protected areas, subsoil TN decreased following the gradient: riparian forests > woodlands > tree savannahs > dry

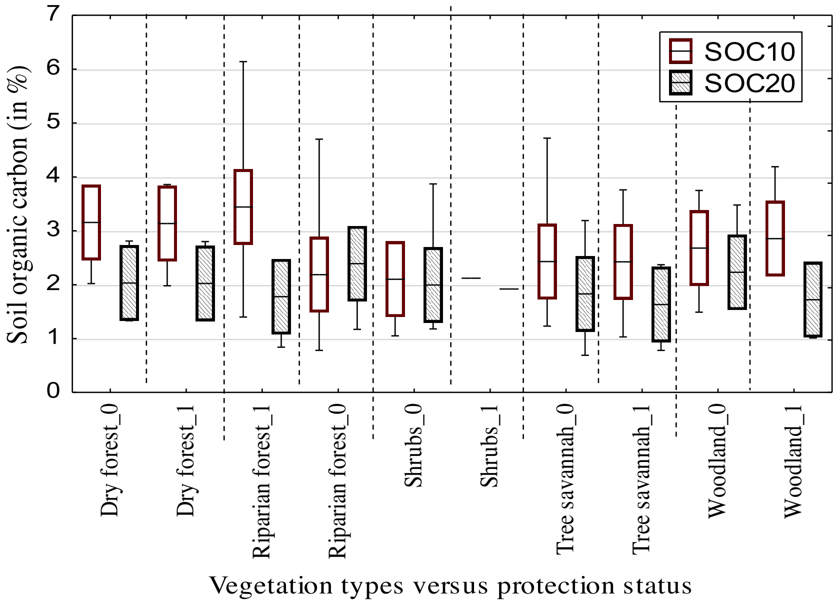

Fig. 3. Effects of land protection status on SOC distribution.

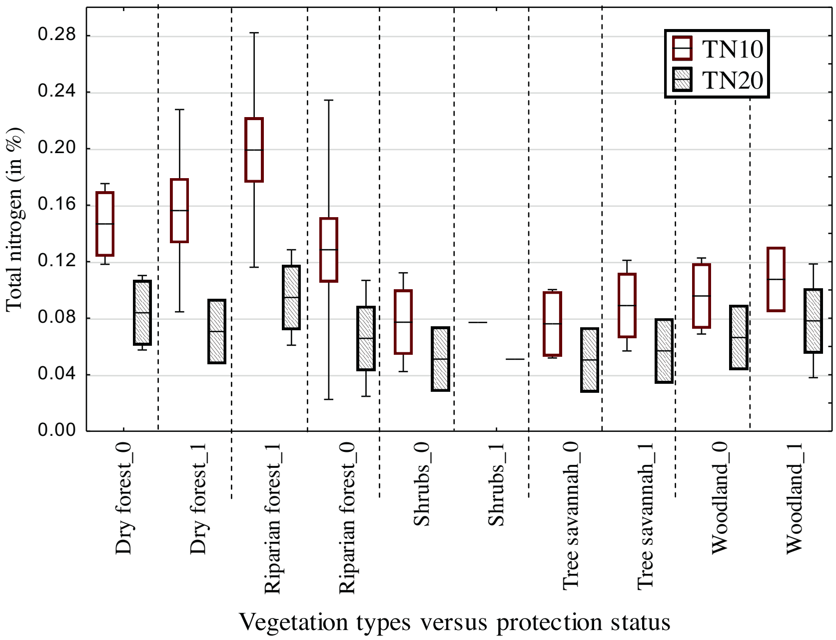

Fig. 4. Effects of land protection status on TN distribution.

forests. In contrast, the decreasing gradient of subsoil TN was dry forests > woodlands > tree savannahs > riparian forests > shrubs.

3.4. Interactions between soil properties and environmental variables at landscape level

Along axis 1, the CCA (Fig. 5) revealed that the first three explanatory variables affecting mostly SOC and TN in the first upper 10 cm, were topography, vegetation canopy cover (related to LUC types), and land protection status. The amount of SOC in the first upper 10 cm and the overall 30 cm is often affected by land protection status, topography and canopy cover. However, SOC in the lower 20 cm tend to be higher when fire, grazing, tree logging occurs in the sites. This suggests that the occurrence of fire and tree logging often reduce the availability of litter that degrades into SOC. Since grazing occurs in bush fallows where fire occurrence is high, it is evident that fallowing has the same effect as fire and logging on SOC in soil. Though pH is less affected by in situ conditions, fallowed soils and submersible conditions are related to high pH values. Along axis 1, human-related activities negatively correlated with high canopy cover, high topography and protected lands, which positively increase soil nutrient contents.

Furthermore, both negative and positive correlations were observed between topographic indices and environmental parameters, and the soil contents in organic carbon and total nitrogen (Table 3). At first glance, strong positive correlations ($p \leq 0.05$) were found between soil chemical properties at both depths, except SOC in the lower 20 cm that exhibited positive but not significant correlations with SOC in lower 20 cm and TN in upper 10 cm. Except SOC in the subsoil (SOC20), Hydrogen potential (pH) had slight negative effects on TN and SOC at the two depths. With regard to the ecological conditions, topsoil organic carbon was positively correlated with TPI whereas subsoil TN was strongly affected by slope. C, K, and R factors defining soil erosion by water had negative effects on SOC and TN at both depth with exception of R factor in the lower 20 cm. Especially, C factor ha significant negative effects on these soil properties in lower 20 cm. Significant correlations were observed between factors that define soil erosion potential, and

Table 3
Correlation matrix between soil chemical properties, different pedogenetic and topographic parameters.

	SOC10	TN10	SOC20	TN20	SOC30	TN30	pH10	pH20	C-factor	K-factor	R-factor	SPI	TWI	Alt	Alt_a_ch	Slope	CA
TN10	0.77*	1															
SOC20	0.12	0.14	1														
TN20	0.64*	0.66*	0.28*	1													
SOC30	0.87*	0.70*	0.59*	0.66*	1												
TN30	0.79*	0.97*	0.20	0.83*	0.74*	1											
pH10	−0.01	−0.03	0.01	−0.10	−0.00	−0.05	1										
pH20	−0.02	−0.09	0.06	−0.03	0.01	−0.07	0.10	1									
C-factor	−0.11	−0.22	−0.29*	−0.26*	−0.23*	−0.25*	0.03	−0.14	1								
K-factor	−0.15	−0.10	−0.18	−0.13	−0.21	−0.11	0.08	−0.03	0.44*	1							
R-factor	−0.02	−0.01	0.00	0.01	−0.01	−0.00	0.01	0.03	0.33*	0.52*	1						
SPI	−0.01	0.09	0.19	−0.15	0.09	0.02	0.11	−0.09	−0.12	−0.01	0.01	1					
TWI	0.00	0.11	0.11	−0.06	0.06	0.06	−0.11	−0.13	−0.05	−0.00	0.05	0.55*	1				
Alt	0.01	0.03	0.10	0.15	0.06	0.08	−0.27*	−0.02	−0.32*	−0.37*	−0.03	−0.12	−0.19	1			
Alt_a_ch	0.00	0.02	−0.04	0.12	−0.01	0.06	−0.18	0.11	−0.23*	−0.12	−0.11	−0.09	−0.30*	0.54*	1		
Slope	0.22	0.07	0.05	0.26*	0.21	0.14	−0.13	0.03	−0.23*	−0.05	0.03	−0.07	−0.37*	0.47*	0.45*	1	
CA	−0.01	0.09	0.19	−0.15	0.09	0.02	0.11	−0.09	−0.11	−0.01	0.01	1.00*	0.55*	−0.13	−0.09	−0.07	1
TPI	−0.26*	−0.18	0.05	−0.20	−0.19	−0.20	0.21	−0.02	0.09	0.02	−0.05	−0.05	−0.41*	−0.00	0.25*	−0.06	−0.05

Note: Correlation coefficients are displayed with star at 95% CI. For acronyms, please refer to other notes.

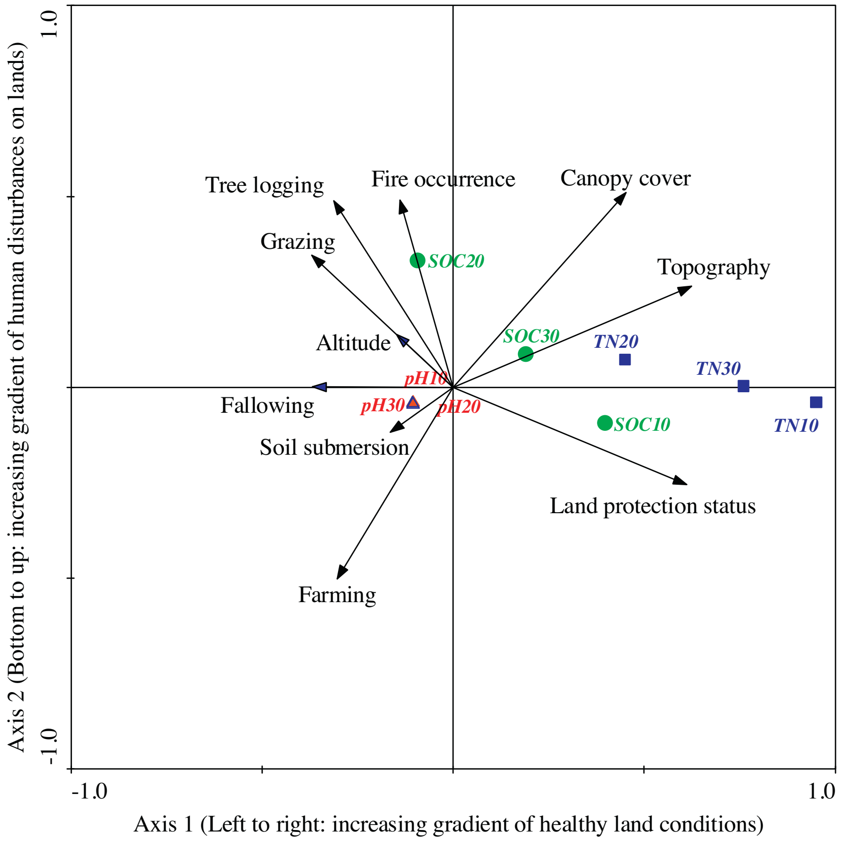

Fig. 5. CCA displaying the relationships between ecological variables and soil chemical properties.

affecting subsequent nutrient availability in the soil. The cover factor C is significantly determined by the altitudes above sea and channel levels as well as the slope.

Additionally, rotated loadings of factor analyses were conducted to reveal and extract the main factors controlling the distribution of SOC and TN at all depths (Table 4). The Varimax indicates that the four first factors explained about 82% of the total variances. Factor 1, with 36% to the explained variance, showed high loadings for the chemical properties (SOC and TN) at all depths, but very low loadings for the environmental variables. It explained the soil richness defined by chemical accumulation in all soil layers. For factor 2, SPI, TWI, and CA exhibited positive high loadings (0.70–0.89), indicating the direct influence of soil moisture and drainage on soil properties. This factor defines mostly topographical conditions likely to affect positively or negatively the soil properties. Similarly, slope, altitudes, CA and SPI defining the factor 3 indicated the influence of landscape positions and soil susceptibility to erosion on soil chemical distribution. Higher topographic indices were often negatively correlated with higher soil vulnerability to erosion, resulting in negative effects on soil chemical contents. The fourth factor is less informative though it indicates high negative loading value of −0.74 for subsoil SOC.

Table 4
Varimax of loading factors of the principal factor analysis.

Variables	Factor 1	Factor 2	Factor 3	Factor 4
SOC10	**0.87**	−0.02	−0.25	0.09
TN10	**0.87**	0.10	−0.22	0.18
TN20	**0.84**	−0.20	−0.11	0.01
SOC30	**0.90**	0.09	−0.03	−0.29
TN30	**0.93**	0.00	−0.20	0.14
SOC20	**0.40**	0.20	**0.34**	**−0.74**
Alt	0.18	**−0.39**	**0.55**	0.22
Alt.ch	0.10	**−0.41**	**0.48**	0.26
Slope	0.26	**−0.37**	**0.36**	0.26
CA	0.06	**0.89**	**0.36**	0.19
SPI	0.06	**0.89**	**0.36**	0.19
TWI	0.06	**0.70**	−0.02	0.09
C-factor	**−0.34**	0.04	**−0.50**	0.06
K-factor	−0.25	0.10	**−0.49**	0.13
R-factor	−0.07	0.08	**−0.33**	0.10
pH10	−0.08	0.13	−0.12	−0.20
pH20	−0.02	−0.11	0.07	−0.13
TPI	−0.24	−0.18	0.15	−0.18
Eigen values	04.43	02.69	01.83	01.07
% of variance explained	36.07	21.87	14.90	08.70
Cumulative% variance explained over factors	36.07	57.94	72.84	81.54

Note: SOC10, SOC20 and SOC30 stand for SOC in the topsoil, subsoil and the overall 30 cm. Ditto for TN and pH. K, R, LS and C factors are the RUSLE input parameters. SPI = stream power index; TWI = topographic wetness index, Alt.ch = altitude above channel; D_road = distance to the main road; D_village = distance to a village center; Land_man = Land management regime; GSL = gross soil loss.

3.5. Soil chemical properties-environment interactions in agro-systems

The CCA of Fig. 6 revealed that the two land uses (agricultural and abandoned lands) are quite similar according to soil characteristics (blue triangles clustered around the centre of the axes 1 and 2). This is because fallowed lands less than three years, not yet recovered. However, the main factors which differentiated sample sites are the ecological variables (black dots). In the right half of the axis 1, fire and grazing are the predominant environmental disturbances occurring in fallows (green rectangles). Fallows in the Mo

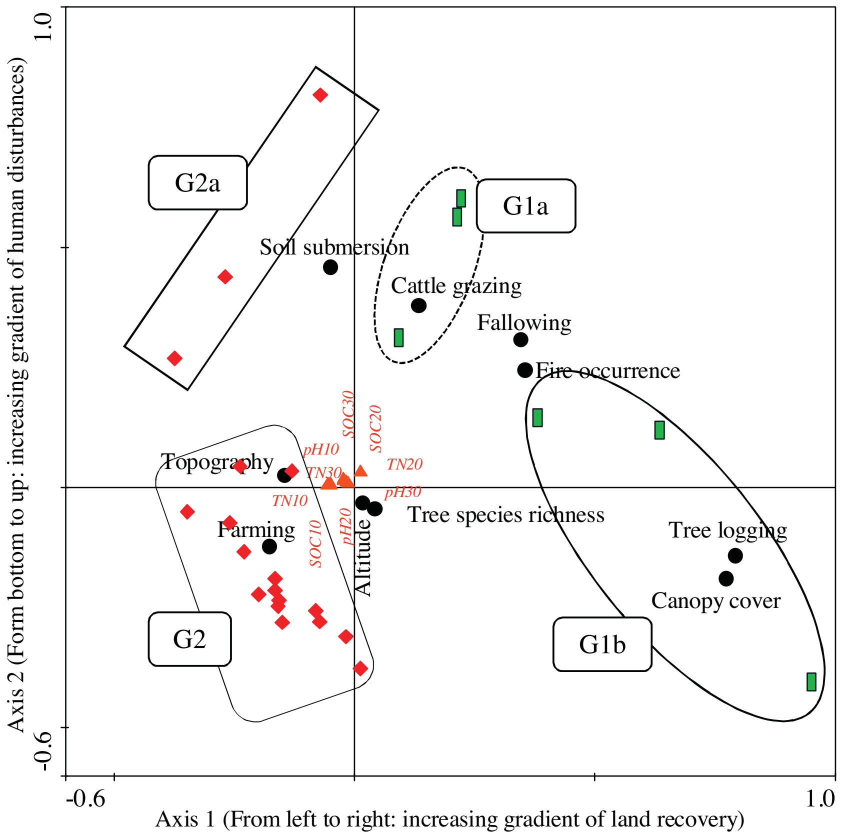

Fig. 6. Canonical Correspondence Analysis (CCA) showing the distribution of and the similarity/dissimilarity among soil samples in agro-systems.

basin are bush fallows where cattle breeders used to set fire for forage. Axis 1 highlighted that chemical properties in farmlands are somehow slightly higher than fallows, probably due to fact that farms are still fertile and have not reached a critical fertility level to be set into fallows. Tree logging related to canopy cover occurred in one site due to the recovering of the vegetation. These environmental disturbances did not occur in farmlands (red diamonds) where tree canopy cover is low, and fire occurrence and grazing are inexistent. Among other environmental features, topography, altitude and woody species richness do not differentiate significantly farms and fallows.

Soil samples in agro-systems exhibited a certain level of similarity/dissimilarity shaped by the intrinsic prevailing environmental variables. Two major groups of agro-systems are discriminated. One hand, G1 composed of 6 sites, corresponds to fallows or abandoned lands after years of cropping. G1 occurs at any topographical position and experiences activities such as fuel wood gathering, grazing and fire occurrence. At higher dissimilarity level, G1 is subdivided into G1a and G1b. G1a is characterized by sites located on riverbanks (S4 and S8) and flat terrain (S34). Woody plant species richness ranges from 15 to 22 with slight vegetation recruitment (high canopy cover). In contrast, sites of G1b are located on submersible soils and have low species richness (6–15). They also experienced grazing and fire effects. On the other hand, G2 is a cluster of 18 sites located in current farmlands. In these sites, no fire, logging, and grazing activities occurs. G2 is made up of G2b corresponding to a mosaic of farm sites located mostly on submersible soils (except S33 and S43) at variable topographic positions. G2a (S35, S22, and S13) were located on submersible soils where grazing activities occurred.

4. Discussions

4.1. Patterns of SOC and TN storage in Mo river basin

The analysis of soil data within the Mo basin showed a spatial variability of SOC and TN in relation to LUC types, land protection status and landforms. In the first instance, the influence of LUC types on SOC and TN was evident through their high contents in natural lands compared to agricultural lands (up to a difference of 2.2%). Similar observations have been reported in the northern landscapes of Togo (Sebastia et al., 2008) and south-eastern landscapes of Ethiopia (Abera and Belachew, 2011). Furthermore, other findings in the same study region reported similar SOC-richer dry forests than savannahs (Diwediga et al., 2015; Fontodji et al., 2009). In this study, SOC in 0–10 cm depth (2.04–3.22%) for all LUC types is slightly higher than those reported by Fontodji et al. (2009) for a topsoil of 0–20 cm depth (1.5–3.15%). This ascertained the fact that the deeper the soil layer, the lower its contents in SOC and TN. In line with Bessah et al. (2016), the highest SOC contents was recorded in the topsoil of all LUC types but varied across them because land use/management and cover might have significant influence.

On the basis that soils of natural vegetation provided the baseline for the potential fertility, similar differences in terms of SOC and TN contents between the croplands and forest soils have been noted in northern Togo, as a consequence of agricultural land use inducing the loss of soil fertility (Sebastia et al., 2008). The cultivation processes and other practices inducing the loss of vegetation cover caused a significant reduction of SOC and TN inputs consecutive to the loss of native vegetation. In addition, Gidena (2016) reported that the low SOC and TN in agricultural lands might be due to the effects of tillage that induces the loss of C as CO_2 by breaking up soil aggregates and exposing the OM to microbes. With regard to TN, the correlation outputs showed that high contents are strongly correlated with high SOC, indicating that practices inducing SOC depletion (Emiru and Gebrekidan, 2013; Xue et al., 2013) would decreased TN contents while conservation would lead to consecutive accumulation of chemicals.

Furthermore, this study conducted in mountainous areas showed that geomorphic positions strongly determined the spatial distribution of SOC and TN, with richer soils in lower topographic positions. Ofori et al. (2013) made similar observations and related that to the surface runoff which increases the nutrient concentration along the toposequence by carrying them downward slopes, especially in the topsoil. Similar to the effects of LUC types, topography induced spatial variability in SOC and TN with topsoil richer than subsoil. However, the spatial patterns of soil conditions, especially its nutrient contents may be induced by many other factors.

4.2. *Factors controlling the distribution of SOC and TN in Mo river basin*

Beside topography and LUC types, other factors such as *in situ* ecological variables and human disturbances affect the spatial distribution of the soil nutrients (Meng et al., 2014; Wang et al., 2013, 2010). This study revealed that land use/cover types, as reported by Yao et al. (2010) and Bessah et al. (2016), affect SOC and TN availability. In the mid, Fontodji et al. (2009) showed that charcoal production reduces the OM availability at the kiln sites, indicating that tree cutting and fire adversely affect soil stability and functions of carbon and nitrogen reservoirs (Novara et al., 2014). As a result of high SOC and TN content in low lands, the overland flow and runoff play an important role in the nutrient transport and sedimentation, increasing the SOC and TN stocks in inland valleys, lowlands and riverbanks (Liu and Bliss, 2003; Yadav and Malanson, 2013). As indicators of surface runoff and soil erosion effects, the negative correlation between the RUSLE factors (K, C and R factors) and the SOC and TN, especially in the topsoil, indicated that erosive rainfall on high erodible and less covered soils deplete the topsoil OM and nitrogen. These effects were less significant in the subsoil, confirming the high sensitivity of the topsoil to management and erosion in the landscape. Though it is established that high amounts of rainfall induces high biomass production and low OM decomposition in soils (Wiesmeier et al., 2014b, 2013), its intensity could have adverse effects on nutrient storage, due to rapid surface runoff that causes the detachment and leaching of finer sediment (Cheng et al., 2010).

4.3. *Land use/management inducing variability in the SOC and TN*

As it is common, current farming systems in the Mo basin rely on the natural land productivity for crop production. This suggests that they induce loss of fertility after years of farming through a depletion of SOC, TN and other nutrients in relation with the management systems. Compared to natural lands, cultivated lands exhibited low records of SOC (3.9%) and TN (0.11%) for a 30 cm depth, but they still have soil high quality thresholds for agricultural purposes, confirming that traditional tillage methods do not excessively disturb soil layers to a depth greater than 30 cm depth as reported by (Vagen and Winowiecki, 2013). In addition, this study revealed high SOC and TN in farmlands compared to fallows probably because the former are still fertile and have not reached a critical impoverishment level to be turned into fallow. This finding contrasted the results of Novara et al. (2014) who found that land abandonment after many years increased the soils nutrients. This may be due to the age of the fallows in this study, which are abandoned lands of less than 3 years, suggesting that replenishment of SOC and TN in soils after years of cropping does not occur immediately after land abandonment.

Furthermore, it has been shown that land clearing and continuous cultivation reduced more than 50%, even worse, of SOC and TN compared to undisturbed native soils (Knops and Tilman, 2000; Parras-Alcaantara et al., 2013; Solomon et al., 2000). In this study, PA soils stored more TN and SOC at the two depths than human-affected soils. This highlighted the positive effects of land protection on healthy soil, appealing for necessary and important measures to enhance land conservation and carbon and nitrogen stocks for both food security and climate change mitigation.

5. Conclusion and implications for sustainable land management and conservation

This paper evaluated the soil conditions in the Mo River basin through an analysis of SOC and TN contents in the various vegetation types and topographical positions in relation with the ecological variables controlling their spatial distribution. All sites exhibited decreasing TN and SOC with increasing soil depth indicating that the topsoil concentrated more SOC and TN. Measured SOC and TN contents for 0–10 cm, 10–30 cm and 0–30 cm depths varied both within and between sites. In the topsoil (0–10 cm), the average TN varied from 0.056% in fallows to 0.159% in dry forests whereas in the subsoil (10–30 cm), the lowest (0.043%) and the highest (0.091%) average TN contents occurred in the woody savannahs and dry forests, respectively. As far as SOC in the topsoil is concerned, a significant difference was observed between vegetation types, with an average SOC ranging from 1.81% in fallows to 3.58% in dry forests. Dry forests, gallery forests, and woodlands were significantly SOC-richer. In contrast, SOC in subsoil layer did not show any significant difference in relation with the vegetation types. Generally, SOC and TN are highly concentrated in the soils under healthy vegetation whereas they decreased with increasing soil depths. This study further showed that the SOC density exhibited high spatial variability in relation to the terrain variability. In the topsoil, flat terrain (1.89%) and riverbank (2.16%) were less SOC-richer whereas lower (2.63%) and mid-slopes (3.53%) exhibited the highest SOC. River banks (2.06%) and summits (2.03%) recorded the highest average SOC. With regard to the TN, its average content in the topsoil varied significantly from 0.05% on flat terrain to 0.150% on mid-slopes whereas the lowest (0.046%) and highest (0.084%) averages were observed on flat terrain and mid-slope, respectively. Generally, environmental disturbances such as fire, grazing, soil erosion and land conservation status are the major factors influencing the contents and spatial variability of SOC and TN. This study achieved the diagnostic of SOC and TN as key characteristics measuring threats to soil health, and identified the drivers of soil-based ESS provision for climate mitigation and food security.

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