DRIVERS OF SOIL ORGANIC CARBON AND TOTAL NITROGEN STOCKS ALONG A CLIMATIC GRADIENT IN WEST AFRICA.

T. L. J. ILBOUDO*[1], L. N'G. DIBY[2], I. D. KIBA[3,5], J. SIX[4], E. FROSSARD[5], N. H. BISMARK[1]

[1]Institut du développement rural, Université Nazi Boni, Bobo Dioulasso, 01 BP 1091 Bobo-Dioulasso 01, Burkina Faso

[2]Institut National Polytechnique Félix HOUPHOUËT-BOIGNY (INP-HB), Ecole Supérieure d'Agronomie (ESA), BP 1313 Yamoussoukro, Côte d'Ivoire

[3]Institut de l'Environnement et de Recherches Agricoles, Ouagadougou, 04 BP 8645 Ouaga-dougou 04, Burkina Faso

[4]Group of Sustainable Agroecosystems, Swiss Federal Institute of Technology, Zurich, 8092 Zurich, Switzerland

[5]Group of Plant Nutrition, Swiss Federal Institute of Technology, Zurich, 8315 Lindau, Swit-zerland

*Correspondence to:tilboudo20@gmail.com

ABSTRACT

Carbon storage in soil is nowadays a world goal. The present study contributes to achieve this goal. In this study, we measured soil organic carbon (SOC) and total nitrogen (TN) content in different land uses in four sites (Liliyo, Tiéningboué, Midebdo and Leo) along a climatic gra-dient in West Africa. We used the Land Degradation Surveillance Framework for data collec-tion. Soil samples were taken, in each site at 0 - 20 cm, 20 - 50 cm, 50 - 80 cm and 80 - 110 cm depth in different land uses. We developed Partial Least Square regression models to pre-dict SOC, TN and clay concentrations from mid-infrared soil spectra. We then calculated SOC and TN stocks per sampling depth and conducted a path analysis to identify the factors controlling this stock. Our results showed that at landscape level, SOC and TN stocks varied with land uses and SOC and TN stocks was higher in humid sites than semi-humid sites par-ticularly at 0 - 20 cm. Soil clay content remained the principal factor of SOC and TN stocks at along the climatic gradient. At land use and site levels, erosion and fire also effected SOC stock while at regional level, it is annual rainfall that also affected SOC. This study indicated protecting soil clay could be the best option to maintain and improve SOC and TN stocks in West Africa.

Key words: Soil organic carbon stock, land use, drivers, climatic gradient and West Africa

RESUME

FACTEURS CONTRÔLANT LES STOCKS DE CARBONE ET D'AZOTE LE LONG D'UN GRADIENT CLIMATIQUE EN AFRIQUE DE L'OUEST

Stocker le carbone dans le sol est de nos jours un objectif mondial. Notre étude contribue à l'atteinte de cet objectif. Cette étude a consisté à mesurer la concentration du carbone orga-nique du sol (SOC) et de l'azote (TN) dans différentes utilisations de terre dans quatre sites le long d'un gradient climatique en Afrique de l'Ouest. Nous avons utilisé le cadre de surveil-lance des terres dégradées pour la collecte des données. Les échantillons de sol ont été préle-vés à 0 - 20 cm, 20 - 50 cm, 50 - 80 cm et 80 - 110 cm. Les stocks de SOC et TN ont donc été calculés en utilisant la densité apparente du sol. Nous avons déterminé les facteurs contrô-lant le stock de SOC en utilisant l'analyse des relations structurelles. Nos résultats ont montré que les stocks de SOC et TN varient en fonction des différentes utilisations des terres. Les stocks SOC et TN étaient plus élevés dans les sites humides par rapport aux sites semi-humides. L'argile était le principal facteur contrôlant les stocks de SOC et TN. En plus, l'érosion et le feu ont aussi affecté la variabilité du stock SOC. La hauteur des pluies a aussi affecté la variabilité du stock SOC. La protection de l'argile dans le sol semble être une solu-tion pour le maintien et l'augmentation des stocks de SOC et TN.

Mots clés : *Carbone organique du sol, utilisation des terres, facteurs, gradient climatique et Ouest Africa.*

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INTRODUCTION

Soil organic carbon (SOC) and soil total nitrogen (TN) storage is nowadays a world goal to reduce climate warning that is already having a significant impact on the world, and on peo-ple's lives (UN COP25). Furthermore, SOC improves soil nutrients retention, soil water hold-ing capacity and soil microbial activities, buffers toxic and harmful substances (Hagedorn *et al.*, 2018). Thus, it affects plant biomass production and increases crops yields (Dayamba *et al.,* 2016, Zvomuya *et al.,* 2008). Therefore, determining factors that control SOC and TN storage could contribute to maintain and to increase SOC and TN stocks and to reduce climate warming. Several studies (Saiz *et al.,* 2012, McBratney *et al.,* 2014, Gray *et al.*, 2019) showed that many factors influence SOC stocks and the effect of these factors depends on the given space scale. At local scale, where climatic conditions are similar, vegetation, soil properties have stronger impact on SOC and TN stocks. Indeed, many studies demonstrated that soil clay, clay ± silt, sand and Fe / Al oxide content and soil bulk density affect SOC stock (Saiz *et al.,* 2012, Tondoh *et al.,* 2016, Araujo *et al.,* 2017). Other studies revealed that soil parent material, rainfall, slope, fire, erosion and vegetation can significantly influence SOC storage (Barré *et al*., 2017, Angst *et al.,* 2018; Zhu *et al*., 2018, Jendoubi *et al.*, 2019, Gray *et al.*, 2019, Prietzel and Christophel, 2014). Land management practices strongly impact SOC stock (McBratney *et al.,* 2014). Zhong *et al.* (2018) showed that SOC stocks increased from semi-arid to humid regions at 0 - 10 cm and 10 - 20 cm of soil depths. At regional scale, climatic conditions, namely temperature and precipitation are key drivers of SOC storage (Wiesmeier *et al.,* 2019 and Adhikari *et al.,* 2019).

However, little data on SOC stock factors are available for West Africa. Moreover, deeper soils and larger scale were rarely included in the precedent studies, besides land uses change constantly.

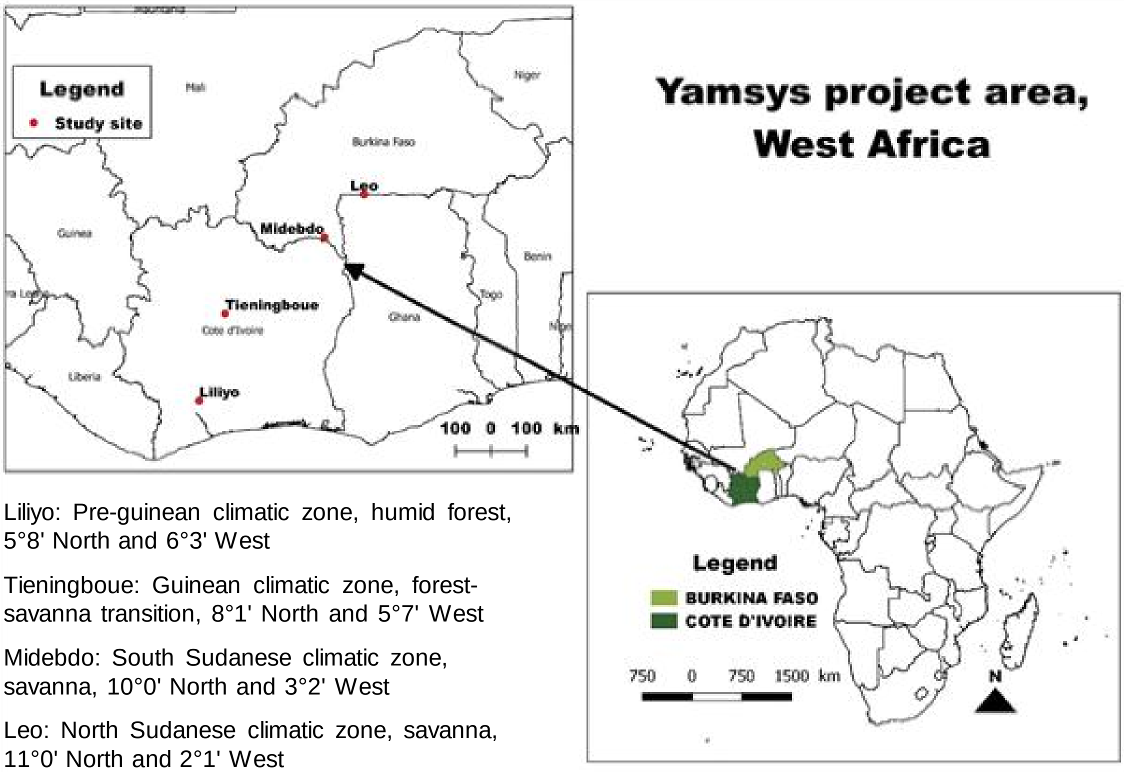
This study tried to fill this gap and aimed to i) demonstrate how land uses affect SOC and TN stocks in different soil depths along a climatic gradient in West Africa, ii) determine how factors are controlling SOC stocks along a climatic gradient in West Africa. The present work is a data base for soil carbon and nitrogen modelling and monitoring.

MATERIAL AND METHODS

STUDY AREAS

We studied four sites situated in different climatic areas in West Africa (figure 1). The studied sites were from the humid forest to the semi-humid savanna. The humid forest area, located at Liliyo in the western south of Côte d'Ivoire, was in Guinean climatic zone (FeSerWAM, 2022). The forest savanna transition area, located at Tiéningboué in the centre of Côte d'Ivoire, was in the Sudanese climatic zone (FeSerWAM, 2022). The semi humid south sa-vanna, located at Midebdo in the western south of Burkina Faso, was in the Sudanese climatic zone (FeSerWAM, 2022). The semi humid north savanna, located at Leo in the western centre of Burkina Faso, was in the Sudano-sahelian climatic zone (FeSerWAM, 2022). From 2005 to 2014, the mean annual total rainfall was around 1568.3 ± 242.4 mm in the humid forest with two humid seasons (May to November), 1241.3 ± 145.7 mm in the humid forest savanna with one humid season (Avril to October), 1067.5 ± 131.2 mm in the semi humid south savanna with one humid season (May to October) and 1052.6 ± 128.6 mm in the semi humid north savanna with one humid season (May to September) (NASA / TRMM, 2015). The mean tem-perature was about 28.0 ± 2.3 °C in humid forest, 29.3 ± 1.8 °C in humid forest savanna, 33.0 ± 3.8 °C in the semi humid south savanna and 34.3 ± 4.1 °C in the semi humid north savanna (NASA / MODIS, 2015).

Soils in humid forest were mostly Ferralsols (Perraud and De la Souche?re, 1970, WRB, 2014) and were derived from granitic rocks and schists (Dabin *et al.*, 1960). Soils in humid forest savanna, were derived from granitic and granito-gneiss rocks (Diatta, 1996) leading mainly to Plinthosols and Nitisols (Dabin *et al.,* 1960, Jones *et al.,* 2013). Other soils such as Luvisols and Lixisols could also be found in this area (Dabin *et al.*, 1960). Soils in semi humid south savanna derived from undifferentiated migmatites and granitic rocks (Hottin and Ouedraogo, 1976) and were mainly Lixisols. Nitisols, Gleysols, Leptosols, Cambisols could also be ob-served (Moreau *et al.*, 1969, WRB, 2014). Soils in semi humid north savanna derived also from undifferentiated migmatites and granitic rocks (Hottin and Ouedraogo, 1976) and were mainly Lixisols and rarely Gleysols under clay - sandy material deeply (Kaloga, 1973). The most common soil clays in these zones were kaolinites, a low-activity clay mineral but illites and smectites were also observed (Dabin *et al.,* 1960, ORSTOM, 1969). These soils were also characterised by the presence of goethite and hematite and were acidic (pHwater of 4 - 6) and have low available nutrients content (Dabin *et al.*, 1960, ORSTOM, 1969). These four zones are considered here as a climatic gradient from the humid forest to the semi-humid north savanna.



Liliyo: Pre-guinean climatic zone, humid forest, 5°8' North and 6°3' West

Tieningboue: Guinean climatic zone, forest-savanna transition, 8°1' North and 5°7' West

Midebdo: South Sudanese climatic zone, savanna, 10°0' North and 3°2' West

Leo: North Sudanese climatic zone, savanna, 11°0' North and 2°1' West

Figure 1 : Climatic gradient and study sites location in West Africa.

Gradient climatique et localisation des sites d'étude en Afrique de l'Ouest.

SAMPLING DESIGN AND FIELD DATA COLLECTION

We collected the field data in humid forest savanna and semi humid south and north savanna from June 2015 to February 2016 and in Liliyo in July 2013. We used, for each site, the Land Degradation Surveillance Framework (LDSF) proposed by Vågen *et al.* (2010) for the data collection and soil sampling. LDSF is a standardized hierarchical field survey designed used to provide a biophysical baseline at landscape level and a monitoring and evaluation frame-work to assessing processes of land degradation (Vågen and Winowiecki, 2018). The LDSF design is composed of a sentinel site or block of 10 km x 10 km divided into 16 equal tiles known as clusters. Each cluster contains a random centroid with 10 sampling plots in which data are collected.

Land use was classified according to vegetation classes proposed in LDSF field guide (Vågen *et al.,* 2010). In addition, we separated annual croplands from perennial croplands due to their presumably difference in C inputs to soil. For each of the LDSF plot, we recorded information on the geographic coordinates and altitude with a GPS. The main slope in each plot was measured with a Omni-slope sighting clinometer. The topography and the impacts of erosion, fire, and grazing were estimated by inspecting the surrounding area visually.

Soil samples were taken at the center-point of each plot at 0 - 20 cm, 20 - 50 cm, 50 - 80 cm and 80 - 110 cm of soil depth. Soil depth restrictions before 110 cm were registered. A total of 2374 soil samples were collected. Each soil sample was kept in a plastic bag and send to the laboratory. Soil samples were air-dried then sieved at 2 mm. The weights of soil fine (< 2 mm) and coarse fractions (> 2 mm) were recorded and soil fine fraction was used for the different analysis.

SOIL MID INFRARED SPECTROSCOPY

We used the mid-infrared spectroscopy method to analyse soil total carbon, total nitrogen and soil texture (Johnson *et al.*, 2019). Ten grams of air-dried soil fine fraction were milled at 200 - 50 µm with a Retsch mixer mill MM 200. The milled soil was used for spectral analysis using Alpha Fourier Transform Infrared (FT- IR) spectrometer equipped with ZnSe optics. Soil scans was done according to Terhoeven-Urselmans *et al.* (2010). The spectra were rec-orded from 4000 cm-1 to 500 cm-1 at 2 cm of resolution after 32 scans. From all soil spectra distribution, 15 % of soil samples (356 soil samples) were randomly selected using the Ke-nard-Stone algorithm for chemical analysis. Soil total carbon and total nitrogen contents in the selected soil samples were measured by combustion of 60 mg milled soil weighed into tin foil capsules (Vario PYRO cube, Elementar Analyse system GmBH). The soil texture of the se-lected samples was also determined by the laser diffraction (LA-950V2 Partica analyser). Given the acidic to neutral conditions of soils in West Africa (Dabin *et al.,* 1960, ORSTOM, 1969), total carbon is assumed similar to organic carbon.

We developed partial least square regression models of total C, total N, clay, silt and sand content using both spectral and chemical analyses data of the selected samples. The models were calibrated with 70 % of the selected samples and validated with the remaining 30 %. C, N and clay models performed well with $R^2 > 0.8$ and RMSEA < 9 (see figures S1, S2, S3 in supplementary material). These models were subsequently used to predict C, N and clay for all the soil samples. Soil total Fe, Al and silt were measure using XRF method.

CARBON AND NITROGEN STOCKS CALCULATIONS

Soil organic carbon (SOC) stock for a given depth was calculated according to equation (1). Soil total nitrogen (TN) stock was also calculated with the same equation including soil total nitrogen concentration instead of soil carbon concentration. Soil bulk density given in soilgrids for each of the four areas was used for stocks calculation.

$$SOC\ stock = SOC * BD * Depth * (1 - frag) * 100 \quad (1)$$

where SOC stock = soil organic carbon stock (t C ha-1), SOC = soil organic carbon concentra-tion in soil fines fraction (< 2 mm) measured in the laboratory (%), BD = soil bulk density (g cm-3), Depth in cm, frag = % volume of soil coarse fragments /100 to account for soil coarse fraction since SOC was measured on the fine fraction only. 100 is used to convert the unit to t C ha-1.

We calculated the sum of SOC stock for all soil depths and all plots and land uses, then ex-trapolated it to get the SOC total stock for 100 km2 expressed in tons for the given area.

PATH ANALYSIS FOR CARBON AND NITROGEN STOCKS DRIVERS

We used path analysis to identify the factors controlling SOC stock and TN stock variability. We used empirical knowledge and assumptions to construct a conceptual model (figure S4 in supplementary material). Soil clay content was assumed to have direct effects on SOC stock and TN stock. Slope and erosion were assumed to influence directly soil clay content and in-directly SOC stock and TN stock. Fire was assumed to increase erosion impact by destroying aboveground biomass and litter on the soil.

Data of measured variables were used to build a path model. Path standardized coefficients and their significance levels were calculated by the confirmatory factor analysis (CFA) ap-proach described by Brown (2006). Only the significant relations ($p < 0.05$) were kept in the model and the goodness of the path model was tested using comparative fit index (CFI) and root mean square error of approximation (RMSEA). CFI values range from zero to one, with large values suggesting a good fit. RMSEA varies from zero to one, the smaller value indicat-ing better model fit (Hu and Bentler, 1999).

STATISTICALANALYSIS

All statistics were done with R software version 3.0.0. Means, standard deviation and stand-ard error were calculated using ANOVA function. Means were compared using Tukey test in lsmeans package, means with same the letter are not significantly different.

RESULTS AND DISCUSSION

RESULTS

Land uses characteristics

Grasslands, perennial croplands and annual croplands were the common land uses for the four studied areas (table S1 in supplementary material). Wooded grasslands were also observed in all zones except in humid forest. Forests (1 %) and bushlands (12 %) were only found in the humid forest savanna. Woodlands (1 %) was only found in semi humid south savanna while shrublands (1 %) were observed in semi-humid south and north savanna. Humid forest was mostly occupied by perennial croplands (92 %) while humid forest savanna zone was occupied by wooded grasslands (30 %), annual croplands (28 %) and perennial croplands (22 %). In semi humid south savanna, wooded grasslands (50 %), grasslands (23 %) and annual croplands (15 %) were mostly observed whereas in semi humid north savanna, annual croplands (48 %) and wooded grasslands (40 %) were mostly represented. Cocoa (*Theobroma cacao* Linn.), palm oil (*Elaeis guineensis* Jacq.) and rubber (*Hevea brasiliensis* (Kunth) Müll.Arg.) were the perennial crops in humid forest while cashew (*Anacardium occidentale* Linn.) was the perennial crop in humid forest savanna and semi humid south and north savan-na. Citrus (*Citrus sinensis* (L.) Osbeck.) plantation and mango (*Mangifera indica* L.) plantation were also found in semi humid north savanna. The four studied sites were yam (*Dioscorea* sp) production zones but there were other annual crops such as rice (*Oriza sativa* L.) and maize (*Zea mays* L.) in humid forest, cotton (*Gossypium herbaceum* L.) and rice in humid forest savanna, millet (*Pennisetum glaucum* (L.) R.Br.), sorghum (*Sorghum bicolor* (L.) Moench) in semi humid south savanna and maize, sorghum and sesame (*Sesamum indicum* L.) in semi humid north savanna. The dominant species in grasslands and wooded grasslands were Rauvolfia vomitoria Afzel. in humid forest, Uapacca togoensis Pax, Terminalia scimperiana Hochst. in humid forest-savanna and Vitellaria paradoxa C.F. Gaertn. and *Combretum collinum* Fresen. Subsp. *Hypolinum* (Diels) in semi humid south and north savanna. The dom-inant species in croplands were Rauvolfia vomitoria Afzel. and *Citrus sinensis* (L.) Osbeck. in humid forest, *Parkia biglobosa* (Jacq.) Benth. and *Margaritaria discoidea* (Baill.) Webster. in humid forest-savanna and Vitellaria paradoxa C.F. Gaertn. in semi humid south and north savanna. Along the gradient, the proportion of perennial croplands decreased while the pro-portion of annual croplands increased and crops such as rice and maize were replaced by millet and sorghum.

Soil characteristics of the studied sites

Clay content varied per climatic zone and per land use (Table 1). In wooded grasslands, at 0 - 20 cm, clay content was lower in semi humid south savanna while clay content was similar in humid forest-savanna and semi humid north savanna. However, no significant difference was found between the four sites in grasslands. In annual and perennial croplands, at 0 - 20 cm humid forest and humid forest-savanna recorded the higher clay content than semi humid south and north savanna. From 20 cm to 110 cm, clay content in semi humid north savanna remained the highest in wooded grasslands (table S2 in supplementary materials). In Grass-lands, no difference was observed except at 50 - 80 cm where humid forest savanna presented higher clay content. In perennial croplands, though no difference was observed at 20 - 50 cm, humid forest-savanna at 50 - 110 cm and humid forest at 80 - 110 cm had the highest clay content. In annual and perennial croplands, humid forest and forest-savanna presented higher clay content and clay content in semi humid south savanna particularly lower in annual croplands and wooded grasslands.

Table 1 : Soil clay (%) content at 0 - 20 cm depth in different land uses along a climatic gradi-ent in West Africa.

Teneur d'argile du sol (%) à 0-20 cm dans différentes utilisations des terres suivant le gradient climatique.

Site	Annual Cropland	Perennial Cropland	Grassland	Wooded grassland
HF	29.7 ± 10.4 ab	32.2 ± 10.1 a	36.4 a	
HFS	32.7 ± 9.0 a	35.2 ± 8.9 a	24.6 ± 7.3 a	24.1 ± 8.2 a
SHSS	20.1 ± 8.2 c	23.1 ± 7.9 b	21.7 ± 7.3 a	20.5 ± 6.3 b
SHNS	24.5 ± 8.5 bc	21.3 ± 3.4 b	26.7 ± 8.6 a	26.8 ± 9.7 a

HF = Humid forest, HFS = humid forest savanna, SHSS = semi humid south savanna, SHNS = semi humid north savanna.

Table 2 : Land uses characteristics along a climatic gradient in West Africa.

Caractéristiques des différentes utilisations des terres suivant le gradient climatique.

Characteristic	Site	Wooded grassland	Grassland	Perennial cropland	Annual cropland
Slope (%)	HF		4.9 ab	7.4 ± 8.6 a	6.3 ± 4.0 a
	HFS	7.7 ± 3.0 a	5.8 ± 3.0 a	5.1 ± 2.5 a	5.3 ± 2.7 a
	SHSS	3.7 ± 1.5 b	3.6 ± 1.4 b	4.0 ± 1.7 a	3.9 ± 1.5 b
	SHNS	3.9 ± 3.7 b	2.7 ± 1.3 b	2.2 ± 1.3 a	2.6 ± 1.4 c

HF =Humid forest, HFS = humid forest savanna, SHSS = semi humid south savanna, SHNS = semi humid north savanna.

In all land uses in general, soils in humid forest-savanna were located on steeper slope than semi humid south and north savanna but no significant difference between the sites was observed in grasslands (table 3). Erosion was observed in all land uses except in perennial croplands in the humid forest and forest-savanna. Less fire impact was observed in humid forest and semi humid north savanna and that might reflect a good management system from the farmers. Grazing and trees cutting impact were observed more in semi humid lands than humid lands.

More than 90 % of wooded grasslands in semi-humid savannas and 77 % in humid forest-savanna were situated in mid-slope. Grasslands were also mostly situated in mid-slope however 27 % of wooded grasslands in humid forest-savanna were situated in foot-slope. In humid forest, 50 % and 29 % of cocoa plantations and oil palm plantations were in mid-slope and foot-slope while 80 % to 92 % of cashew plantations were in mid-slope in humid forest-savanna and semi humid south and north savanna. Annual croplands, especially rice fields were located in bottom land and foot-slope in humid forest while 87 % of annual croplands (cotton and yam) in humid forest-savanna were in mid-slope. In semi humid south savanna, 96 % of annual croplands especially millet and yam fields were situated in mid-slope while in semi-humid north savanna it was 78 % of annual croplands especially maize, sorghum, sesame and yam fields that were situated in mid-slope.

Table 3: Impact of erosion, fire, grazing and tree cutting in land uses along a climatic gradient in West Africa.

Impacts de l'érosion, du feu et pâturage dans les différentes utilisations des terres suivant le gradient climatique.

Characteristic	Site	Wooded grassland	Grassland	Perennial cropland	Annual cropland
Erosion (%)	HF	97	90	30	90
	HFS	80	90	23	90
	SHSS	100	100	100	100
	SHNS	100	100	100	100
Fire (%)	HF		100	0	0
	HFS	90	80	20	73
	SHSS	99	82	100	100
	SHNS	11	0	17	12
Grazing (%)	HF		0	0	0
	HFS	33	40	11	18
	SHSS	90	97	85	92
	SHNS	79	10	50	26
Trees cutting (%)	HF		0	2	10
	HFS	47	30	23	71
	SHSS	70	82	92	100
	SHNS	97	90	83	93

HF = Humid forest, HFS = humid forest savanna, SHSS = semi humid south savanna, SHNS = semi humid north savanna

Soil organic carbon and total nitrogen stocks along the climatic gradient

SOC stock varied differently with the climatic areas in each land use (figure 2). In wooded grasslands, SOC stock was higher in humid forest-savanna compared to the semi humid south and north savanna at 0 - 20 cm. However, SOC stock in humid forest-savanna became similar to semi-humid north savanna from 20 to 110 cm. SOC stock was higher in semi humid north savanna than in semi-humid south savanna from 50 cm to 110 cm. In grasslands, SOC stock was higher in humid forest-savanna than semi humid south and north savanna at 0 - 20 cm and 20 - 50 cm while from 50 cm to 110 cm similar SOC stock was observed in all land uses. Equally, in perennial croplands, SOC stock was higher in humid forest and forest-savanna than in semi humid south and north savanna at 0 - 20 cm. However, SOC stock at 20 - 110 cm was similar in humid forest and semi humid south and north savanna whereas SOC stock in humid forest savanna was the highest. In the humid forest, cashew plantations in humid forest-savanna recorded higher SOC stock compared to cocoa and palm plantations (figure 4). Cashew plantations in humid forest-savanna had in average 15 years old while cashew planta-tions in semi humid south and north savanna had less than 10 years old.

Comparably, in annual croplands, SOC stock was higher in humid forest and forest-savanna than in semi-humid south and north savanna at 0 - 20 cm. SOC stock, at 20 - 50 cm, was similar in humid forest and semi humid south and north savanna while the highest SOC stock was recorded in humid forest-savanna. At 50 - 80 cm, SOC stock was similar in all land uses but at 80 - 110 cm, SOC stock was higher in humid forest-savanna.

In general, at least 50 % of carbon were concentrated within 0 - 20 cm in the humid forest croplands while in humid forest-savanna and semi humid south and north savanna, it is within 0 - 50 cm. This fact suggests that carbon can be easily lost if the lands are not well managed. SOC stock decrease with soil depth except in semi humid north savanna where SOC stock increased significantly at 20 - 50 cm in wooded grasslands and at 20 - 80 cm in perennial croplands.

Soil TN stock variation followed the same trend as SOC stock between the studied sites and the land uses (figure 3). However, in annual croplands TN stock decreased from humid forest to semi humid savanna at 0 - 20 cm and, at 50 - 80 cm, TN stock in humid forest-savanna was higher than TN stock in semi humid south savanna and humid forest contrary to their similarity observed with SOC stock.

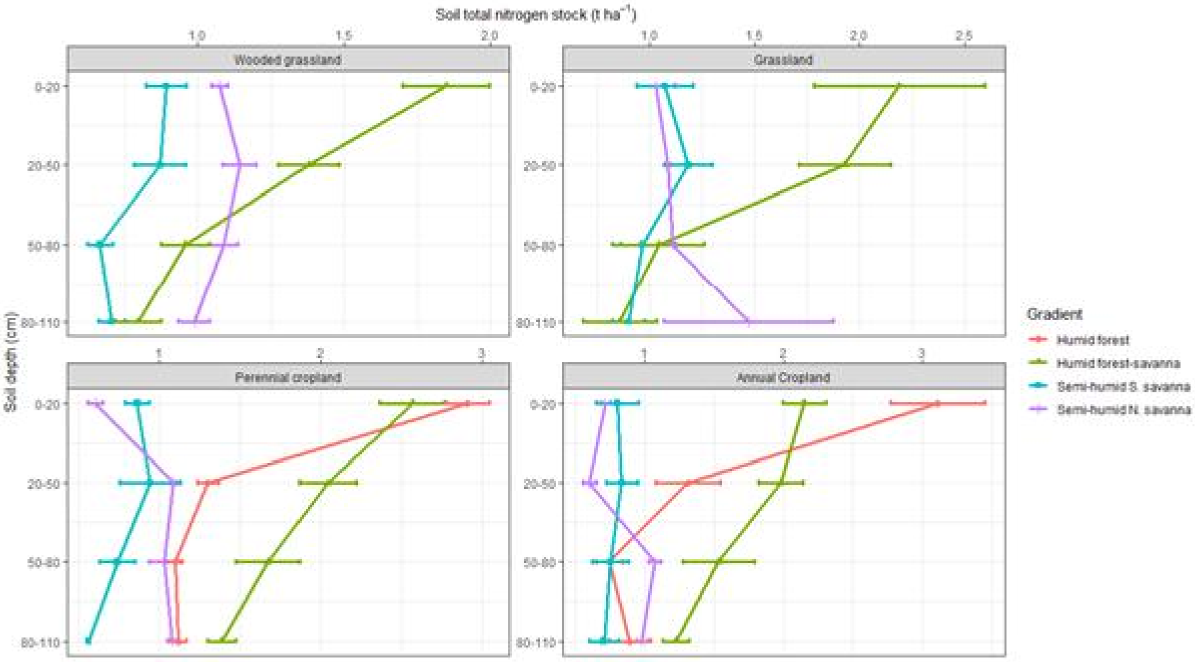


Figure 2: Soil organic carbon stock variation per land use along a climatic gradient in West Africa (Mean ± SE, means were compared using Tukey test in lsmeans package R software, means with same the letter are not significantly different between the climatic areas).

Variation du stock de carbone organique par utilisation de terre suivant le gradient climatique en Afrique de l'Ouest.

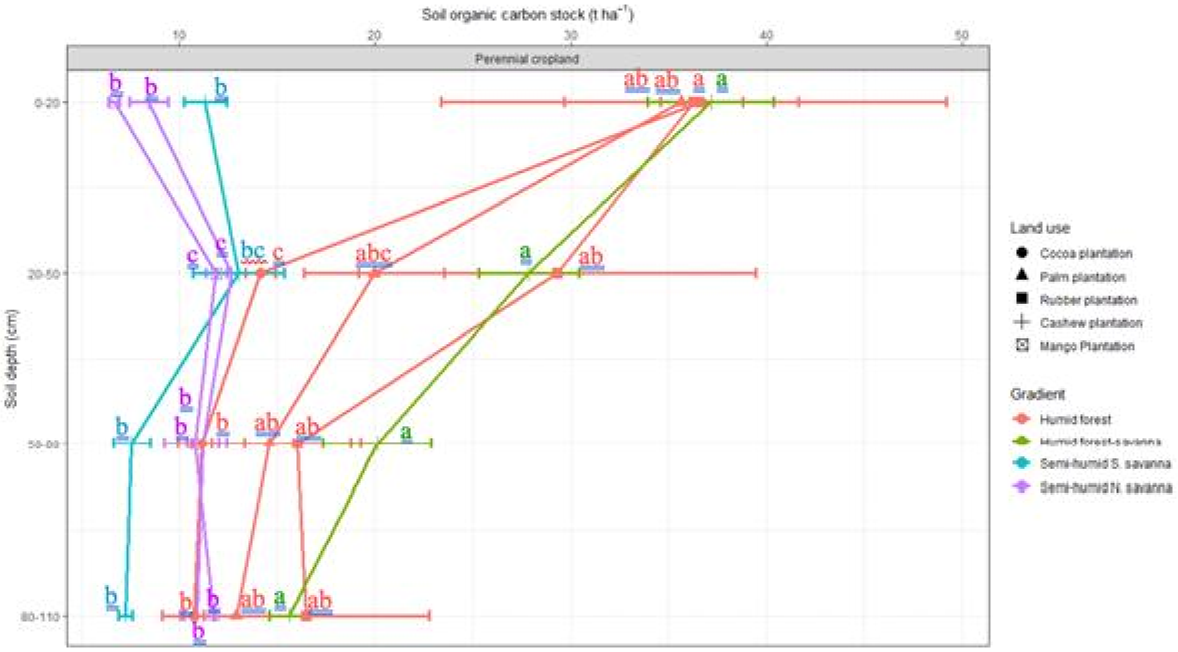


Figure 4: Soil organic carbon stock variation in perennial croplands along a climatic gradient in West Africa (Mean ± SE, means were compared using Tukey test in lsmeans package R software, means with same the letter are not significantly different between the climatic areas).

Variation du stock de carbone organique dans les cultures pérennes suivant le gra-dient climatique en Afrique de l'Ouest.

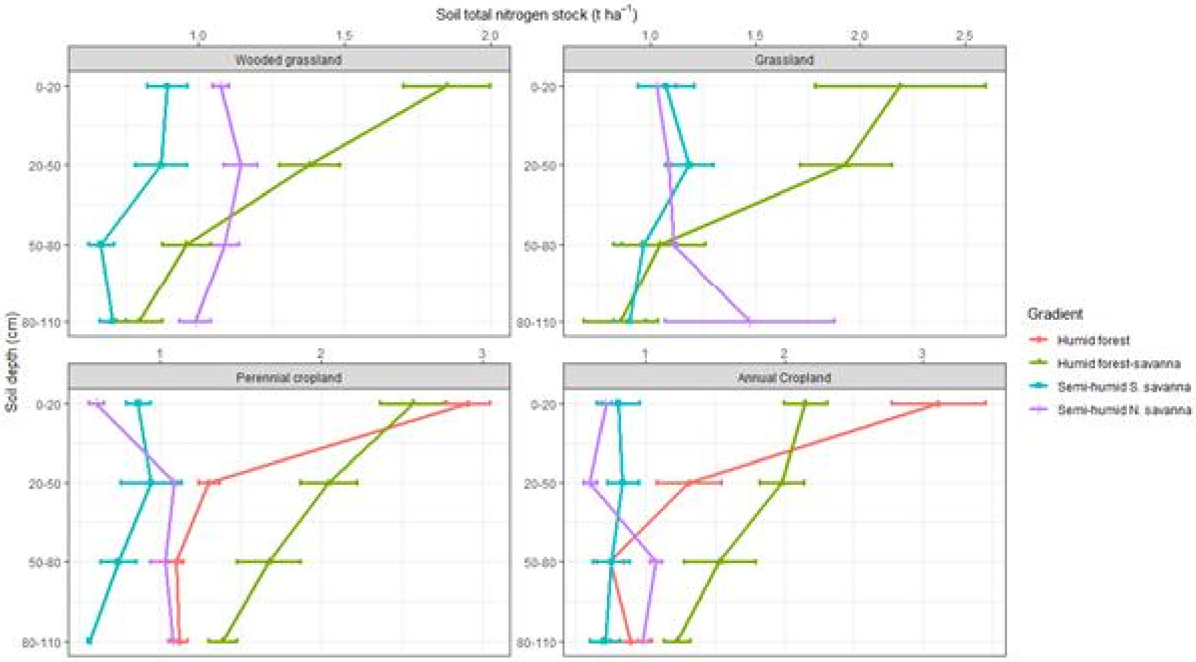


Figure 3: Soil total nitrogen stock variation in land uses along a climatic gradient in West Af-rica (Mean ± SE, means were compared using Tukey test in lsmeans package R software, means with same the letter are not significantly different between the climatic areas).

Variation du stock de l'azote total par utilisation de terre suivant le gradient clima-tique en Afrique de l'Ouest.

Drivers of soil organic carbon and total nitrogen stocks along the climatic gradient

At land use level

The number, nature and strength of drivers varied with land uses at plot (0.1 ha) level. Figure 5 showed that in wooded grasslands, SOC stock in humid forest savanna was driven at 0 - 20 cm by clay (0.68), erosion (-0.29) and fire (-0.10) whereas SOC stocks in the semi humid south and north savanna were affected by clay (0.73 and 0.46).

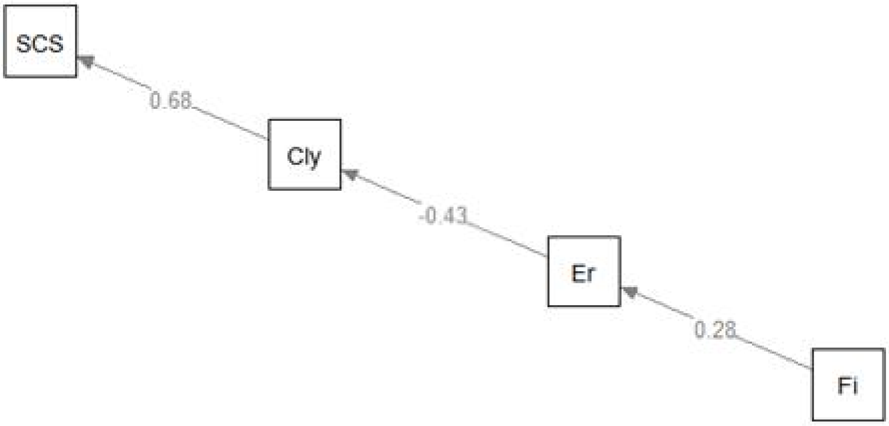


Figure 5: Soil organic carbon stock drivers at 0-20 cm by path analysis in wooded grasslands in humid forest savanna, West Africa (SCS= soil organic carbon stock, Cly= soil clay content, Er= erosion impact, Fi= fire impact, Slp= slope, single-headed arrows indicate direct causal relationships and double-headed arrows indicate unanalyzed correlations. Numbers are path coefficients and numbers within single-headed arrows indicate proportion of total variance explained for each variable).

Déterminants du stock de carbone organique à 0 - 20 cm des savanes boissées dans la zone humide forêt - savane en Afrique de l'Ouest.

TN stocks were affected by SOC stock and clay in all land uses and erosion and fire affected also TN stock in humid forest-savanna. Clay effects on TN stock were stronger than SOC stock effects at the four soil depths in humid forest-savanna however in semi humid sites TN depended strongly on SOC stock at 0 - 50 cm. Our result indicates that in semi humid sites, after the conversion of wooded grasslands to croplands SOC should be protected in order to maintain TN.

In Grasslands, SOC stocks in humid forest-savanna and semi humid north savanna were af-fected by clay content (0.85 and 0.84) but only from 50 to 110 cm. However, in semi humid south savanna SOC stock was affected by clay content from 0 to 110 cm with higher effect (0.85) observed at 20 - 50 cm.

TN stocks were solely affected by SOC stock in humid forest-savanna and semi humid north savanna whereas in semi humid south savanna, TN stock was affected by SOC stock and clay content; clay content had stronger effect at 0 - 50 cm.

In perennial croplands, clay content and erosion in humid forest and clay content in semi hu-mid south savanna affected SOC at the four soil depths. However, clay content affected SOC stock in humid forest-savanna from 20 to 110 cm and only from 80 to 110 cm in semi humid north savanna. The strongest effect of clay content was observed in semi humid south savan-na.

TN stocks were strongly affected by SOC stock, followed by clay content in humid areas and semi humid south savanna for all depths but in semi humid north savanna SOC stock affected TN stock only at 20 - 50 cm.

In annual croplands, SOC stocks in humid areas and semi humid north savanna were affected by clay content content at 0 - 50 cm while in semi humid south savanna, SOC stock was af-fected by clay content in the four soil depths. TN stocks were mainly affected by SOC fol-lowed by clay in humid forest-savanna and semi humid south savanna while TN stocks were solely affected by SOC stock in humid forest and semi humid north savanna.

In general, clay content is the common and major factor controlling SOC stocks while SOC stock is the common factor controlling TN stock for all land uses. Compared to the other land uses especially at 0 - 20 cm, annual croplands recorded stronger clay content effects on SOC stock and SOC stock effects on TN stock. Clay content affected directly TN stock in wooded grasslands and annual croplands in humid forest-savanna and particularly in semi humid sites. These results indicated protecting clay in the soil is the key to maintain and improve SOC stock thus to improve TN stock.

At sentinel site level

The number and the type of drivers controlling SOC and TN stock depended on the site. Within the 100 km2, soil clay content (0.44) and erosion (-0.10) affected SOC stock at 0 - 20 cm in humid forest while clay content (0.51), erosion (-0.14), slope (0.20) and fire (-0.06) affected SOC stock in humid forest-savanna. Clay content (0.64 and 0.47) also affected SOC stock at 0 - 20 in semi humid south and north savanna but slope (0.10) also affected SOC stock in semi humid north savanna. The effects of these drivers decreased with soil depth from 0 - 20 cm to 80 - 110 cm for each site. Figure 5 showed that clay content effect on SOC stock increased with the increase of humidity at 0 - 50 cm except in semi humid north savan-na. However, its effect presented the contrast trend at 50 - 110 cm except in semi humid south savanna at 50 - 80 cm. Along the climatic gradient, erosion and fire effects on SOC stock were lower however their effects on soil clay content were not negligible in the humid sites contrary to semi humid sites. Soil protection measures should be considered in humid areas especially for erosion in humid forest and erosion and fire in humid forest-savanna which areas are usually neglected in soil protection programmes.

In humid forest at 0 - 20 cm, TN stock were controlled by SOC stock (0.75) and clay content (0.33) affected TN stock indirectly through SOC stock (figure 6). SOC stock (0.70), clay (0.52), erosion (-0.14), fire (-0.04) and slope (0.20) affected TN stock in humid forest while only SOC stock (0.55 and 0.81) and clay (0.70 and 0.49) affected TN stock in semi humid areas (figure 5). Along the climatic gradient, contrary to clay, SOC stock effect on TN stock decreased from humid forest to semi humid south savanna but increased in semi humid north savanna at 0 - 20 cm and 80 - 110 cm. The opposite trend was observed at 20 - 50 cm but the effects of clay and SOC stock varied very much at 50 - 80 cm. Soil horizon at 50 - 80 cm may be a transition horizon. Clay content presented in addition a direct effect on TN stock from humid forest savanna to semi humid north savanna at 0 - 20 cm as well as at the other depths. This result indicates that nitrogen could be conserved by clay in these soils even with low carbon content.

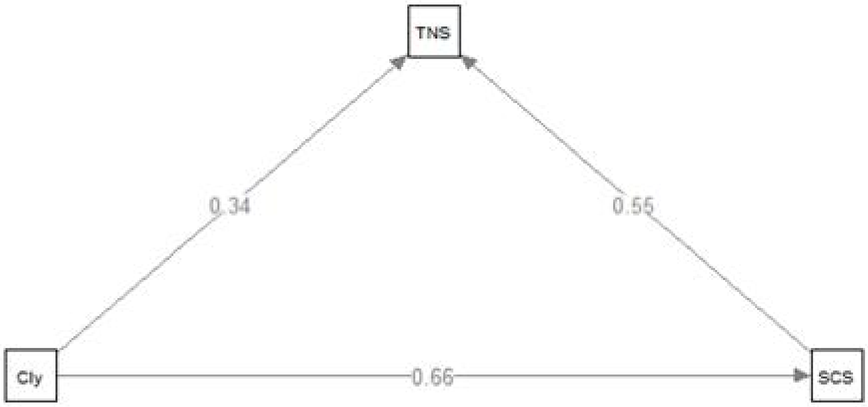


Figure 6: Soil total nitrogen stock drivers at 0-20 cm by path analysis in semi humid south savanna, West Africa (TNS= soil total nitrogen stock, SCS= soil organic carbon stock, Cly= soil clay content. Single-headed arrows indicate direct causal relationships. Numbers are path coefficients and numbers within single-headed arrows indicate proportion of total variance explained for each variable.).

Déterminants du stock de carbone organique à 0 - 20 cm dans la zone semi humide sud savane en Afrique de l'Ouest.

At regional level

Drivers that controlled SOC stock varied with soil depths at regional level (figure 7). Clay content effect varied from 0.46 to 0.57 and increased with soil depth except at 20 - 50 cm. However, the effects of erosion (-0.14 to -0.20) and fire (-0.10) decreased with soil depth while slope affected SOC stock only at 0 - 20 cm. Rainfall also had an effect (0.21) on SOC stock. SOC stock effect on TN stock varied from 0.51 to 0.76 and increased from humid forest to semi humid area except in semi humid north savanna where it decreased. Clay content effect on TN stock varied from 0.48 to 0.70 and increased with soil depth from humid forest savan-na to semi humid areas but decreased form humid forest to humid forest savanna. Erosion and fire presented the same trend as clay content.

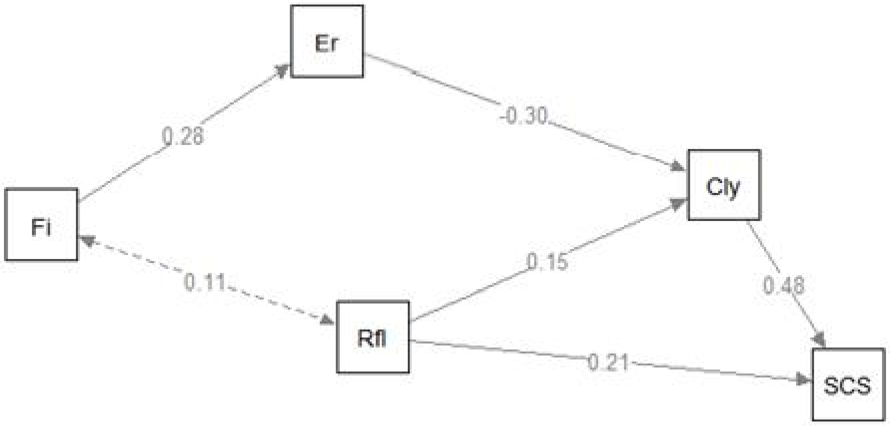


Figure 7: Soil organic carbon stock factors determined at 0-20 cm by path analysis in West Africa (SCS= soil organic carbon stock, Cly= soil clay content, Er= erosion impact, Fi= fire impact, Slp= slope, Rfl= annual rainfall, single-headed arrows indicate direct causal relation-ships and double-headed arrows indicate unanalyzed correlations. Numbers are path coeffi-cients and numbers within single-headed arrows indicate proportion of total variance ex-plained for each variable.)

Déterminants du stock de carbone organique à 0 - 20 cm en Afrique de l'Ouest.

DISCUSSION

Our results showed that in wooded grasslands, SOC stock was higher in humid forest-savanna compared to the semi humid south and north savanna at 0 - 20 cm while SOC stock in humid forest-savanna was similar to semi-humid north savanna from 20 to 110 cm. This may be due to their similar clay content in these two sites but the higher production of litter in humid for-est-savanna due to higher rainfall could explained the observation at 0 - 20 cm. The general low clay content in semi humid south savanna may explained the fact that SOC stock was higher in semi humid north savanna than in semi-humid south savanna from 50 cm to 110 cm. Compared to the humid forest, cashew plantations in humid forest-savanna recorded higher SOC stock compared to cocoa and palm plantations (figure 4). This is similar to N'Gbala *et al.* (2017) that found cocoa plantation had a low potential of carbon storage in centre west of Cote d'Ivoire.

Carbon stocks in annual croplands in humid forest and forest-savanna were higher than carbon stocks measured by Nwaogu *et al.* (2018) in croplands in southern region of Nigeria. This may be due to the difference in soil management (Diwediga *et al.,* 2017). Our results showed that SOC stock was higher in humid areas than semi-humid areas particularly at 0 - 20 cm. Saiz *et al.* (2012) and Zhong *et al.* (2018) found also that SOC stock decrease from humid to semi humid areas at 0 - 20 cm and this was due to the higher rainfall and low temperature as shown by Tayebi *et al.* (2021) and Ge *et al.* (2020) that lead to higher plant biomass production and litter decomposition.

At land use level, clay was the main driver of SOC stocks while Clay and SOC were the main drivers of TN stock. Bationo *et al.* (2007) also find that soil nutrients depended solely on SOC in West Africa and this may be due to the low cation exchange capacity of the main clay (kao-linites) of the region (ORSTOM, 1969).

At sentinel site level, clay content remained the principal factor of SOC stock at 100 km^2 scale along the climatic gradient and this result is similar to the results of the previous studies (Hounkpatin *et al.,* 2018). However, clay content seemed to be the main driver in upper soils in humid areas compared to the semi humid areas. Indeed Al/Fe-(hydr) oxides bind with car-bon also therefore contribute to SOC storage (Fang *et al.,* 2018). The higher total Fe and Al content in these soils may explained this observation (table S3 in supplementary materials).

Along the climatic gradient, erosion and fire effects on SOC stock were lower however their effects on soil clay content were not negligible in the humid sites contrary to semi humid sites. This fact may be due to the presence some of anti-erosion measures in the semi humid sites and also a good knowledge on erosion by farmers especially in semi humid north savanna (Nyamekye *et al.,* 2018).

At regional level, our results confirmed that clay content was the main factors controlling SOC stock and agrees with Funes *et al.* (2019) and Wiesmeier *et al.* (2019) findings. These results suggested for the two studied country, clay protection measures are the key to main-tained and improve SOC and TN stock.

CONCLUSIONS

Soil carbon and nitrogen were measured in different land uses and drivers affecting soil organic carbon (SOC) and total nitrogen (TN) stocks variability were investigated at different levels along a climatic gradient in this study. Humid sites presented higher SOC and TN stocks compared to semi humid sites at 0 - 20 cm. However, from 20 to 110 cm, SOC and TN stocks were similar in the sites except in croplands in humid forest-savanna. In general, land uses affected SOC and TN stocks and their vertical distribution along the climatic gradient. At land use level, clay content affected SOC stock in all land uses but erosion and fire affected in addition SOC stock in wooded grasslands in humid forest savanna. At sentinel site level, clay content remained the principal factor of SOC stock at along the climatic gradient. Erosion and fire effects on SOC stock were relatively higher on clay content in the humid sites contrary to semi humid sites. At regional level, clay content and annual rainfall affected mainly SOC stock followed by erosion and fire. Although clay content presented stronger effect in some land uses and sites, SOC stock remained the principal factor controlling TN stock at land use, sentinel site and reginal levels. This study indicated protecting soil clay could be a solution to maintain and improve SOC and TN stocks in West Africa. Thus, erosion and fire impacts on soil should be limited.

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AUTHORS' CONTRIBUTIONS

T. L. Jeanne Ilboudo collected field data, did the laboratory analysis and wrote this paper. N'guessan Lucien Diby supervised field data collection, laboratory analysis and corrected this paper. Johan Six and Emmanuel Frossard and Bismark Hassan Nacro supervised field data collection and laboratory analysis.

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