The role of Sudanese Forests Agro-ecosystem in improving the cation exchange capacity and exchangeable bases of a sandy soil in western Burkina Faso.

Abstract

The objective of this study is to evaluate the influence of Sudanese forests on the chemical equilibrium and exchangeable bases of sandy soils in the Bondoukuy region. The study examines the impact of forest cover on soil fertility and the mechanisms through which these natural ecosystems promote soil health and productivity in the region. The Cation Exchange Capacity (CEC) of soil represents its capacity to retain and exchange nutrient cations with plant roots. In Sudanian ForestsAgro-ecosystem, sandy soils are characterized by a dominance of coarse particles, which exhibit a low specific surface area and low cation retention capacity, in contrast to clayey soils. A low CEC restricts soil fertility and the capacity of the soil to sustainably provide essential nutrients to plants. It was hypothesized that the CEC of the topsoil in forests of western Burkina Faso would demonstrate a significant increase due to substantial environmental changes during the fallow period. To test this hypothesis, a comparison was made between soil fertility in forests and fallows, and that of cultivated plots, which were considered the control for this increase. A total of 15 plots were selected, with five plots allocated to each situation. The vegetation and soil of the plots were described in detail. Composite soil samples were taken from the 0-20 cm horizon. The soil analyses in the laboratory were conducted on several parameters, including texture, pH-H_2O, pH-KCl, carbon, nitrogen, CEC and exchangeable bases. The results of the observations enabled the classification of the soils as tropical ferruginous soils with iron and manganese sesquioxides. The original materials indicate that the soil exhibits sandy properties. This was demonstrated by the granulometric study, which revealed that the soils under investigation exhibited an essentially sandy texture on the surface horizon. This results in a low retention capacity for exchangeable bases. The woody vegetation of the forest exhibits a greater diversity of flora than that of the fallows. This has a significant impact on the enhancement of the CEC, due to the replenishment of the soil with plant debris of varying organic compositions. The overall pH is slightly acidic, with a range of 5.63 to 5.71. The soils of forests exhibit higher concentrations of carbon and nitrogen than those of the fallows and fields. The observation of chemical balances has enabled the identification of forests as an environment conducive to optimal plant nutrition. Overall, forests enhance the CEC and exchangeable bases, despite the values being below the threshold recommended for tropical sandy soils. It is therefore necessary to implement measures to promote sustainable agriculture and enhance agricultural productivity in this region, where soil nutrients are naturally scarce.

Keywords :Forest, Fallow, CEC, Exchangeable bases, Sandy soil.

1. INTRODUCTION

Cation exchange capacity (CEC) is defined as the number of moles of exchangeable cations adsorbed by electrostatic force per unit mass of soil. It plays an important role in soil nutrient retention (Brady & Weil, 2017) and in regulating soil pH changes (Luo *et al*., 2015; Xu *et al*., 2012), thus making it vital for maintaining the structure and function of terrestrial ecosystems. It can affect the structure and function of ecosystems by controlling the supply of exchangeable cations (i.e., Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}, and Fe^{3+}) to the soil (Lucas *et al*., 2011; Mueller *et al*., 2012). Given that different plant species have varying requirements for concentrations and ratios of calcium, magnesium, potassium, and sodium, alterations in these cations can affect plant biodiversity (Chen *et al*., 2013). In addition to being essential for plant growth (Likens *etal*., 1998; McLaughlin and Wimmer, 1999), the availability of these nutrients affects plant tolerance to drought and pathogens (DeHayes *et al*., 1999; Demchik and Sharpe, 2000), thereby affecting primary productivity and the overall structure of terrestrial ecosystems. Conversely, elevated levels of Al^{3+} and Fe^{3+}have the potential to impede vegetation productivity as a consequence of their toxicity (Lieb *et al*., 2011). Furthermore, CEC plays a role in maintaining the stability of terrestrial ecosystems by buffering changes in soil acidity (Bowman *et al*., 2008). Decreased soil pH has the potential to alter biological activity and cation supply, which could have negative impacts on terrestrial ecosystems (Kirk *et al*., 2010). In the context of environmental change, a comprehensive understanding of the temporal dynamics of CEC is crucial for predicting the responses of ecosystem structure and function and for guiding management policies aimed at maintaining ecosystem stability. In light of the considerable spatial and temporal variations in the determining factors (e.g., climatic factors, edaphic factors, and human activity) of CEC dynamics, a comprehensive investigation of the temporal dynamics of CEC across diverse environmental settings is imperative. Several studies have demonstrated cation loss in soils as a consequence of soil acidification, harvesting, and land use change (Högberg*et al*., 2006; Lu *et al*., 2015; Watmough & Dillon, 2003). These studies have provided insights into the spatial variation and environmental drivers of CEC over large geographic scales. However, there is a paucity of knowledge regarding the temporal dynamics of CEC over small spatial scales. However, these observations are limited to the site scale, and it is unclear whether they are representative of a larger ecosystem, such as savannas, forests, fallows, or cultivated areas. In West Africa, sandy soils are typically deficient in phosphorus (P) and nitrogen (N), and in some cases, they are acidic (pH <7), which renders crop viability contingent upon the application of fertilizers (Serpantié, 2003). Furthermore, the low organic matter and clay content of sandy soils, coupled with the scarcity of phosphorus and nitrogen and the acidic pH, results in a limited capacity to retain essential nutrients, which ultimately constrains agricultural productivity. It is therefore imperative to enhance the cation exchange capacity (CEC) and exchangeable bases to improve the fertility of sandy soils in SudanianForestAgro-ecosystems, particularly in West Africa, and specifically in Burkina Faso.The role of SudanianForests in soil fertility management and the regulation of ecological dynamics in semi-arid regions, particularly in Burkina Faso, is of great importance. They contribute to the improvement of soil structure and chemical composition, thereby influencing cation exchange capacity (CEC) and the availability of exchangeable bases, including Ca^{2+},Mg^{2+}, K^+, and Na^+. In the context of sandy soils, such as those in the Bondoukuy region in western Burkina Faso, an understanding of these dynamics is of particular importance for the improvement of agricultural productivity and the maintenance of ecosystem resilience. In the context of the SudanianForests of western Burkina Faso, the issue is further compounded by traditional agricultural practices, climate variability and soil degradation, which serve to further reduce the natural fertility of these soils. This makes it an ideal ecosystem in which to explore CEC dynamics.It was hypothesized that the CEC of the topsoil in the Forests of western Burkina Faso would demonstrate a significant increase due to the substantial environmental changes that occurred during the fallow period. To test this hypothesis, a comparison will be made between the soil fertility of forests and fallows, with cultivated plots serving as controls. This will facilitate an understanding of the processes by which the CEC and exchangeable bases are enhanced in these sandy soils. The findings will inform the development of tailored agricultural techniques and strategies for enhancing land productivity while maintaining the ecological integrity of these vulnerable ecosystems.

2. MATERIAL AND METHODS

2. 1 Study area

The study was carried out in the Bondoukuy region, located in the Sahel-Sudan climatic ecotone. This region represents the cotton production area (Fig. 1). Bondoukuy is situated between 11°51'N and 3°45'W, with an elevation above sea level of 360 m. The average annual rainfall of the study area is 850 mm, with the maximum rainfall occurring in August. The daily maximum temperature ranges between 31 and 39°C, with an average annual potential evapotranspiration of approximately 1900 mm. The natural vegetation cover in the area is predominantly composed of open woody savanna, whereas the dominant grass biome is *Andropogon gayanus*, *Pennisetum pedicellatum* and *Loudetiatogoensis* (Fournier *et al*., 2001). For centuries, human activity in Bondoukuy has had a significant impact on the local ecosystem. The primary economic activities in the region are subsistence farming, which is focused on cereal crops, and cash crop farming, which is centred on cotton. Despite the regular ploughing of the most fertile soils, less fertile land is increasingly subjected to a short period of fallowing, with a typical duration of approximately five years. The annual ploughing, based on cotton–maize rotations, typically results in the deterioration of soil structure, increased erosion, and a reduction in soil organic matter content. The second most prevalent activity in the study area is extensive animal husbandry. Consequently, the region is

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subjected to excessive grazing and faces considerable pressure to meet the demands for aerial biomass (tree bark, firewood and perennial stems) from the local rural communities.

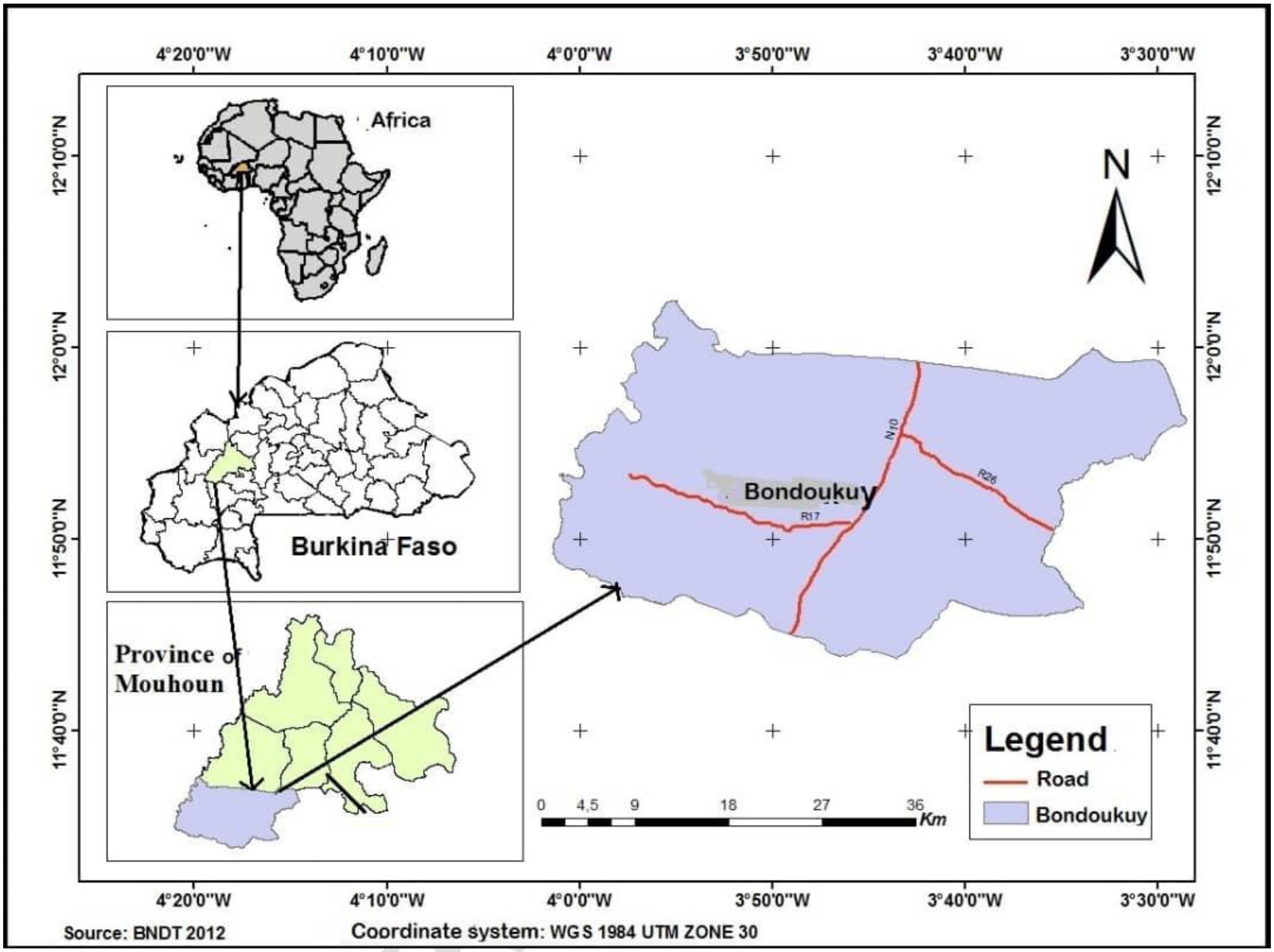

Fig. 1. Location of the study area

2.2 Selection and description of the plots studied

Three distinct situations were selected for analysis, namely forests, 20-year fallows and fields. Each situation was represented by a sample size of five plots. The control plots, represented here by the fields, have been in permanent cropping for a period exceeding ten years. The old 20-year fallows represent the intermediate stage of fertility restoration, while the SudanianForests represent the equilibrium or climax stage, where soil fertility is fully restored. The diverse situations (in cropping or vegetative) and associated activities are described in detail based on comprehensive observations and surveys.The floristic composition of the forests and fallows was investigated through floristic surveys. The soils were described based on pedological profiles and identified using the French classification system (CSPS, 1967), which was further corroborated by the global reference base (FAO-WRB, 2015) and confirmed by the national Bunasol guidelines (2005). This is to facilitate a more nuanced understanding of the use of the environment and elucidate the disparate values of the physicochemical parameters obtained.

2.3 Measurement of physicochemical parameters

The physicochemical parameters of the soil were studied using composite soil samples obtained with an auger at a depth of 0-20 cm. This layer is of particular interest as it corresponds to the depth mainly explored by the roots. To account for intra-plot variability, five samples were collected from the plot (four from the four corners and one from the centre). These

samples were then combined to form a single representative sample. The following physicochemical analyses were conducted.
-Particle size analysis was conducted by sedimentation, following the destruction of organic matter, via the pipette method on an automatic granulometer, with five fractions according to the Atterberg scale (Clays < 2 µm <Fine silts<20 µm < Coarse silts < 50 µm < Fine sands < 200 µm < Coarse sands < 2 mm) (CIRAD, 2017). Subsequently, the fine and coarse sands were added, reducing the number of fractions to four.
-The C analysis was conducted according to the modified Walkley-Black method (CEAE, 2003), while the N determination was performed using the Kjedahl method. The Ca, Mg, Na, K and Mn were determined by ICP spectrometry (CIRAD, 2017). The CEC was obtained by continuous flow colourimetric ammonium assay (CIRAD, 2017), while the exchangeable bases were measured by percolation (CIRAD, 2017). The pH-H_2O and pH-KCl measurements were conducted using an automated titration chain with a sampler (CIRAD, 2017). All of the aforementioned analyses were conducted at the soil biogeochemistry laboratory of the École Normale Supérieure of Paris (ENS).

2.4 Data Analysis

The data were subjected to an analysis of variance (PROC ANOVA) and a simultaneous test of comparison of means by Scheffé (1959), which is regarded as the most effective test for comparing means (Scherrer, 1989). A significance level of 0.5% was employed. The aforementioned analyses were conducted using the Stat View software (SAS, 2020).

3. RESULTS

3.1 Plots soil description

The majority of soils in the area are classified as belonging to the "iron and manganese sesquioxides" soil class. These are tropical ferruginous soils, characterized by a sandy to sandy-silty texture at the surface. These soils are developed on a sandy-clayey substrate, which is sometimes gravelly, derived from autochthonous or non-autochthonous ferrallitic alteration materials. The local alterations and backfills, based on kaolinite, are deficient in weatherable minerals. Kaolinite clay exhibits minimal swelling and shrinkage properties and does not contribute to cation exchange capacity (CEC). The presence of iron oxides, which serve to stabilize the structure of ferrallitic soils and enhance their drainage properties, is observed in the form of spots and concretions within the deeper horizons. The substantial or inadequately developed structure encourages the accumulation of water and the formation of crusts, which impedes the penetration of roots by sensitive plants in the absence of loosening by fauna, the roots of perennial plants, or the use of a tool. These soils are susceptible to water table and rill erosion. Conversely, the resulting high cohesion renders these soils quite resistant to gully erosion. The high erosiveness of the Sudanese climate and the ability to form surface crusting result in selective and insidious water table erosion. Cropping, in its conventional form, is accompanied by erosion, whereas the covering of herbaceous vegetation is sufficient to control.

3.2 Floristic Characteristics

In Bondoukuy, as is the case with Sudanese ecosystems in general, the vegetation is characterised by a relatively high proportion of woody and perennial herbaceous species (Table 1).Except for permanent fields, the floristic records obtained characterize the vegetation of Sudanese forests and fallow lands (Table 1). However, some species are characteristic of fallows, including *Andropogon gayanus* in herbaceous plants and *Pterocarpuserinaceus* in woody plants. This flora remains relatively uniform and less diverse compared to other vegetal formations in the region. In both forests and fallow land situations, despite the advanced resting stage of the former in comparison to the latter, there is a notable lack of significant floristic richness.In general, three taxonomic groups of woody plants are particularly prevalent: Leguminous, Combretaceae and Rubiaceae. In arid conditions, the number of Combretaceae species increases, while the number of Leguminous decreases. A similar outcome is observed in the case of herbaceous plants. Conversely, wooded forests exhibit a paucity of leguminous herbaceous plants, which suggests a proclivity of Leguminous for fallow land. It can be observed that plant formations are organized according to biotopes, but not solely on this basis. Indeed, factors such as fire, temporary cropping and selective cutting exert a significant influence on the physiognomy and flora of plant formations, particularly during the stages of reconstitution following cropping or certain developments.In forest ecosystems, the woody vegetation is more prevalent, and the woody layer is often dominated by large-sized individuals, typically between 6 and 10 metres in height. In contrast, fallow lands exhibit a sparser vegetation cover, with a woody layer that is most often dominated by medium-sized woody plants (2 to 6 m). Similarly, the basal cover and the density of clumps of perennial grasses (*Andropogon gayanus* and *A. ascinodis*) are greater in forests than in fallow lands. The results of the surveys indicate that the forests in question are of a considerable age, having originated from very old fallow lands. As a result, their appearance corresponds to multiple developments at different stages of growth. Such forests are

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typically uzed by the indigenous population as a land reserve or, on occasion, as a venue for traditional rituals. It is within living memory that these forests have not been cultivated, with the last instance of such occurring in 1927. Additionally, the surveys indicate that the fallow lands observed are exclusively under the control of the local indigenous population, who practise a fallow cropping system. The fields are primarily cultivated for cotton, corn, and sorghum. These are perennial crops cultivated in wooded parkland due to the soil's high fertility. Approximately twenty species of woody and herbaceous plants were preserved during the clearance process, with the most notable examples being *Vitellaria paradoxa* and *Andropogon gayanus*.

The vegetation observed in the forests and fallow lands is described in detail in the preceding section.

- Dense groves and forests, which lack a grassy layer and comprise woody vegetation exceeding 80% of the total cover. This physiognomy, which was more abundant in 1927, is now found only in small areas. These include gallery forests and cut-off riparian cords, spring forests (at the bottom of the cuesta front), sacred forests protected from fire, termite mound groves, and groves of collapsed cuirass. In these groves, the annual herbaceous plants burn before the rains stop, which protects the groves from fire later. These fertile environments, protected from fire, represent the closest approximation to the "climax" of the "dense dry forest". The population of hemi-ombrophilous species of these formations is characterised by a rich diversity of fire-sensitive leguminous, including *Pterocarpus erinaceus*, lianas (*Saba senegalensis*) and shrubs (*Capparis corymbosa*, *Ziziphus mauritiana*, *Diospyros mespiliformis*), which flourish in the undergrowth.

-The open forests with a low grass layer (35-80% woody cover) are composed mainly of the following species: *Vitellaria paradoxa*, *Isoberliniadoka*, *Daniella oliveri* and *Burkeaafricana*. These species are typically found in foothill and hillside habitats, with occasional occurrences in interfluves.

-Tree and shrub fallows encompasses a range of habitats with varying degrees of woody cover, representing distinct stages of reconstitution across diverse biotopes or pseudo-climaxes of xeric biotopes. In shrub fallows, species that exhibit a tendency to reject and sucker, such as *Terminalia avicennoides*, *Pteleopsissuberosa*, *Detariummicrocarpum*, and seedlings of trees from the wooded parkland *Vitellaria paradoxa*, tend to become dominant. The herbaceous flora is dependent on the reconstitution stage, with ruderal species giving way to annuals, which in turn are succeeded by *Andropogon gayanus* and *Andropogon ascinodis*. The formation of shrub fallows, which exceed 50% woody cover at a low height, is observed in areas where grazing has been excessive.

Table 1. Floristic characteristics of the studied sites (most represented species)

	Plots		
Vegetation	**Forest**	**Fallows**	**Fields**
Woody species	*Albizzia chevalieri* *Anogeissus leiocarpus* *Grewia mollis* *G. bicolor* *Boswelliadalzielli* *Combretumnigricans* *Isoberliniadoka* *Lanneamicrocarpa* *Lanneavelutina* *Grewiatenax* *Nauclea latifolia* *Pterocarpus erinaceus* *Ximenia americana Tephrosia pedicellata* *Terminalia avicennoïdes* *Combretumglutinosum* *Vitellariaparadoxa* *Desmodiumvelutinum* *PiliostigmathonningiiPiliostigmareticulatum.* *Bombax costatum, Mayntenus senegalensis,* *Feretiaapodanthera, Parinaricuratellifolia,* *Sterculiasetigera, Pericopsislaxiflora* *Diospyrosmespiliformis,* *SwartziamadagascariensisCappariscorymbosa,* *Ziziphus mauritianaMitragynainermis,* *Berliniagrandifolia, Raphia sudanica, Acacia polyacantha, Acacia sieberiana*	*Vitellariaparadoxa* *Anogeissusleiocarpus* *Terminaliaavicennoïdes* *T. laxiflora* *Piliostigmathonningii* *Piliostigmareticulatum* *Combretummicrantum* *C.glutinosum* *C. nigricans* *C. molle* *Guiera senegalensis* *Swartziamadagascariensis*	*Adansoniadigitata* *Bombax costatum* *Vitellariaparadoxa* *Parkia biglobosa* *Lanneaacida* *L. microcarpa* *L. velutina*

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Perennials herbaceous	*Gladiolus klattianus* *Crinum humile* *Dioscorea dumetorum* *Lippiachevalieri* *Vernonia purpurea* *Cyanotis longifolia Andropogon gayanus* *Andropogon ascinodis* *Cymbopogonshoenanthus* *Costus spectabilis* *Cochlospermumtinctorium* *C. planchoni* *Leptadeniahastata* *Lantana rhodesiensis* *L. camara*	*Tephrosia pedicellata* *Andropogon gayanus* *A. ascinodis* *Borreria stachydea* *Cochlospermumtinctorium* *C. planchoni* *Leptadeniahastata* *Lantana rhodesiensis* *L. camara* *Sporobolus festivus*	*Andropogon gayanus*
Annuals herbaceous	*Aspiliahelianthoides* *Commelinaforskalei* *Cissus gracilis* *Ampelocissus pentaphylla* *Andropogon pseudapricus*	*Andropogon fastigiatus* *Evolvulusalsinoides* *Tephrosia pedicellata* *Pennisetum pedicellatum,* *P. polystachyon* *Loudetiahordeiformis* *Borreria stachydea* *Rottboeliaexaltata*	*Sorghum bicolor* *Gossypium spp* *Pennisetum typhoïdes* *Zea mays*

3.3 Soil Physical characteristics

The variance analyses unambiguously demonstrate a situation effect concerning texture (Table 2). The forests exhibit markedly different clay (11.46%), fine silt (7.58%) and coarse silt (11.64%) contents when compared to the cultivated plots (6% clay, 6.31% fine silt and 9.99% coarse silt). On the other hand, there are no significant differences with fallow land. The rate of fine elements (less than 20 µm) is higher in forestsand fallows lands than in fields. Notwithstanding the relatively low proportion of sand in forests (69.32%) and fallows land (68.46%) in comparison to cultivated plots (77.76%), the rate of coarse elements (>50 µm) is higher than those of fine elements (<20 µm). Which confirms the sandy nature of the soil in all three situations.

Table 2. Soil Physical Characteristics at 0-20 cm depth. The means displaying the same letter per row are not significantly different (n=15, *P<0.005*), with the standard error represented in parentheses.

	Plots		
Parameters	**Forests**	**Fallows**	**Fields**
Clays (%)	11.46^{a}	12.08^{a}	6^{b}
	(1.73)	(1.16)	(2.71)
Fine silts (%)	7.58^{a}	7.8^{a}	6.31^{a}
	(3.09)	(3.09)	(1.1)
Coarse silts (%)	11.64^{a}	11.66^{a}	9.99^{b}
	(2.25)	(1.51)	(5.74)
Coarse + Fine sands (%)	69.32^{a}	68.46^{a}	77.7^{a}
	(4.28)	(8.19)	(3.24)

3.4 The Organic and acid-base status of soils

The variance analysis demonstrates a highly significant situation effect ($P < 0.0001$) on the distribution of chemical parameters in the 0-20 cm horizons of the soil in the studied situations (Table 3). The Scheffé test enables the differentiation of the situations at the level of organic matter contents (C, N), exchangeable bases and CEC. The results obtained permit a detailed examination of the dynamics of soil fertility reconstitution and the enhancement of CEC through the investigation of the diverse chemical and organic characteristics of the soil (Table 4).

Table 3: Results of analyses of variance (ANOVA/SAS) of the effect of situations (forests, fallows and cultivated fields) on the chemical characteristics of the soil at depth 0-20 cm, n = 195.

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Variables	$F_{8.45}$	P	R²	CV
C (%)	50.13	<0.0001	0.90	35.2
N (%)	38.65	<0.0001	0.80	30.12
C/N	20.65	<0.0001	0.56	25.6
pH-H_2O	12.34	0.1420	0.27	12.5
pH-KCl	13.63	0.1400	0.19	9.6
Ca^{2+} (meq.100g^{-1})	11.43	0.0230	0.31	19.8
Mg^{2+} (meq.100g^{-1})	18.32	<0.0001	0.73	20.67
Mn^{2+} (meq.100g^{-1})	22.53	<0.0001	0.67	27.32
K^+ (meq.100g^{-1})	30.15	<0.0001	0.77	22.8
Na^+ (meq.100g^{-1})	17.80	<0.0001	0.60	26.7
CEC (meq.100g^{-1})	16.45	<0.0001	0.79	24.5
SEB (meq.100g^{-1})	12.53	0.133	0.25	15.2
SEB/CEC (%)	33.13	<0.0001	0.52	31.5

3.4.1 pH-H_2O and pH-KCl

The results of the statistical analyses conducted on the pH values are not statistically significant (table 3). Conversely, the pH of the various scenarios under examination is acidic, with values ranging from 5.52 to 5.86 for pH-H_2O and from 4.78 to 5.28 for pH-KCl. The findings indicate that despite 20 years of fallow land, the forest has not resulted in an improvement in soil pH.

3.4.2 Carbon

The analyses conducted on the mean of carbon contents of the various situations yielded statistically significant results, with notable differences observed between forests (0.76%), fallows (0.7%), and fields (0.26%) (Table 4). The carbon content increased by 0.53% from fields to forests, and by 0.06% from fallows to forests (Fig. 2). Conversely, there is a pronounced decline in the carbon content from forests to fields. The fallow stage thus marks the initial phase of carbon storage, which then accumulates sustainably during the forest.

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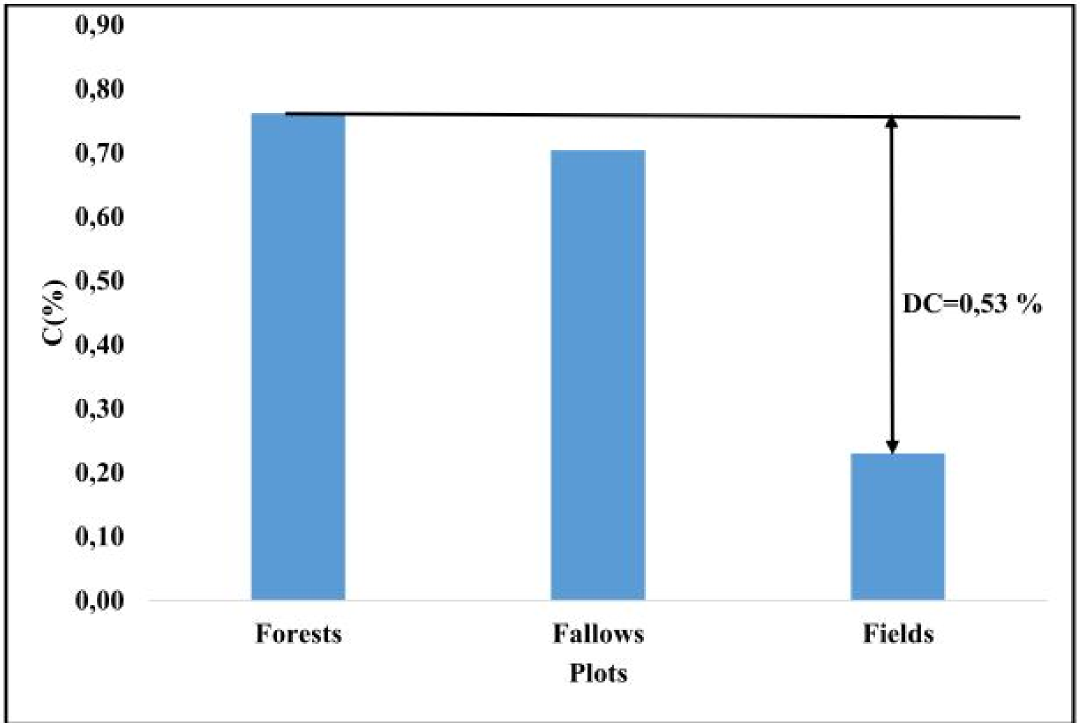

Fig. 2. Difference in carbon content (DC)

3.4.3 Nitrogen

The statistical analysis of nitrogen averages revealed a highly significant situation effect ($P < 0.005$). The nitrogen content of the samples exhibited considerable variation, with values ranging from 0.033% in forests to 0.031% in fallows and 0.015% in fields (Table 4). A gain of 0.015% is observed from forests to fields and 0.002% from forests to fallows. Conversely, the transition from the field to the forest results in a loss of 0.015% (Fig. 3). It can be concluded that the nitrogen content is reconstituted with the fallow and appears to stabilize in the forest.

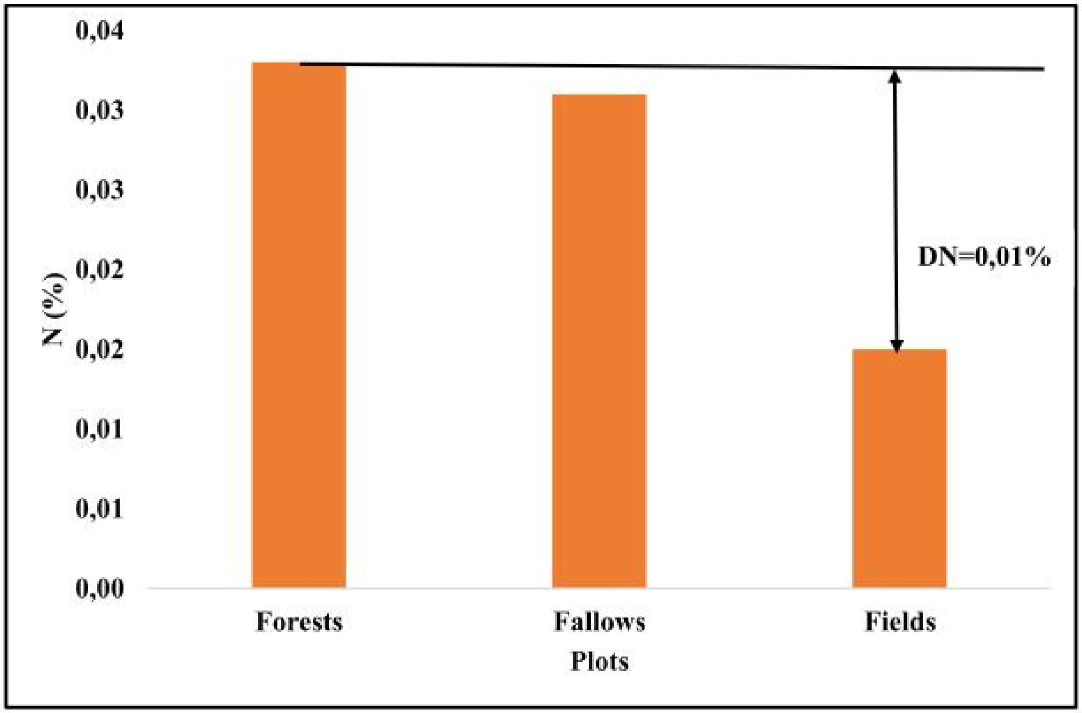

Fig. 3. Difference in nitrogen content (DN)

3.4.4 C/N ratio

The C/N ratio is an indicator of the degree of decomposition of organic matter. The ratio varies from 18 to 24 and is statistically significant depending on the situation (Table 4). The C/N ratio differentiates between forests (C/N=23), fallows (C/N=24) and fields (C/N=18). The low C/N ratio observed in fields suggests that mineralization occurs rapidly, whereas the high C/N ratio observed in forests and fallows indicates that mineralization occurs more slowly, which is indicative of a lack of nitrogen.

Table 4. Soil chemical and acid-bases characteristics at 0-20 cm depth. The means displaying the same letter per row are not significantly different (n=15, *P<0.005*), with the standard error represented in parentheses.

	Plots		
Parameters	**Forest**	**Fallows**	**Fields**
C (%)	0.76^{a}	0.7^{a}	0.26^{b}
	(0.24)	(0.1)	(0.02)
N (%)	0.033^{a}	0.031^{a}	0.015^{b}
	(0.01)	(0.01)	(0.03)
C/N	23^{a}	24^{a}	18^{b}
	(4.77)	(7.27)	(2.86)
pH-H2O	5.86^{a}	5.52^{a}	5.71^{a}
	(0.44)	(0.52)	(0.27)
pH-KCl	5.28^{a}	4.78^{a}	4.78^{a}
	(0.48)	(0.53)	(0.47)

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3.5 Nutrient status according to exchangeable bases

Table 5 illustrates the mean levels of soil fertility, as indicated by the average values of CEC and exchangeable bases.

3.5.1 Cation Exchange Capacity (CEC) and Exchangeable Bases

CEC represents the total exchangeable cation content of a soil, comprising the cations Ca^{2+}, Mg^{2+}, K^{+}, Na^{+} and Mn^{2+}. The mean CEC values obtained in the various experimental conditions ranged between 13 and 3.48 meq.100 g^{-1} (Table 5). The results of the statistical analyses indicated that there was a significant situation effect on the different values obtained. Forests exhibit higher values (13 meq.100g^{-1}) than fallows (9 meq.100^{-1}) and fields (3.48 meq.100^{-1}).
The mean Ca^{2+} values obtained exhibited a range of 3.23 to 2.3 meq.100 g^{-1}. The statistical analyses are not significant on the Ca^{2+} contents. The calcium values are statistically identical in the three situations (Table 5).
The mean magnesium content exhibited a range of 1.73 to 0.8 meq.100 g^{-1}. A significant situation effect on magnesium contents was observed. Indeed, the forests situation exhibits the highest contents (1.73 meq.100g^{-1}) in comparison to the fallow (1.08 meq.100g^{-1}) and field (0.8 meq.100g^{-1}) situations (Table 5).
The mean potassium values ranged from 1.11 to 0.17 meq.100 g^{-1} (Table 5). The situation effect is highly significant, as fallows and fields exhibit a potassium deficiency compared to forests.
The results of the analysis indicated a highly significant impact of the situation on the mean sodium values (Table 5). Forestsand fields exhibited the highest rates (0.022 meq.100g^{-1}) in comparison to fallows (0.01 meq.100g^{-1}).
The mean manganese values exhibited a range of 0.04 to 0.012 meq.100 g^{-1}. The statistical tests demonstrate a highly significant situation effect (Table 5). The data indicates that there is a manganese deficiency in fallows when compared to forests and fields.

3.5.2 Base saturation rate

The saturation rate is defined as the ratio of the sum of exchangeable bases to the cation exchange capacity. It serves as an indicator of the chemical richness of the soils and the cationic lining of the adsorbent complex. The figure ranges from 98.56% to 45.44% (Table 5). The statistical analysis revealed a highly significant situation effect. The saturation rate is notably elevated in agricultural fields (98.56%) while it is considerably diminished in forests (47.2%) and fallows (45.44%)(Table 5).

Table 5. Characteristics of the nutrient statuses at a depth of 0-20 cm in the soil of the studied situations. The means displaying the same letter per row are not significantly different (n=24, *$P<0.005$*), with standard error in parentheses.

	Plots		
Parameters	**Forest**	**Fallows**	**Fields**
Ca^{2+} (meq.100g^{-1})	3.23^{a}	2.3^{a}	2.4^{a}
	(0.41)	(0.35)	(0.56)
Mg^{2+} (meq.100g^{-1})	1.73^{a}	1.08^{a}	0.8^{b}
	(0.14)	(0.11)	(0.25)
K^{+} (meq.100g^{-1})	1.11^{a}	0.69^{b}	0.17^{c}
	(0.07)	(0.1)	(0.05)
Na^{+} (meq.100g^{-1})	0.022^{a}	0.01^{b}	0.022^{a}
	(0.01)	(0.01)	(0.01)
Mn^{2+} (meq.100g^{-1})	0.04^{a}	0.012^{b}	0.04^{a}
	(0.03)	(0.01)	(0.03)
SEB(Sum of bases) (meq.100g^{-1})	6.14^{a} (1.26)	4.09^{b} (0.86)	3.43^{b} (0.87)
CEC (meq.100g^{-1})	13^{a}	9^{b}	3.48^{c}
	(0.13)	(0.88)	(0.7)
Bases saturation SEB/CEC (%)	47.2^{a} (3.8)	45.44^{a} (2.08)	98.56^{b} (2.01)

3.6 Nutrient status according to chemical balances

To diagnose mineral balances and assess the relative deficiency of exchangeable bases in soils, specific values are calculated (Fig. 4).

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3.6.1 Calcium/Magnesium Balance

The Ca/Mg ratio values obtained in the various experimental conditions ranged from 1.9 to 3 (Fig.4). The results of the statistical analysis permit the differentiation of the fields (3) from natural situations of forests (1.9) and fallows(2.1).

3.6.2 Magnesium/Potassium Balance

The Mg/K ratios exhibited a range of 4.65 to 1.55. The results of the analyses indicated a statistically significant effect of the situations on the Mg/K ratio. The low ratios observed in forestsand fallows (1.55)are in stark contrast to those seen in fields, which exhibit higher values (4.65) (Fig.4).

3.6.3 K/CEC (%) Balance

The potassium (K) saturation percentages in the various scenarios exhibited a range of 9 to 5%. The results of the statistical analyses indicated a statistically significant difference between the values observed in the different situations. Forests(9%) and fallows (8%), which exhibit a higher rates, are in contrast to low ratios of fields (5%) (Fig. 4).

3.6.4 (Ca+Mg)/K Balance

The values of the (Ca+Mg)/K ratio from the various scenarios span a range of 18.6to 4.5. The results of the statistical analyses demonstrated a highly significant situation effect. The low ratios observed in forests (4.5) and fallows (4.9)are in stark contrast to those seen in fields (18.61) (Fig. 4).

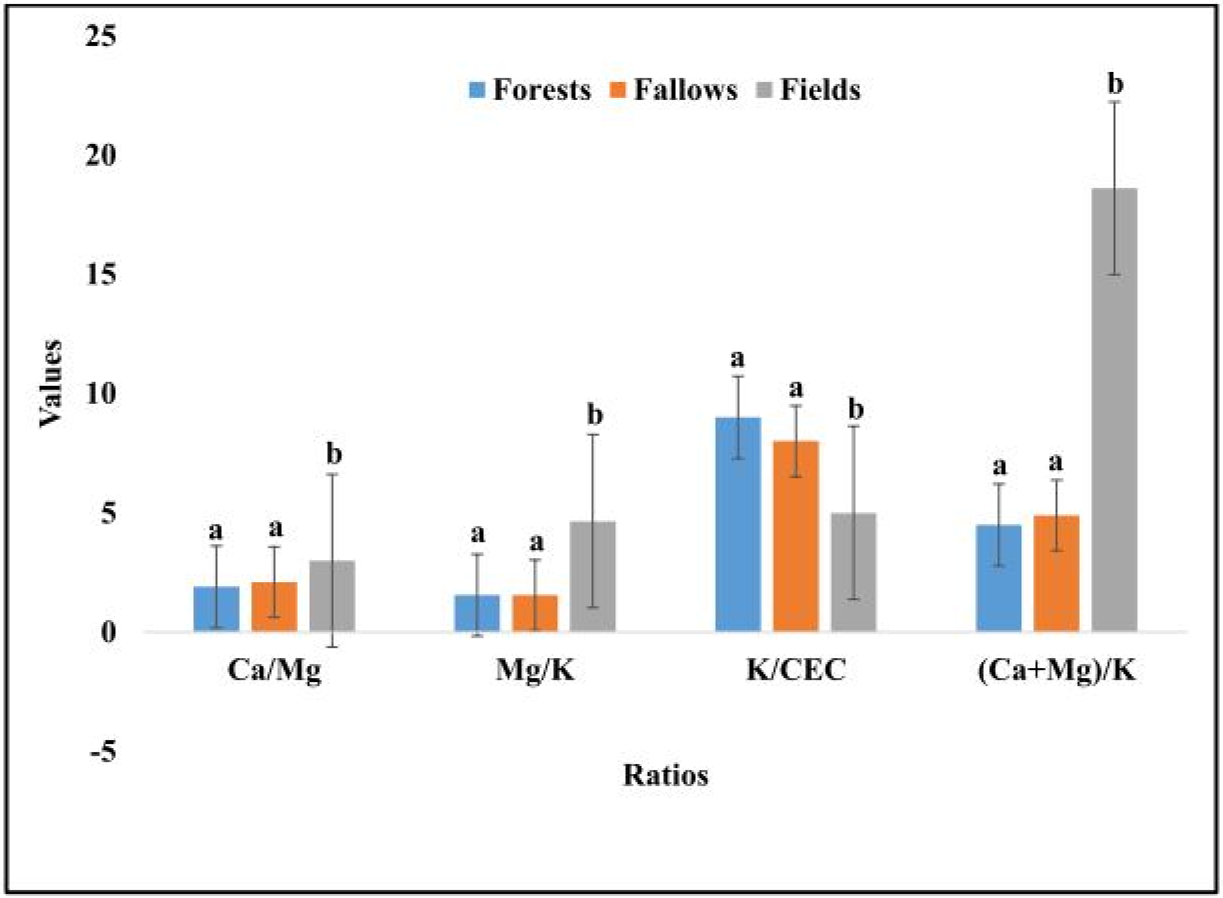

Fig. 4. Characteristics of the soil chemical balances of the plots studied. Means displaying the same letter are not significantly different (n=12, *P<0.005*).

4. DISCUSSION

4.1 Role of soil texture and type

The upper layers (0-20 cm) of soil in the various situations under consideration are characterized by a sandy texture. The sandy texture of the soil provides favourable conditions for drainage, air circulation and root penetration. However, this condition is not without its disadvantages. The soil exhibits a low capacity for water retention (Mulaji *et al*., 2016; Bationo &Buerkert, 2001; Curtin & Smillie, 2000; Lal, 1997). The clay content is minimal in these superficial horizons, with a concentration of between 12 and 6%. The low clay content is a disadvantage for the soils under study (Baize, 2000). The author posits that clay is the most active granulometric fraction due to its multifunctional nature, which includes associations with organic matter, cohesion of aggregates, cation and anion fixation on exchange sites, and water retention. A paucity of clay results in a reduction in soil fertility. In the case of low clay contents (less than 20%), the addition of organic matter is necessary to compensate for the deficit in colloids. Notwithstanding, forests and fallows exhibit a higher clay content than fields. This demonstrates that the practice of fallowing cultivated soils and subsequently returning them to forests conditions has the effect of improving the clay texture of the soil. However, the capacity of clays to store cations and enhance the CEC is more dependent on their intrinsic characteristics than on their relative abundance in the soil. Several studies (Brady & Weil, 2017; Lal & Shukla, 2004; McBride, 1994) have demonstrated that it is smectite and montmorillonite, rather than kaolinite, that contribute the most to an increase in the cation exchange capacity (CEC) of a soil. The provenance of the sandy-clay substrate, which is sometimes gravelly, also has an impact on the improvement of CEC. Tropical ferruginous soils are frequently deficient in primary minerals, exhibiting a prevalence of secondary minerals such as iron oxides (e.g., hematite, goethite) and aluminum oxides (e.g., gibbsite). The cation exchange capacity of these minerals is comparatively low in comparison to clays such as smectites or illites. Our findings have been corroborated by several authors in similar studies (Sanchez, 2019; Brady & Weil, 2017; Lal, 2006; Dubroeucq& Volkoff, 1998). The texture and cation exchange capacity (CEC) of a given soil may be influenced by many factors, including the presence of vegetation.

4.2 Role of vegetation in improving CEC

The vegetation of western Burkina Faso is characterized by a high degree of diversity, encompassing a range of morpho-structural types that are mutually reinforcing in their exploitation of the environment. Following the initial clearing and temporary cultivation, the forest state reestablishes itself through a series of intermediate states. The potential for cropping is contingent upon the provision of sufficient time for the vegetation to recuperate before another disturbance occurs. Furthermore, forests ecosystems are characterized by resilience, which is maintained through the presence of disturbances. The physiognomy of the Sudanianforests is therefore, representative of a succession of intermediate states, characterized by the presence of both young and old fallows. These fallows are the consequence of local agricultural practices that ensure their preservation throughout the crop cycle, as they serve the purpose of restoring soil fertility (Serpantié, 2003; Yoni*et al.*, 2018). The biodiversity of this region is rich, though not particularly specific to forests. The flora of spontaneous forests formations in Bondoukuy has been found to comprise only 22% of Sudanese species, with a high proportion of species with a wide distribution or Sahelian, notably via ruderals of fallow land and weeds of crops. This would indicate a process of "degradation" and disturbance by loss of specificity (Devineau*et al.*, 1997). The authors highlight the floristic significance of forests in comparison to fallows land. The floristic richness of forests provides a significant input of plant matter, which plays a crucial role in restoring soil fertility. The dynamic equilibrium achieved in forests and fallows soils thus permits the restoration of soil fertility to a full or near-complete extent. This results in an improvement in the CEC and exchangeable bases of sandy soils. Boyer (1978) demonstrated that the concentration of specific cations (Ca^{2+} and Mg^{2+}) in the surface layer of the soil is influenced by vegetation. Indeed, the clearing and subsequent burning of a forest allows for the injection of considerable quantities of calcium and magnesium into the soil, with respective increases of two and threefold. In contrast, the quantities in question are considerably lower in fallow land (Marschner, 2012; Boyer, 1978). The diverse flora of forests, in comparison to that of fallows land, explains the relatively high levels of exchangeable bases that have been observed. It is, therefore, crucial to emphasize the contribution of forests to the restoration of soil fertility. In addition to the deposition of plant matter that nourishes the soil, various factors contribute to the enhancement of CEC, including the composition of the substrate, climate, pH, and other elements.

4.3 Influence of pH

The pH of the soil is a determining factor in the type of activity that exists or is predominant. The soil pH values obtained from the three situations are, on the whole, slightly acidic, with a pH range of 5.52 to 5.86. In the studies conducted by Bationo *et al.* (2006) and Baize (2000), the pH threshold for optimal activity was identified as 5.5. The pH values obtained in this study are higher than the threshold previously mentioned, indicating that the chemical and microbiological reactions

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occurring in the soil are occurring properly. In general, cultivated plants flourish in soil with a pH of 5.5 to 7, which is considered neutral or slightly acidic (Landon, 1991; Baize, 2000). Low pH values in soil impede plant growth by inhibiting nitrification. However, it is not possible to attribute the observed improvement in CEC to pH alone. The effect is indirectly related to the content and nature of clays. The pH exerts a considerable influence on CEC enhancement by modulating the negative charges of soil constituents, notably organic matter and charge-dependent clays (Bortoluzzi*et al.*, 2006). As with texture and vegetation, the pH exerts an influence on CEC. Nevertheless, what role the organic matter plays in CEC improvement?

4.4 The impact of soil organic matter (SOM)

The incorporation of organic matter into soil can enhance soil fertility. It is an effective indicator of plant health. However, in the context of this study, the observed values are relatively low. The low organic matter content of these soils renders them susceptible to degradation by water erosion during periods of heavy rainfall (Mulaji *et al.*, 2016). Furthermore, the sandy texture intensifies the loss of soil nutrients and the reduction of CEC, which are already exacerbated by the low organic matter content. Conversely, an examination of the organic matter contents of forests in comparison to fallows and fields reveals that they remain stable during the fallow period, whereas the fields exhibit low organic matter content. It can be concluded that the fallow does not result in a significant improvement in organic matter content in comparison to the forest. This is attributable to the reintroduction of plant debris to the soil, which is largely similar in forests and fallows. At the field level, the low organic matter content can be attributed to the permanent presence of crops and, in some cases, the lack of restitution of crop residues. It is important to note, however, that in the context of sandy soil in Bondoukuy, the improvement of CEC is strongly correlated with organic matter. The findings of several studies are in alignment with our own (Sparks, 2003; Six *et al.*, 2002; Kätterer& Andrén, 1999; Batjes, 1996; Stevenson, 1994; Rowell, 1994; Syers *et al.*, 1970). It can be concluded that the organic matter plays an essential role in improving the CEC of sandy soils. It permits the retention and release of the cations essential for plant nutrition, enhances the structure and water retention of the soil, and fosters superior long-term fertility.

4.5 Dynamics of the CEC and exchangeable bases

CEC is defined as the capacity of a soil to retain and exchange cations, which are positive ions such as potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+). Soils with a low CEC, such as sandy soils, exhibit reduced nutrient retention, resulting in the leaching of cations, particularly under conditions of heavy rainfall (Brady & Weil, 2017; McBride, 1994). Exchangeable bases represent the essential cations (K^+, Ca^{2+}, Mg^{2+}, Na^+) that are available to plants. An enhancement in these bases directly enhances soil fertility (Kopittke*et al.*, 2007; Donahue *et al.*, 1990). The findings of Fang *et al*. (2017) indicate that CEC is significantly influenced by climatic conditions, precipitation levels, topographical features and human activities. This phenomenon is exemplified in our sandy soils in the context of human activities. A comparison has been made between the CEC of the soil in forests and fallows and that of fields under permanent cultivation, which are considered to be the controls. Furthermore, it is important to acknowledge the correlation between CEC and the clay-humic complex. The CEC of soil is therefore contingent upon the quantities of clay and organic matter that it contains, as well as the nature of these elements and the pH of the soil. The mean CEC value derived from the forest soil (13 meq.100g^{-1}) is approximately threefold that of the field soil (3.48 meq.100g^{-1}). However, these values are markedly below the threshold of 15 meq.100g^{-1}, as outlined by Sawadogo (2006) for sandy soils. This can be attributed to the relatively low clay and organic matter contents observed in our samples (Baize, 2000). Indeed, as this author posits, organic matter in soils plays a significant role in both agronomical and environmental processes, including the adsorption and retention of water, exchangeable bases, phosphorus, nitrogen, and trace metal elements. Consequently, the low CEC values of our soils result in a diminished buffering capacity (Baize, 2000).

About exchangeable bases (Ca, Mg, K, Mn and Na), forests exhibit higher values than the fallows and fields in all the scenarios under investigation. In addition, the values obtained are below the threshold values determined for tropical sandy soils (8 meq.100g^{-1}) (Landon, 1991; Boyer, 1982). The saturation rate of the adsorbent complex by alkaline and alkaline-earth cations serves as a valuable agronomic and environmental indicator of the chemical richness of the soil. This, in turn, determines biological activity, structural quality and reserves of fertilizing elements. The mean saturation rate values indicate that forestsand fallowssoils are more fertile than fields' soils. It can be concluded that fallow land has not resulted in a significant alteration to the saturation rate of bases. These soil conditions under fallow land may be attributed to the previous cultivation that preceded the fallow period. The findings of Fournier *et al*. (2000) on sandy soil indicate that fallow soil from animal-drawn cultivation exhibits a rapid regeneration process, in contrast to fallow soil from motorized cultivation. The soil conditions under fields are readily explicable, given that the cultivated plants export nutrients from the soil, despite regular fertilizer inputs in certain areas.

4.6 The influence of chemical balances

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The equilibrium of chemical balances between diverse cations (Ca^{2+}, Mg^{2+}, K^{+}) and soil CEC is of paramount importance for the fertility of sandy soils and the nutrition of plants in general. The Ca/Mg ratio is frequently regarded as a crucial factor in maintaining optimal soil structure and balanced nutrient availability (Brady & Weil, 2017). However, the presence of excess calcium can reduce the availability of magnesium, while the accumulation of excess magnesium can compact the soil, thereby reducing aeration and water infiltration (Brady & Weil, 2017; Dorlodot*et al*., 2005; Cox, 1979). The optimal Ca/Mg ratio for tropical sandy soils is between 3 and 5, as proposed by Landon (1991). The values of the ratios obtained in the three situations under consideration are less than or equal to 3, which suggests the possibility of Mg inhibition and Ca deficiency in the soils under investigation.

The Mg/K ratio plays an essential role in plant nutrition and cation balance within the soil. An excess of magnesium can result in competition with potassium for exchange sites on the soil matrix (Brady & Weil, 2017). This may result in a limitation of potassium uptake by plants. For these two antagonistic cations, the optimal Mg/K ratio is between 3 and 5 for sandy soils (Kouadio *et al*., 2018; Boyer, 1982). Except for forests and fallows, which exhibit a Mg/K ratio of 1.55, that of fields is 4. This suggests that magnesium deficiency may occur in forests and fallows. A low ratio may indicate an excess of potassium, which could result in a magnesium deficiency for some plants. This imbalance in nutrition and reduction in CEC may have adverse effects on plant growth and development. As demonstrated by Dognin*et al*. (1981), an optimal Mg/K ratio enables the maximization of cation exchange sites and the balanced absorption of nutrients by plants.

The K/CEC ratio represents the proportion of potassium in relation to the total cation exchange capacity of the soil. In soil with a fine particle content of 20%, the optimal K/CEC ratio is 3 to 5% (Brady & Weil, 2017). A ratio that is too high may indicate potassium saturation, which has the potential to impede the absorption of other cations. As posited by Fallavier and Olivin (1988), in sandy soils, potassium is preferentially exchanged to the detriment of other cations, provided that it does not saturate the CEC beyond 30%. In the present case, only forests (9%) and fallows(8%) exhibit high ratios, whereas fields, serving as controls, display ratios of 5%. The low ratio observed in both cases indicates a limited availability of potassium in the soil, which could potentially impact plant nutrition. Conversely, the presence of excessive potassium in forests has the potential to disrupt the absorption of magnesium and calcium.

The (Ca+Mg)/K ratio represents the overall relationship between calcium, magnesium and potassium and is employed to assess the overall cation balance in the soil. It ensures an optimal balance between these major cations, thereby enhancing soil fertility. It is generally recommended that the ratio of calcium and magnesium to potassium be between 10 and 15 in sandy soil (Brady & Weil, 2017). A ratio that is too low can result in soil structure issues and impede the absorption of calcium and magnesium. Conversely, a ratio that is too high can restrict the availability of potassium. The ratio of calcium and magnesium to potassium in the soils of our forests and fallows is approximately 5, whereas in fields, it is approximately 18. The availability of calcium and magnesium is therefore problematic in these natural situations, despite the renewal of the stock of plant matter. Conversely, in fields the supply of K is constrained. This is substantiated at the field level in areas of permanent cultivation, where organic amendments are restricted to crop residues for specific crops (Dakouo, 2012). In fallows' lands, which are transitional phases before forests this is attributed to the replenishment of soil potassium through the decomposition of plant matter from species with low potassium content.

5. CONCLUSION

This study demonstrated the significance of forest and fallow agro-ecosystems in the restoration of soil fertility through a comparative analysis of the enhancement of cation exchange capacity (CEC) and exchangeable bases. The measurement of a range of chemical and physical soil parameters enabled a comparison of the characteristics of forests soil with those of fallows and cultivated fields. It is evident that fallow land, which represents the intermediate phase of fertility restoration, does not exert a significant influence on the enhancement of CEC and exchangeable bases. It is imperative to allow sufficient time for the forest to become established before expecting significant increases in CEC and exchangeable bases. These increases are observed at the levels of all the physicochemical parameters measured in the forest soil, including texture, carbon (C), nitrogen (N), calcium (Ca^{2+}), magnesium (Mg^{2+}), manganese (Mn2+), sodium (Na^{+}), and potassium (K^{+}). The enhancement of the CEC and exchangeable bases of sandy soil in the Sudanianforest of western Burkina Faso thus necessitates an integrated soil management strategy, encompassing the following approaches.

-(i) The adaptation of cultural practices involves the contribution of organic matter, such as compost or manure and crop residues, as well as amendments of clay minerals, including kaolinite or bentonite. Additionally, the use of calcium amendments, such as dolomite, and the implementation of agroforestry are also key elements. Furthermore, the incorporation of leguminous as cover crops and the establishment of fallow systems are also essential aspects of this adaptation.

- (ii) The judicious management of water resources, specifically the use of mulch to reduce losses, is a crucial aspect of sustainable agriculture.

These approaches have the dual objective of enhancing the soil's capacity to retain nutrients and improving the availability of exchangeable bases, which are essential for plant growth. These approaches also facilitate the

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advancement of sustainable agriculture and enhance agricultural productivity in this region, where soil nutrients are naturally scarce.However, our study did not take into account agronomic aspects in order to estimate losses due to the export of crops at the level of permanent fields.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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