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Dynamic of CEC and exchangeable bases influenced by a soudanian forest in hydromorphic soil of Western Burkina Faso

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ABSTRACT: The CEC (Cation Exchange Capacity) of a soil represents its capacity to retain and exchange nutrient cations with plant roots. In Sudanese modified natural forests, hydromorphic soils are characterised by a silty-clayey texture and a large specific surface area, which enables them to retain cations in a manner that is distinct from sandy soils. It was hypothesised that the CEC of the topsoil in modified natural forests in western Burkina Faso would demonstrate a significant increase as a consequence of the substantial environmental changes that occurred during the fallow period. To test this hypothesis, a comparison was made between the soil fertility of the forests and fallows and that of the cultivated plots, which were selected as witnesses to the increase. A total of 15 plots were selected, with five plots allocated to each situation. The vegetation and soil characteristics of each plot were documented. Soil samples were taken from the 0-20 cm horizon to create composite samples. The laboratory soil analyses included a number of parameters, including texture, pH in water and KCl solutions, carbon, nitrogen, CEC and exchangeable bases. The observations yielded a classification of the soils as tropical ferruginous hydromorphic soils with iron and manganese sexquioxide. The original materials indicate that the soil is predominantly silty-clayey in composition. The granulometric study demonstrated that the soils exhibited a predominantly silty-clayey texture in the surface horizon. This results in a high retention capacity for exchangeable bases. The woody vegetation of the forests is characterised by a greater diversity and richness of flora than that of fallow land. 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 value of 5.98 for pH in water (H2O) and 6.41 for pH in soil. Forest soils exhibit elevated concentrations of carbon (1.48% C) and nitrogen (0.1% N) in comparison to fallow soils (0.65% N, 0.05% N) and agricultural fields (0.34% C, 0.03% N). The observation of chemical balances has identified forests as suitable locations for optimal plant nutrition. In general, forests enhance the CEC and exchangeable bases, despite the values remaining below the recommended threshold for tropical ferruginous hydromorphic soils. It is thus imperative to implement strategies that will foster sustainable agricultural practices and enhance agricultural productivity in this region, where soil nutrients are naturally scarce.

KEYWORDS: Forest, fallow, CEC, exchangeable bases, hydromorphic soil.

1 INTRODUCTION

The physical and chemical properties of most soils are influenced by their ion exchange characteristics, including the quantity and equilibrium of individual ions present [1]. CEC serves as a principal indicator of soil fertility. Similarly, exchangeable bases are crucial for maintaining the nutritional balance required by plants [2]. Furthermore, CEC plays a role in maintaining the stability of terrestrial ecosystems by buffering changes in soil acidity [3]. A decrease in soil pH could alter biological activity and cation supply, which could have negative impacts on terrestrial ecosystems [4]. 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 policies for managing ecosystem stability. Given the substantial spatial and temporal variations in the determining factors (e.g., climatic and edaphic factors and human activity) of CEC dynamics, a comprehensive study of the temporal dynamics of CEC across multiple environmental situations is required. The Sudanese forest ecosystem, rich in biodiversity, contributes significantly to the improvement of soil physicochemical properties. Forest litter, plant matter, and decomposition processes under forest cover promote soil enrichment in organic matter [5]. In addition, tree roots and other forms of vegetation help stabilize soil structure, limiting erosion and improving nutrient retention [6-7]. Modified natural forests [8] in the Sudanian zone on hydromorphic soil represent plant formations endemic to tropical Africa. The climate is characterised by a dry season and a wet season [9]. Soil hydromorphism is defined by the presence of either temporary or permanent waterlogging [10]. In the absence of adequate management, these soils can result in low agricultural productivity, thereby exacerbating food insecurity in the region [11]. The existing literature on the role of forests in improving CEC and exchangeable bases is extensive [12-15]. However, there is a paucity of data concerning the comparative dynamics of CEC and exchangeable bases in hydromorphic soils of modified natural forests, fallows and fields in the Sudanian zone. Therefore, in a context where anthropogenic pressures (such as deforestation and intensive agricultural practices) threaten these ecosystems, it is imperative to understand and promote practices that favour the increase of CEC and exchangeable bases. It was hypothesised that the cation exchange capacity (CEC) of the topsoil of the hydromorphic soil of modified natural forests in western Burkina Faso would demonstrate a significant increase as a consequence of 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 the use of permanent crop plots as a control. This will facilitate an understanding of the processes by which the CEC and exchangeable bases are enhanced in hydromorphic soils within the Sudanian zone. 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. Furthermore, this entails the sustainable management of modified natural forests and the implementation of agroforestry practices tailored to local conditions, thereby enhancing the resilience of hydromorphic soils and ensuring food security in the region.

2 MATERIALS AND METHODS

2.1 STUDY SITE

The study was conducted in the Bondoukuy region, situated on the northern border of the South Sudanian climatic zone, known as the cotton farming zone (Figure 1). Bondoukuy lies 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 about 1900 mm. The natural vegetation cover in the area is predominantly composed of open woody savannah, whereas the dominant grass biome is *Andropogon gayanus, Pennisetum pedicellatum* and *Loudetia togoensis* [16].

For centuries, human presence in Bondoukuy has markedly affected the local ecosystem. Subsistence (cereals) and cash crop (cotton) farming are the main activities practiced in the area. Although the most fertile soils are regularly ploughed, less fertile ones are increasingly subjected to a short period of fallowing (~5 years). The annual ploughing, based on cotton–maize rotations, usually leads to the collapse of soil structure, erosion and reduction of soil organic matter content. The second most common activity in the study area is extensive animal husbandry. As a result, the area is overgrazed and exposed to high demands for aerial biomass (tree bark, firewood and perennials stems) by the local rural communities.

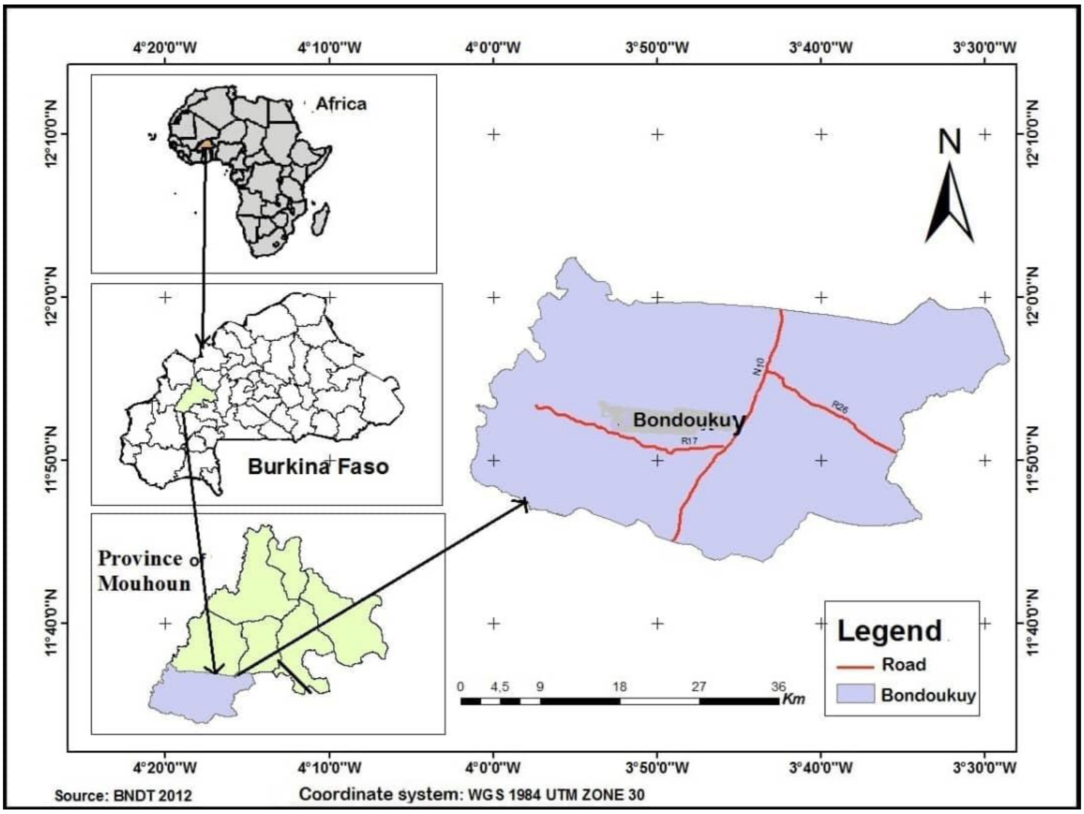

Fig. 1. Study map

2.2 SELECTION AND DESCRIPTION OF THE PLOTS STUDIED

Three scenarios were selected for investigation, namely forests, 20-year fallows and fields. Each scenario was represented by five plots. The control plots, represented here by the fields, have been in permanent cultivation for a period exceeding ten years. The old 20-year fallows represent the intermediate stage of fertility restoration, whereas the modified natural Sudanian forests represent the equilibrium or climax stage, where soil fertility is fully restored.

The diverse circumstances (in cultivation or vegetation) and associated activities are delineated based on comprehensive observations and assessments. The flora of forests and fallow lands was examined through floristic surveys. The soils were described based on pedological profiles and identified using the French classification system [17], which was then reinforced by the global reference base [18] and confirmed by the national Bunasol guidelines [19]. This is to facilitate a more nuanced comprehension of the utilisation 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 by sedimentation, after destruction of organic matter, by the pipette method on an automatic granulometer with 5 fractions according to the Atterberg scale (Clays: 0-2µm, Fine silts: 2-20 µm, Coarse silts: 20-50 µm, Fine sands: 50-200 µm and Coarse sands: 200 µm-2 mm) [20]. Subsequently, the fine and coarse sands were added, reducing the number of fractions to 4.

-The C analysis was conducted in accordance with the modified Walkley-Black method [21], while the N determination was performed using the Kjedahl method. The Ca, Mg, Na, K and Mn determinations were carried out by ICP spectrometry [20]. The CEC is obtained by determining the ammonium concentration through continuous flow colorimetry [20]. The exchangeable bases are quantified through percolation [20], while the pH of the water and KCl solutions are measured using an automated titration chain with a sampler [20]. All of the aforementioned analyses were conducted at the soil biogeochemistry laboratory of the École Normale Supérieure de Paris (ENS).

2.4 DATA ANALYSIS

The data collected were subjected to an analysis of variance (PROC ANOVA) and to a simultaneous test of comparison of means by Scheffé [22] considered to be the most reliable test sensitive to small differences between means [23]. All tests were performed with an alpha level of 5%. These analyses were performed using the Stat View software [24].

3 RESULTS

3.1 DESCRIPTION OF PLOTS' SOIL

In the Bondoukuy region, hydromorphic soils are observed in low-lying areas in proximity to watercourses and in depressions where water accumulates temporarily. The aforementioned lowlands are characterised by a silty clayey texture. In general, no correlation was observed between texture and depth of hydromorphy or induration. The following categories are distinguished.

- The soil is classified as hydromorphic (3%), exhibiting a paucity of humus and a shallow gley (<80 cm) and pseudogley at the surface, with a silty tendency. The primary limitations of these soils are the occurrence of flooding in specific years and the presence of grass cover.
- The soil is classified as hydromorphic leached tropical ferruginous (16%), with a silty tendency, and is present at shallow depths (>10% of red pseudogley spots between 20-40 cm). Such soils are present in lowland areas with lower slopes and in secondary thalweg channels. The surface of these soils may exhibit the presence of damp spots for an extended period following the cessation of precipitation, which may be indicative of capillary rise. This phenomenon is particularly prevalent in lower-sloped areas and basins, as well as along secondary drainage axes. The initial two categories of soil are characterised by a high moisture content, yet they are not susceptible to flooding. These soil types are conducive to the establishment of shrub and forest vegetation, but they impose significant limitations on the cultivation of grassland.
- The soil is classified as a leached tropical ferruginous soil, representing 18% of the total soil type. It exhibits moderately deep hydromorphism, with the presence of red pseudogley spots observed at depths between 40 and 60 centimetres. Additionally, the soil may contain concretions, representing 15 to 40% of the total soil volume, situated at the base of slopes and basins. These soils correspond to the limit of humid soils. In order to classify these soils according to their water reserve, it is necessary to take into account their texture, which is predominantly silty.

- The soil types include leached ferruginous soils with deep hydromorphism (5%) (>60 cm), modal ferruginous soils (reddened and without hydromorphism), hydromorphic ferruginous to ferrallitic transition soils, and transition from hardened to hydromorphic ferruginous soils. These are sandy-silty soils with a tendency to dry out easily, which makes them relatively straightforward to maintain.

The proportion of ferrallitic soils (23%) exhibiting weak desaturation in B is typical of the modal formation, comprising ridges and plateaus in the piedmont of armoured hillocks. Despite being classified as moderately dry soils, the enhanced structural integrity and elevated iron content, particularly in the piedmont position of armoured hillocks, impart a superior organic retention capacity to these soils compared to leached ferruginous soils with deep hydomorphy. Furthermore, farmers frequently regard these soils as superior.

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). As is the case in Sudanese forests and fallows, three taxonomic groups are predominant among woody species: The dominant taxonomic groups among woody species are leguminous, Combretaceae and Rubiaceae. The number of Combretaceae species increases and the number of leguminous decreases in response to a reduction in hydromorphy. 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 fallows. It can be seen that plant formations are organised according to a number of factors, including biotopes and hydromorphy. Indeed, fire, temporary cultivation, selective cutting and grazing are significant factors that are likely to exert a strong influence on the physiognomy and flora of plant formations at different stages of reconstitution after cultivation or certain developments.

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

	Plots		
Vegetation	**Forests**	**Fallows**	**Fields**
Woody species	*Albizzia chevalieri, Anogeissus leiocarpus, Grewia mollis* *G. bicolor, Boswellia dalzielli* *Combretum nigricans* *Isoberlinia doka* *Lannea microcarpa* *Lannea velutina* *Grewia tenax* *Nauclea latifolia* *Pterocarpus erinaceus* *Ximenia americana, Tephrosia pedicellata, Terminalia avicennoïdes* *Combretum glutinosum* *Vitellaria paradoxa* *Desmodium velutinum* *Piliostigma thonningii Piliostigma reticulatum.* *Bombax costatum, Mayntenus senegalensis, Feretia apodanthera, Parinari curatellifolia, Sterculia setigera, Pericopsis laxiflora* *Diospyros mespiliformis,* *Swartzia madagascariensis Capparis corymbosa, Ziziphus mauritiana Mitragyna inermis, Berlinia grandifolia, Raphia sudanica, Acacia polyacantha, Acacia sieberiana*	*Vitellaria paradoxa* *Anogeissus leiocarpus* *Terminalia avicennoïdes* *T. laxiflora* *Piliostigma thonningii* *Piliostigma reticulatum* *Combretum micrantum* *C.glutinosum* *C. nigricans* *C. molle* *Guiera senegalensis* *Swartzia madagascariensis*	*Vitellaria paradoxa* *Lannea microcarpa* *Lannea velutina*
Perennials herbaceous	*Gladiolus klattianus* *Crinum humile* *Dioscorea dumetorum* *Lippia chevalieri* *Vernonia purpurea* *Cyanotis longifolia, Andropogon gayanus, Andropogon ascinodis* *Cymbopogon shoenanthus* *Costus spectabilis* *Cochlospermum tinctorium*	*Tephrosia pedicellata* *Andropogon gayanus* *A. ascinodis* *Borreria stachydea* *Cochlospermum tinctorium* *C. planchoni* *Leptadenia hastata* *Lantana rhodesiensis* *L. camara* *Sporobolus festivus*	*Andropogon gayanus*

	C. planchoni *Leptadenia hastata* *Lantana rhodesiensis* *L. camara*		
Annuals herbaceous	*Aspilia helianthoides* *Commelina forskalei* *Cissus gracilis* *Ampelocissus pentaphylla* *Andropogon pseudapricus*	*Andropogon pseudapricus* *Rottboelia exaltata* *Loudetia togoensis*	*Sorghum bicolor* *Gossypium spp* *Zea mays*

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 typically utilized 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 cultivation 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.

- The area is characterised by 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 humid, fertile environments, protected from fire, represent the closest approximation to the "climax" of the "dense dry forest". The population of hemi-ombrophilous species and humid environments of these formations is characterised by a rich diversity of fire-sensitive legumes, 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, Isoberlinia doka, Daniella oliveri* and *Burkea africana*. 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, Pteleopsis suberosa, Detarium microcarpum,* 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 savannas, which exceed 50% woody cover at a low height, is observed in areas where grazing has been excessive.

3.3 SOIL PHYSICAL CHARACTERISTICS

The results of the analysis clearly demonstrate a situation effect with regard to the texture (Table 2). It is evident that the forests exhibit markedly disparate clay (24.72%), fine silt (17.44%) and coarse silt (19.12%) compositions when compared to the fallows (14.41% clay, 8.57% fine silt and 18.87% coarse silt) and fields (9.8% clay, 6.74% fine silt and 15.72% coarse silt). It can be concluded that the proportion of fine elements (less than 20 µm) is greater in the forest area than in the fallow land and agricultural fields. The sand content in the forests is relatively low, with a mean value of 38.72%. This is statistically different from the sand content in the fallows (mean value of 57.15%) and fields (mean value of 67.74%). The proportion of coarse elements (>50 µm) in the forest is less than that of fine elements (>20 µm), which corroborates the silty-clayey composition of the soil.

Table 2. Soil Physical Characteristics at 0-20 cm depth. Means displaying the same letter per row are not significantly different (n=12, P<0.005), standard error in parentheses

	Plots		
Parameters	**Forests**	**Fallows**	**Fields**
Clays (%)	24.72a (3.43)	14.41b (1.16)	9.8c (1.22)
Fine silts (%)	17.44a (7.05)	8.57b (0.74)	6.74c (1.48)
Coarse silts (%)	19.12a (0.83)	18.87a (2.1)	15.72b (3)
Coarse + Fine sands (%)	38.72a (10.49)	57.15b (2.25)	67.74b (5.18)

3.4 THE ORGANIC AND ACID-BASE STATUS OF SOILS

The analysis of variance demonstrates a highly statistically significant effect of the situation (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 in question at the level of organic matter contents (C, N), exchangeable bases and CEC. The results obtained permit an in-depth analysis of the dynamics of soil fertility reconstitution and the enhancement of CEC through the examination of the diverse chemical and organic elements.

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

Variables	$F_{8.45}$	P	R^2	CV
C (%)	60.23	<0.0001	0.90	35.2
N (%)	40.55	<0.0001	0.80	30.12
C/N	30.45	<0.0001	0.56	25.6
pH-H_2O	15.43	0.122	0.27	12.5
pH-KCl	16.67	0.1300	0.19	9.6
Ca^{2+} (meq.100g^{-1})	30.13	<0.0002	0.53	20.8
Mg^{2+} (meq.100g^{-1})	22.42	<0.0001	0.73	20.67
Mn^{2+} (meq.100g^{-1})	26.53	<0.0001	0.67	27.32
K^+ (meq.100g^{-1})	40.25	<0.0001	0.77	22.8
Na^+ (meq.100g^{-1})	19.80	<0.0001	0.60	26.7
CEC (meq.100g^{-1})	20.45	<0.0001	0.79	24.5
SEB (meq.100g^{-1})	15.53	<0.0003	0.55	24.2
SEB/CEC (%)	53.13	<0.0001	0.52	31.5

3.4.1 PH-H2O AND PH-KCL

The results of the statistical analyses conducted on the pH values are not statistically significant. Conversely, the pH of the various scenarios under examination is characterised by a weakly acidic profile, with values ranging from 6.36 to 5.98 for pH in water and from 5.4 to 5.12 for pH in KCl (Table 4). The findings indicate that despite 20 years of fallow land, the forest has not significantly altered the pH of the soil.

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

	Plots		
Parameters	**Forests**	**Fallows**	**Fields**
C (%)	1.48a (0.37)	0.65b (0.12)	0.34c (0.06)
N (%)	0.1a (0.02)	0.054b (0.01)	0.03b (0.01)
C/N	15a (2.07)	12b (0.78)	11b (3.9)
pH-H2O	6.36a (0.65)	5.98a (0.56)	6.41a (0.97)
pH-KCl	5.4a (0.69)	5.12a (0.7)	5.23a (1.06)

3.4.2 CARBON

The statistical analyses conducted on the mean carbon (C) contents of the various scenarios yielded significant results (P < 0.0001) (Table 3), with a clear distinction between forest (1.48%), fallow (0.65%), and field (0.34%) scenarios (Table 4). The carbon content increased by 1.14% from fields to forests, while the transition from fallows to forests resulted in an increase of 0.83%. Conversely, a pronounced decline in carbon content is evident when moving from forests to fields (Figure 2). The fallow stage, therefore, represents the initial phase of carbon storage, which accumulates sustainably during the subsequent forest phase.

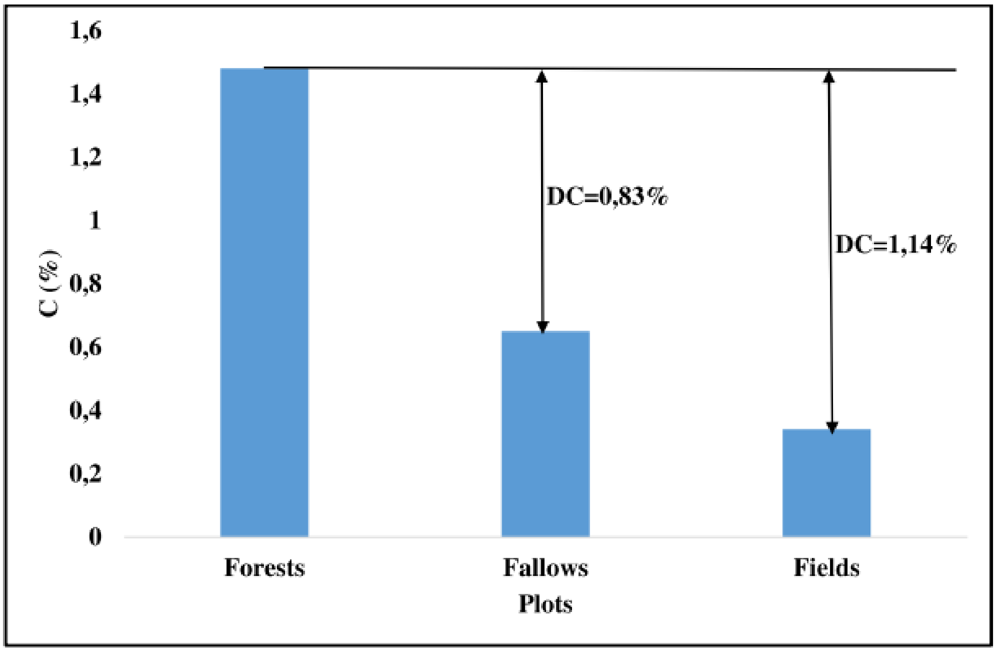

Fig. 2. Difference in carbon content (DC)

3.4.3 NITROGEN

The statistical analysis of nitrogen averages revealed a highly significant situation effect (P < 0.001) (Table 3), with forests exhibiting notable differences from fallows and fields, which demonstrated statistical similarity (Table 4). The nitrogen levels observed vary considerably, with values ranging from 0.1% in forest areas to 0.054% in fallows and 0.03% in fields. A gain of 0.07% is observed when moving from forests to fields, while a gain of 0.046% is observed when moving from forests to fallows. Conversely, the transition from field to forest results in a loss of 0.07%. The losses and gains in nitrogen observed in fallows are twice those observed in fields (Figure 3). It can be concluded that nitrogen is reconstituted during the fallow period and appears to stabilise in the forest.

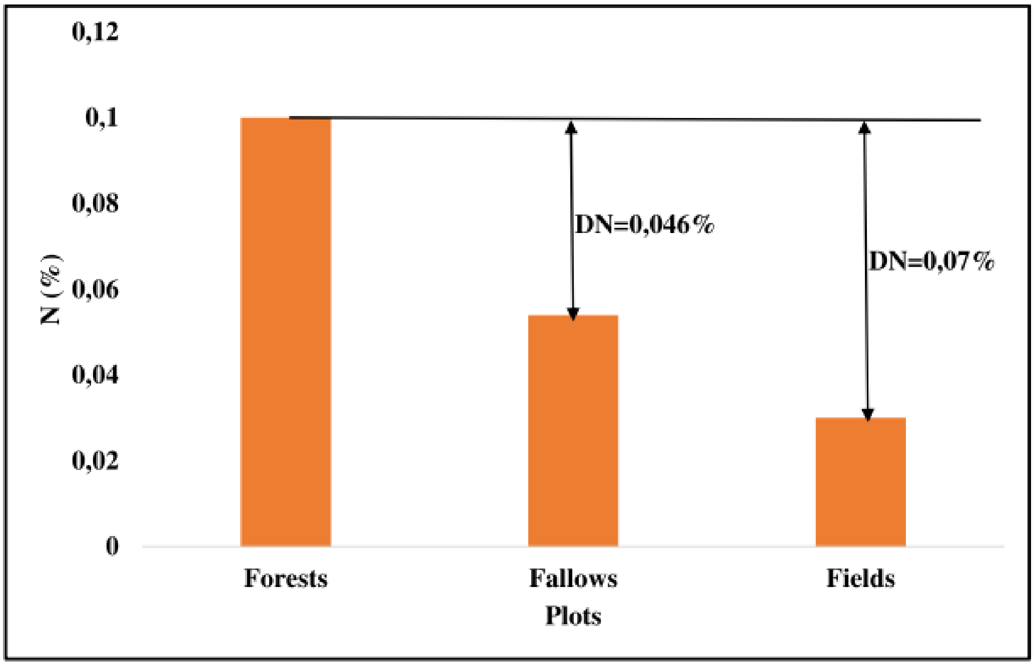

Fig. 3. Difference in nitrogen content

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 11 to 15 and is statistically significant depending on the circumstances under consideration. Forests (C/N=15) are distinguished from fallows (C/N=12) and fields (C/N=11) (Table 4). The low C/N ratio observed in fallows and fields suggests a rapid rate of mineralisation, whereas the high C/N ratio observed in forests indicates a slower rate of mineralisation, which is translated here by a lack of nitrogen.

3.5 NUTRIENT STATUS ACCORDING TO EXCHANGEABLE BASES

Table 5 illustrates the soil fertility level based on the mean CEC values and exchangeable bases.

Table 5. Characteristics of nutrient status at 0-20 cm depth of soil in the studied situations. Means displaying the same letter per line are not significantly different (n=24, P<0.005), standard error in parentheses

	Plots		
Parameters	Forests	Fallows	Fields
Ca^{2+} (meq.100g^{-1})	9.6a (0.41)	3.3b (0.35)	2.66b (0.9)
Mg^{2+} (meq.100g^{-1})	4.7a (0.14)	2.1b (0.11)	1.1b (0.48)
K^{+} (meq.100g^{-1})	2.7a (0.07)	1.6b (0.09)	0.184b (0.06)
Na^{+} (meq.100g^{-1})	1.02a (0.01)	0.8a (0.01)	0.02b (0.02)
Mn^{2+} (meq.100g^{-1})	1.01a (0.03)	0.5a (0.03)	0.02b (0.02)
Sum of exchangeable bases (SEB) (meq.100g^{-1})	19.03a (0.87)	8.3b (1.4)	4c (1.43)
CEC (meq.100g^{-1})	20a (0.89)	10b (1.45)	4.14c (1.46)
Bases saturation SEB/CEC (%)	95.15a (2.08)	83b (1.89)	95.12a (1.91)

3.5.1 Exchangeable Bases And Cation Exchange Capacity (CEC)

The mean calcium values obtained ranged from 9.6 meq.100g^{-1} to 2.66 meq.100g^{-1}. The statistical analyses revealed a highly significant effect of the situation on Ca^{2+} levels. The forest samples exhibited higher values (9.6 meq.100g^{-1}) compared to the fallow (3.3 meq.100g^{-1}) and field (2.66 meq.100g^{-1}) samples, which demonstrated statistically similar values.

The mean magnesium levels ranged from 4.7 to 1.1 meq.100 g^{-1}. A significant situation effect on magnesium levels was observed. It is evident that forest situations exhibit the highest contents (4.7 meq.100g^{-1}) in comparison to fallows (2.1 meq.100g^{-1}) and fields (1.1 meq.100g^{-1}), which demonstrate statistically equivalent contents.

The mean potassium values observed ranged from 2.7 to 0.184 meq.100g^{-1} (Table 5). A highly significant situation effect was observed ($P < 0.0001$), with fallows (1.6 meq.100g^{-1}) and fields (0.184 meq.100g^{-1}) exhibiting deficiencies in K compared to forests (2.7 meq.100g^{-1}).

The results of the analysis indicated a highly significant impact of the situation on the mean sodium values. The highest rates were observed in forests (1.02 meq.100g^{-1}), followed by fallows (0.8 meq.100g^{-1}) and fields (0.02 meq.100g^{-1}).

The mean manganese values exhibited considerable variation, ranging from 1.01 to 0.024 meq.100g^{-1} (Table 5). The results of the statistical tests indicated the presence of a highly significant situation effect. The data indicated that forests exhibited significantly higher manganese levels than fallows and fields, suggesting a deficiency in the latter two situations.

CEC represents the set of exchangeable cations present in the soil, including calcium, magnesium, potassium, sodium and manganese. The mean CEC values obtained in the different situations are between 20 and 4.14 meq.100g^{-1} (Table 5). The statistical analyses revealed a highly significant situation effect ($P < 0.00001$) on the observed differences in the values obtained. The mean CEC values for forests are higher (17 meq.100g^{-1}) than those for fallow land (10 meq.100g^{-1}) and fields (4.14 meq.100g^{-1}).

3.5.2 Bases Saturation Rate

The saturation rate is defined as the ratio of the sum of exchangeable bases to the cation exchange capacity. The figure ranges from 95.15% to 83% (Table 5). A highly significant situation effect was identified through the statistical analysis. The saturation rate serves as an indicator of the chemical richness of the soils and the cationic lining of the adsorbent complex. The saturation rate is notably elevated in forest and agricultural settings, reaching 95.15% and 95.12%, respectively.

3.5.3 Nutrient Status According To Chemical Balances

In order to diagnose mineral balances and assess the relative deficiency of exchangeable bases in soils, specific values are calculated (Figure 4).

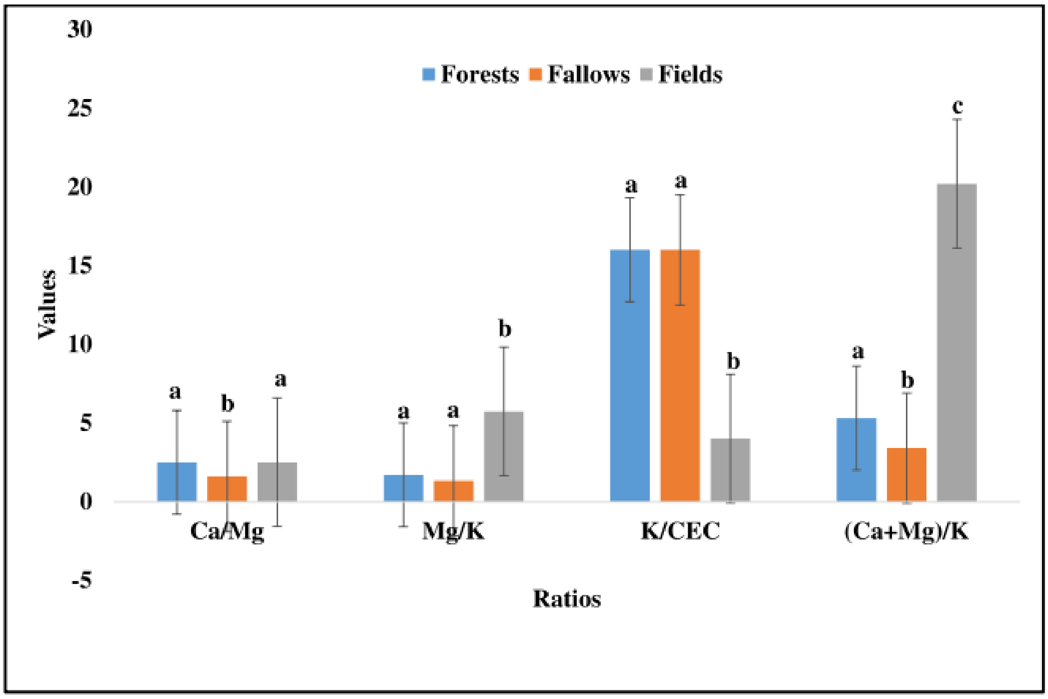

Fig. 4. Chemical balance of soil in different situations

3.5.3.1 CA/MG BALANCE

The Ca/Mg ratio values obtained in the various experimental conditions ranged from 2.5 to 1.6 (Figure 4). The results of the statistical analysis indicated that there was no statistically significant difference between the values obtained in the forest and field settings. These two scenarios are in contrast to those observed in fallows.

3.5.3.2 MG/K BALANCE

The Mg/K ratios observed ranged from 5.73 to 1.32. The results of the statistical analyses indicated a statistically significant effect of the situations under consideration on the Mg/K ratio. The Mg/K ratios observed in forests (1.7) and fallows (1.3) are comparatively low, whereas those in fields are high (5.73) (Figure 4).

3.5.3.3 K/CEC RATE (%)

The proportion rate of potassium (K) in saturation varies considerably depending on the circumstances, with values ranging from 16% to 4%. The results of the statistical analyses indicated the presence of a significant difference and a situation effect. Forests and fallows, which exhibit statistically identical rates (16), are juxtaposed against fields (4) (Figure 4).

3.5.3.4 CA+MG) /K BALANCE

The mean values of the (Ca+Mg) /K ratio from the various experimental conditions exhibited a range of 5.3 to 20.2. The results of the statistical analyses clearly demonstrated a highly significant situation effect. The low ratios observed in fallow land (3.4) are in stark contrast to those seen in forests (5.3), which in turn are distinct from the high ratios observed in fields (20.2) (Figure 4).

4 DISCUSSION

4.1 TEXTURE ROLE

The upper layers (0-20 cm) of soil in the various situations under consideration are characterised by a silty-clayey texture. This texture confers structural stability upon the soil and provides a substantial specific surface area for the retention of nutrients. The clay content is notably elevated in these surface horizons, reaching levels between 9 and 24.72%. The elevated clay content of these soils renders them highly chemically reactive. It is notable that the clay content of forests (24.72%) is approximately twice that of fields (9.8%). This suggests that the clay fraction undergoes reconstitution during fallow periods (15.41%), which then stabilises in the forest. The significance of the clay fraction has been elucidated in the context of CEC dynamics in hydromorphic soil [25-29]. As stated by Baize [30], clay is the most active granulometric fraction due to its multifunctional nature, which includes associations with organic matter, the cohesion of aggregates, the fixation of cations and anions on exchange sites, and water retention. However, the capacity of clay minerals to retain cations and enhance the cation exchange capacity (CEC) is more dependent on their intrinsic properties than on their relative abundance in the soil. In hydromorphic soils, the specific type of clay present can have a significant impact on the soil's properties and functions. In particular, smectites, illites and montmorillonites, which possess a negative charge, thereby enabling them to attract and retain cations. This directly contributes to an increase in the CEC [25, 27, 31, 32]. The provenance of the low-humus substrate, characterised by a shallow gley (<80 cm) and pseudogley, is also a contributing factor in enhancing the CEC. Indeed, hydromorphic tropical ferruginous soils are often the site of certain processes, such as the reduction of metal oxides (Fe, Mn), which can influence the reactivity of clays and the availability of cations [26, 28, 29, 33].

Due to their coarseness relative to clays, fine silts also participate in water storage, thereby influencing the accessibility of nutrients during periods of excess water or drainage. This, in turn, has the effect of improving the CEC [26, 28, 33, 34]. Furthermore, coarse silts exert an influence on soil structure and water distribution, which can indirectly affect cation dynamics in hydromorphic soils by facilitating or limiting water and nutrient movements [26, 34, 35]. Our observations have been corroborated by several authors in similar studies [25, 36, 37, 38, 39]. The texture and cation exchange capacity (CEC) of a soil are sometimes influenced by the presence of vegetation and other factors.

4.2 VEGETATION ROLE

The vegetation of western Burkina Faso is characterised by a high degree of diversity in terms of morpho-structural types, which are adapted to different environmental conditions. The physiognomy of Sudanese forests is therefore representative of a succession of intermediate states between 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 [11, 40]. The biodiversity of this region is considerable, though not particularly forest-specific. The dynamic equilibrium achieved in the soil of forests and fallows thus permits the restoration of soil fertility to a significant extent. This results in an improvement in the CEC and the exchangeable bases of hydromorphic soils. Boyer's [41] research demonstrated that the concentration of specific cations (Ca^{2+} and Mg^{2+}) in the surface layer of the soil is influenced by vegetation. In forests on hydromorphic ferruginous soils, the woody layer exhibits greater coverage and larger individuals than in fallows. Furthermore, the perennial herbaceous layer is observed to occur in clumps of more uniform size, planted at a higher density in forests than in fallows. As a consequence, wet forests generate a considerable quantity of organic matter (such as fallen leaves and plant detritus) which decomposes at a relatively slow rate due to the high humidity. The organic matter improves the cation exchange capacity (CEC) of the soil, due to the presence of organic colloids (humus) with a high cation exchange capacity. The greater abundance of woody plants in forest vegetation, in comparison to that observed in fallows, provides the opportunity to restore soil fertility through the return of plant matter to the soil. Indeed, woody plants serve as reservoirs for mineral salts (particularly phosphorus) and provide soil with energy through litter and exudates [42]. The installation of these structures prioritises the survival function, with the constitution of a tuberous pivot (reserves of photosynthates and water) supplied by seasonal aerial parts [43]. In some cases, woody plants are eliminated by fires, which act as a selective force on species. Conversely, the vegetation of fallow land is dominated by perennial grasses (hemicryptophytes), which are well adapted to fires and grazing. As a result, the tillering plates, buds and young stems that are used for survival and regrowth following fires are located underground or protected at the base of the tuft by a dense mass of dead tissues [44]. The results demonstrate that the clearing of a forest would facilitate the injection of three times more calcium and twice as much magnesium and potassium into the soil in comparison to that of a fallow land. The diverse flora of the forests, in comparison to that of fallow land, would account for the relatively high contents of exchangeable bases obtained. It is therefore crucial to highlight the significance of forests in the restoration of soil fertility.

4.3 PH ROLE

The pH of the soil is a determining factor in the type of activity that exists or predominates, whether that be acid or basic. The pH values of forest soil (6.36) and fields (6.41) are generally slightly neutral, while that of fallow land (5.98) is slightly acidic. It has been demonstrated that the pH value increases gradually over time during the long-term storage of organic matter during plant succession, as evidenced by Falkengren-Grerup [45]. In the studies conducted by Bationo *et al.* [46] and Baize [30], the optimal pH range for optimal activity was found to be between 5.5 and 6.5. The pH values obtained in this study are higher than the aforementioned threshold, indicating that the chemical and microbiological reactions in the soil are occurring in a manner that is conducive to the proper availability of nutrients. In general, cultivated plants develop in a harmonious manner in soil with a pH of 5.5 to 7, which is considered neutral or slightly acidic [30, 47]. A reduction in soil pH has been demonstrated to impede plant growth by inhibiting nitrification. Nevertheless, pH levels alone are an inadequate explanation for the observed enhancement in CEC. The effect is indirectly related to the content and nature of the clays. Hydromorphic soils have a tendency to accumulate H^+ ions (resulting in acidification), which can lead to a reduction in CEC over time by competing with other cations. A soil with a higher acidity level will exhibit a reduced CEC, due to the fact that soil colloids are less effective at retaining nutrients. In particular, acidic hydromorphic soils have been observed to exhibit a lower CEC [27]. This is not the case in the present study, in which the soils are weakly neutral. Furthermore, it is notable that the CEC (20 meq.100g-1) of the forests in question is twice that of the fallow land (10 meq.100g-1) and five times higher than that of the fields (4.14 meq.100g-1). The combination of a weakly neutral pH and a high clay content therefore renders the forest an ecosystem conducive to an increase in CEC. As with texture and vegetation, pH exerts an influence on CEC. Nevertheless, it remains unclear what role organic matter plays in enhancing CEC.

4.4 EFFECT OF SOIL ORGANIC MATTER (C, N)

The presence of organic matter (C, N) in tropical ecosystems has been demonstrated to enhance soil fertility. It is an effective indicator of plant health. In the context of our study, the C and N values are higher in forests (1.48% C, 0.1% N), representing a twofold increase in C and N compared to fallow land (0.65% C, 0.054% N) and a fourfold increase compared to fields (0.34% C, 0.03% N). The high organic matter content in forests serves to protect the soil from degradation by water erosion during periods of heavy rainfall [48]. The high organic matter content and silty-clayey texture of forests also contribute to the accumulation of soil nutrients and an increase in CEC. Conversely, a comparison of the contents of forests with those of fallow land and fields demonstrates a dynamic of organic matter that then increases during the fallow period. It is evident that a considerable increase of 1.14% in carbon is observed when comparing permanent crop situations to forests via fallow land. The transition from fallow land to forests allows for a gain of 0.83% in carbon. The transition at the nitrogen level provides a gain of 0.07% N, starting from fields to forests, while the transition from fallow land to forests gives a gain of 0.046% N. It can be demonstrated that fallow practices have the effect of enhancing the organic matter content of soil, which then becomes stabilised in forest ecosystems. This is attributable to the reintroduction of plant matter to the soil, which is of a considerably higher density in forests than in fallow land. In agricultural fields, the low organic matter content can be attributed to the continuous presence of crops, the inherent richness of the soil, and, in some cases, the lack of replenishment of crop residues. It should be noted, however, that in the context of hydromorphic soil in Bondoukuy, the improvement in CEC is strongly correlated with organic matter. Indeed, soil hydromorphism facilitates the accumulation of organic matter in the upper layer, as decomposition is slowed down in anaerobic conditions [49]. The negative charge of organic matter allows it to retain cations, thereby increasing the CEC [50, 51]. However, if soils are excessively saturated and oxygen-poor, incomplete decomposition can also result in the formation of recalcitrant organic compounds, which are less effective in retaining cations [27, 52, 53]. Our observations are corroborated by several studies [51, 54, 55, 56, 57, 58]. It can be concluded that organic matter plays an essential role in improving the cation exchange capacity (CEC) of hydromorphic soils. It permits the retention and release of cations that are essential for plant nutrition, enhances soil structure and water retention, 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 K+, Ca2+, Mg2+, and Na+. A soil with a CEC of 10 to 20 meq.100g^{-1} is regarded as moderate and acceptable for crops, whereas a soil with a CEC exceeding 20 meq.100g^{-1} is considered favourable for nutrient retention in fertile soil, such as hydromorphic soils. This is supported by the findings of several studies [25, 32, 59]. The CEC of forests was found to be 20 meq.100g$^{-1,}$ which is double that of fallow land (10 meq.100g^{-1}) and five times higher than that of fields (4.14 meq.100g^{-1}). The CEC of the hydromorphic forest soil is indicative of stability and nutrient richness for plants. Furthermore, it is important to acknowledge the correlation between the CEC and the clay-humic complex, as well as the organic matter content. The elevated CEC observed in forest soils can be attributed to the combined influence of two key factors: a high silty-clayey texture and a high organic matter content. The CEC of fallow land, although lower than that of forests, remains within acceptable limits, thereby facilitating the establishment of crops. Conversely, the CECs for hydromorphic soils in the control fields are notably low, yet crop cultivation is feasible. The findings of Fang *et al.* [60] indicate that the CEC is significantly influenced by climatic conditions, precipitation levels, topographical features and human activities. This is exemplified by our hydromorphic soils. A comparison has been made between the CEC of forest and fallow land soil and that of fields under permanent cultivation. The functional particularity of CEC precludes its storage in cultivated soils. This is indicative of the low value obtained, despite the favourable nature of the soil in question with regard to the increase in CEC.

Exchangeable bases represent the essential cations (K+, Ca2+, Mg2+, Na+) that are available to plants. An enhancement in these bases directly enhances soil fertility [61, 62]. The study revealed that forest soils exhibited a pH value of 19 meq.100g-1, which was approximately twice that of fallow soils (8 meq.100g^{-1}) and approximately five times that of field soils (3.94 meq.100g^{-1}). The forest values exceed the threshold (2<SBE<15 meq.100g^{-1}) for hydromorphic tropical soils [41, 47, 63]. It should be noted that these values may fluctuate in response to temporary waterlogging associated with hydromorphism. It can be surmised that this results in some cations being favoured at the expense of others. The elevated levels of exchangeable bases in forest soils provide compelling evidence of enhanced CEC in these ecosystems. This increase has been observed to occur in a gradient from fields to forests, with intermediate fallow situations exhibiting intermediate values. Notwithstanding the fact that the land in question has been subjected to permanent cultivation, the soil in the fields in question displays values that fall within the threshold established for hydromorphic tropical soils. This therefore permits the continuation of permanent agricultural activity. Nevertheless, the removal of forest or fallow vegetation would result in the introduction of cations into the soil at a rate five times greater than that observed in the fields.

The saturation rate is an invaluable environmental indicator of the chemical richness of the soil, which determines the biological activity, quality and reserves of fertilising elements. The mean saturation rate values indicate that the three scenarios are situated on highly fertile soils, with forest areas exhibiting a saturation rate of 95%, fallow lands displaying a saturation rate of 83%, and agricultural fields exhibiting a saturation rate of 95%. Therefore, the transformation of fallow land into forest has not resulted in a significant alteration in the saturation rate of the bases. These soil fertility states under forests and fallow land may be attributed to the previous cultivation of the latter prior to its conversion to fallow land. The work of Serpantié [11] on hydromorphic soil has demonstrated that fallow soil from animal-drawn cultivation regenerates rapidly, in contrast to that from motorised cultivation. The soil states observed in the fields are identical to those observed in the forests and fallow land, and these observations can be readily explained by the fact that heavy tillage is preferentially carried out with a plough by the local population, who are keen to preserve soil fertility.

4.6 INFLUENCE OF CHEMICAL BALANCES

The equilibrium of chemical balances between diverse cations (Ca^{2+}, Mg^{2+}, K^{+}) and soil CEC is a crucial factor influencing soil fertility and plant nutrition in general. The Ca/Mg ratio is frequently regarded as a crucial factor in maintaining optimal soil structure and balanced nutrient availability [25]. 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 [25, 64, 65]. The optimal Ca/Mg ratio for tropical hydromorphic soils is between 2 and 4.5 [27, 47]. The values of the ratios obtained in the present study range from 1.6 to 2.5. This suggests the potential for inhibition of Mg and a deficiency of Ca in our soils. The occurrence of waterlogging for part of the year may or may not favour the presence of one of the two elements. Such consequences would be detrimental to plant nutrition, resulting in soil compaction or poor aeration. The soil ratios observed in forest and field ecosystems are higher (2.5) than those recorded in fallow land (1.6). This supposition is based on the assumption that plant nutrition is optimal in the first two situations, in contrast to the potential calcium deficiency observed in fallow land.

The Mg/K ratio plays a pivotal role in plant nutrition and cation balance within the soil. An excess of magnesium can compete with potassium for exchange sites in the soil matrix [25]. This may result in a limitation of potassium uptake by plants. In the case of these two cations, which are known to be antagonistic, the optimal ratio falls between 2 and 4 [41]. With the exception of fields exhibiting a Mg/K ratio of 5.73, forests and fallows display a Mg/K ratio of 1.7 and 1.32, respectively. This suggests that a magnesium deficiency may occur in forest ecosystems. The low ratio may indicate an excess of potassium, which could result in a magnesium deficiency for some plants, thereby disrupting the nutritional balance and reducing the CEC. As demonstrated by Dognin *et al.* [66], maintaining an optimal Mg/K ratio optimises the utilisation of cation exchange sites and facilitates balanced nutrient absorption by plants. Conversely, in hydromorphic soils, the conditions of water saturation and low oxygenation result in a greater alteration of primary minerals, which is likely to be the case for forest and fallow soils. Indeed, these two scenarios exhibit the presence of persistent vegetative cover, in contrast to cultivated fields. It can be surmised that the excess potassium is linked to the constant return of slowly decomposing plant matter to the soil, a consequence of hydromorphy.

The K/CEC ratio represents the proportion of potassium relative to the total cation exchange capacity of the soil. In hydromorphic Sudanian soil (40% fine elements), a K/CEC ratio of 2 to 5% is deemed satisfactory for the majority of plants [25]. The ratio may be influenced by the retention of water and the potential leaching of potassium during periods of heavy rainfall. Values that are too high indicate potassium saturation, which can result in the blockage of the absorption of other cations. As stated by Fallavier and Olivin [67], potassium is preferentially exchanged in hydromorphic soils, with the consequence that other cations are displaced. However, this process is limited by the saturation of the CEC, which should not exceed 30%. Notwithstanding the elevated clay and organic matter concentrations, the effective availability of nutrients may be diminished by water saturation. In the present case, the forest and fallow areas exhibit a ratio of 16%, while the control fields display a ratio of 4%. The low ratio of potassium in the soil, as observed in the fields, indicates a potential limitation in the availability of this nutrient for plant nutrition. Conversely, the elevated levels of potassium observed in forest and fallow soils have the potential to disrupt the absorption of other cations. This excess in forest and fallow soils can be attributed to the constant renewal of the K-rich plant litter.

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. An optimal ratio of (Ca+Mg) /K of 10 to 20 is typically recommended for hydromorphic soil [25]. 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 the soil constituents in our forests and fallow land is 5.3 and 3.4, respectively, while that of cultivated fields is 20. The availability of calcium and magnesium is therefore problematic in natural vegetation situations, despite the permanent renewal of the stock of plant matter. Conversely, in agricultural fields, the supply of potassium is constrained. This is justified at the field level, where organic amendments are limited to crop residues for certain crops [68] and potassium is preferentially taken up by crops. In fallow lands, which represent a transitional phase prior to forestation, this phenomenon can be attributed to the restitution of plant matter comprising species with low potassium content. The natural plant composition thus influences the renewal of cation stocks and the enhancement of the CEC in general.

5 CONCLUSIONS

This study demonstrated the significance of modified natural forest and fallow ecosystems in the restoration of soil fertility dynamics through a comparative analysis of CEC enhancement and exchangeable bases. In Sudanese hydromorphic soils, cation exchange capacity (CEC) dynamics are enhanced by the presence of clay minerals, which possess a large surface area and cation retention capacity. The contribution of fine silts is comparatively limited, whereas coarse silts play a more prominent structural role. Furthermore, hydromorphic conditions exert an influence on soil chemistry, modifying the reactivity of clays and the availability of essential cations. The high organic matter content associated with a weakly acidic pH creates a favourable environment for CEC enhancement in forest soils. The measurement of a range of soil chemical and physical parameters enabled a comparison of forest soils with those of fallows and fields. It is evident that the intermediate stage of fertility reconstitution, represented by fallow, does not significantly contribute to the enhancement of CEC and exchangeable bases. It is essential to allow for the establishment of the tertiary forest before expecting to observe significant increases in CEC and exchangeable bases. These increases are observed at the levels of all the physicochemical parameters measured, including texture, carbon (C), nitrogen (N), cation exchange capacity (CEC), calcium (Ca^{2+}), magnesium (Mg^{2+}), manganese (II) (Mn^{2+}), sodium (Na^{+}), and potassium (K^{+}).

Increasing the CEC and exchangeable bases of a hydromorphic soil of the Sudanian forest of western Burkina Faso must therefore be based on integrated soil management with innovative approaches such as adapted cultural practices.

These approaches aim not only to increase the soil's capacity to retain nutrients, but also to improve the availability of exchangeable bases that are essential for plant growth. These approaches also help promote sustainable agriculture and improve agricultural productivity in this region where soils are naturally poor in nutrients.

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.

CONFLICTS OF INTEREST

All authors declare no conflicts of interest regarding the publication of this paper.

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