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Influence of agroforestry system based on cocoa tree on the physico-chemical properties of soils of the Luki Biosphere Reserve in the Democratic Republic of Congo

Alasca Ekuya Lombolu[1], Jeancy Ntuka Luta[1], François Kabambi[1], Irène Kibale Mande[1], Bhely Angoboy Ilondea[2], Yves-Dady Botula[2], Paul Mafuka[1]

[(1)]University of Kinshasa. Faculty of Agricultural Sciences and Environment. Soil Sciences Research Center (CReSSol). BP 117 Kinshasa XI (DRC). E-mail: alascaekuya@gmail.com
[(2)]National Pedagogical University. Faculty of Agricultural Sciences and Environment. BP 8815 Kinshasa (DRC)

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ABSTRACT

Description of the subject. In the Democratic Republic of Congo, cocoa-based agroforestry systems in natural forests in general and in the Luki Biosphere Reserve in particular have an impact on the characteristics of cultivated soils.
Objective. This study examines the impact of the cocoa-based agroforestry system on the physico-chemical properties of the Luki Biosphere Reserve soils, Democratic Republic of Congo. It seeks to characterize this agroforestry system and assess its influence in the soil compared to a natural forest.
Methods. The study was conducted in the Luki Biosphere Reserve (LBR), one of the main cocoa producing areas in the DRC. The climate is tropical humid with two distrinct seasons dry and wet. The agroforestry system studied include plots established by INERA and farmers between 1961 to 2017. Soil samples were collected and analyzed to determine several soil physico-chemical properties, such as: bulk density, granulometry, pH, nitrogen, organic carbon, phosphorus and potassium.
Results. Soils in cocoa-based agroforestry system have a pH wich varied between 3.2 to 4.5, while forest soils have a pH around 3.5. The INERA 2017 plot had the highest pH, at 4.5. Nitrogen content is 23.5 $mg.kg^{-1}$ in natural forest, and very low in agroforestry system. However, potassium and phosphorus reach respectively the levels of 31 and 14 $mg.kg^{-1}$ in some agroforestry plots, by the way the value recorded for both elements in the natural forest was very low. Carbon stock is higher in the natural forest, 16 $g.kg^{-1}$, but lower in agroforestry system 9.23 to 11.54 $g.kg^{-1}$.
Conclusion. The natural forest has high nitrogen and carbon levels, while the INERA 1961 plot shows the highest phosphorus and potassium concentrations. Tree density and species diversity significantly impact carbon storage and soil fertility, highlighting the importance of their management in agroforestry system.
Keyword: Agroforestry, cacao tree, deforestation, physicochemical properties of soils, Luki Biosphere Reserve.

RESUME

Influence du système agroforestier à base de cacaoyer sur les propriétés physico-chimiques des sols de la réserve de biosphère de Luki en République démocratique du Congo
Description du sujet. En République Démocratique du Congo, les systèmes agroforestiers à base de cacaoyer dans les zones forestières en général et dans la Réserve de Biosphère de Luki en particulier ont impact sur les caractéristiques des sols cultivés.
Objectif. Cette étude évalue l'impact du système agroforestier à base de cacaoyers sur les propriétés physico-chimiques des sols de la Réserve de Biosphère de Luki, en République démocratique du Congo. Elle vise à caractériser ce système agroforestier et à évaluer son influence sur les sols en comparaison avec une forêt naturelle périphérique.
Méthodes. L'étude a été réalisée dans la Réserve de Biosphère de Luki (RBL), l'une des principales zones de production de cacao en RDC. Le climat est tropical humide, avec des saisons distinctes, sèches et humide. Les

systèmes agroforestiers étudiés incluent deux parcelles installées par l'INERA et des agriculteurs entre 1961 et 2017. Des échantillons de sol ont été prélevés et analysés pour déterminer plusieurs propriétés physico-chimiques, telles que la densité apparente, la granulométrie, le pH, l'azote, le carbone organique, le phosphore et le potassium.
Résultats. Les sols des systèmes agroforestiers à base de cacaoyers présentent un pH compris entre 3,2 et 4,5, tandis que les sols forestiers ont un pH d'environ 3,5. La parcelle INERA 2017 présente le pH le plus élevé, à 4,5. La teneur en azote est de 23,5 mg.kg^{-1} dans la forêt naturelle, et très faible dans les systèmes agroforestiers. À l'inverse, le phosphore et le potassium atteignent des niveaux élevés dans certaines parcelles agroforestières, avec respectivement 31 mg.kg^{1} et 14 mg.kg^{1} pour le potassium et le phosphore, soit plus que la valeur enregistrée pour les deux éléments dans la forêt naturelle. Le stock de carbone est plus élevé dans la forêt naturelle (16 g.kg^{1}), mais inférieur dans les systèmes agroforestiers (9,23 à 11,54 g.kg^{1}).
Conclusion. La zone forestière présente de fortes concentrations en azote et en carbone, tandis que la parcelle INERA 1961 présente les concentrations les plus élevées en phosphore et en potassium. La densité des arbres et la diversité des espèces influencent significativement le stockage du carbone et la fertilité des sols, soulignant ainsi l'importance de leur gestion dans les systèmes agroforestiers.

Mots-clés : Agroforesterie, cacaoyer, déforestation, propriétés physico-chimiques des sols, Réserve de Biosphère de Luki.

1. INTRODUCTION

In Africa, agroforestry has been expanding, mainly in regions where rural populations rely heavily on forests for their livelihoods (Asaah *et al.*, 2013). The practice helps to mitigate deforestation and provides a diversified source of revenue for many poor rural communities, who often subsist only on agriculture (ICF, 2019). Therefore, in regions where it is practiced, agroforestry contributes to improving household incomes and reducing poverty. This system contributes also to the protection of ecosystems by enriching soils and reducing erosion (Camara *et al.*, 2012).

A major perturbation to forest ecosystem dynamics is deforestation for agriculture. In a large number of countries in the Congo Basin, forests are being cleared to make charcoal and the access to agriculture. This deforestation is not only for slash-and-burn agriculture, long considered the main driver of tropical deforestation, but also for the cultivation of cash crops such as cocoa and coffee (Plas, 2020; Mikobi *et al.*, 2021). Because cocoa is a demanding crop, the soils after the forest provide the fertility necessary for its proper development. A few species of trees that are not removed when the field is opened also provide the necessary shade. These form a cocoa tree - tree association, commonly called cocoa agroforestry (Nutriche, 2014; Oscar, 2022).

The main cocoa producing countries in Africa face a double challenge: maintaining or increasing cocoa yields while stabilizing existing production areas in order to limit deforestation and soil degradation (Adji *et al.*, 2021). To overcome this challenge, it is essential to conduct a study to understand this agroforestry model in order to evaluate its environmental sustainability. It aims to characterize and assess the influence of cocoa tree-based agroforestry systems on the physicochemical properties of soils compared to a native forest environment.
Existing research in DR Congo generally focuses on cocoa productivity or the spatial mapping of cultivated areas (Eblé *et al.*, 2022), but often overlooks the complex interactions between different plant species, biodiversity and long-term effects on soil health. The aim of this study is to characterise and assess the influence of cocoa-based agroforestry systems on the physico-chemical properties of soils, compared with a natural forest in Luki, DRC.

2. MATERIALS AND METHODS

2.1. Study site choice

This study was conducted in the Luki Biosphere Reserve (LBR) and its environs (Figure 1). The choice of this environment is justified by the fact that the Democratic Republic of Congo has three main cocoa production basins: in the East, the provinces of Kivu (North and South) and the Great East (Haut-Uele, Bas-Uele, Ituri); the Central Basin: the provinces of Equateur and Bandundu; and the Western Basin in the Central Congo, where the Luki Biosphere Reserve is located. The area of the reserve covers 33,811 hectares and extends between 13°04' and 13°17' eastern longitude and between 5°30' and 5°45' southern latitude; its altitude varies between 150 and 500 m (Nsenga, 2004).

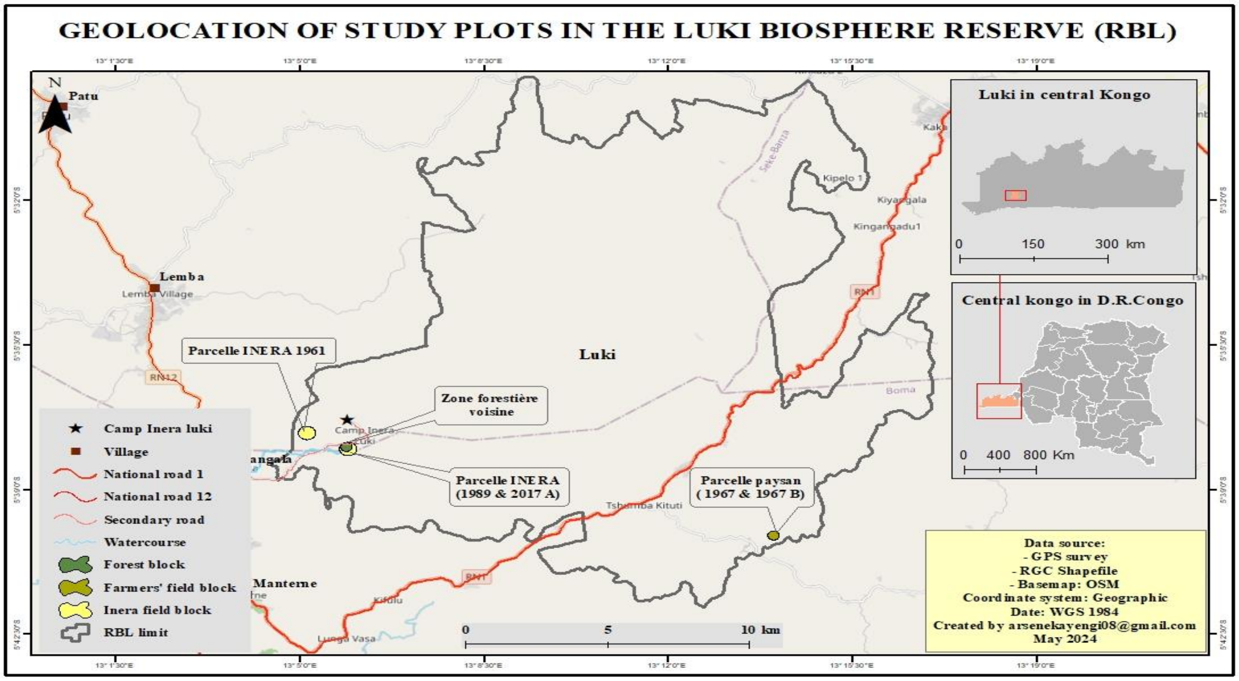

Figure 1. Map of the Luki Biosphere Reserve

This reserve is characterized by a tropical humid climate type Aw5 according to the Köppen-Geiger classification, characterized by two seasons: a long rainy season of five months (mid-September to mid-February), a short dry season of one month (mid-February to mid-March), a short rainy season of two months (mid-March to mid-May) and a long dry season of four months (mid-May to mid-September). The annual temperature varies between 19 °C and 30 °C, and precipitation ranges from 649 mm to 1853 mm (Nyange, 2014).

2.2. Description of the cacao-based agroforestry systems studied

The cacao-based agroforestry systems studied were installed using agro-silvicultural techniques (silvo-cacao tree) practiced in 1948 and 1956, when *Terminalia superba* plantations were established in the Luki Biosphere Reserve. The approach used was "standardization from below (UB) with deforestation, which allowed the establishment of limba plantations using agro-silvicultural techniques. As reported by Mangaza *et al.* (2022), 49.5 % of the biomass in these agroforestry systems consists of cacao trees.

However, the agroforestry plots managed by INERA and the farmers are subject to different practices. Those of INERA benefit from intensive maintenance, with practices such as permanent weeding and removal of suckers to improve the quality and productivity of the trees. The INERA 1989 R plot even underwent rejuvenation pruning at the age of 32. On the other hand, the 1967 farmers' plots, such as Paysan 1967 B, did not benefit from these practices.

2.3. Methodology of the study

Identification of cocoa tree agroforestry systems

The choice of cocoa tree plantations was made taking into consideration the availability of producers in the study area and the year of planting. The plots studied in this work are those of INERA and of farmers working in the Luki Biosphere Reserve. The manager of the INERA cocoa department and the cocoa farmers were asked a series of questions to determine the history of their plots, the tree species associated with cocoa trees, the cultivation practices used, and the perception of the role these trees play in their plots. The six plots of agroforestry systems studied were distributed as follows: four plots planted by INERA between 1961 and 2017 (one in 1961, two in 1989 and 2017); two other plots planted by INERA in 1967, but under the supervision of the farmers; and a natural natural forest.

Soil sampling and analysis

Soil samples were collected from the plots, taking into consideration the topographic variations of each plot. They were collected from 0 to 25 cm depth. Bulk density samples were taken at the same depth using the Copecky cylinder. A total of 55 composite soil samples were collected. These were taken from the INERA plots with an area of 2 ha (35 samples), from the farmers' cocoa tree plots with an area of 1.7

ha (13 samples) and from the natural secondary forest with an area of 1 ha (7 samples).

Soil samples were first air dried in the shade and then sieved (diameter < 2 mm). pH was measured in water at a soil : water ratio of 1:2. The Kjeldhal method was used to analyze the total nitrogen concentration, and the Walkley Black method was used to analyze the organic carbon content (Glosolan, 2019). Bulk density was determined using the cylinder method. Available phosphorus was extracted by the Bray II method (Bray and Kurtz, 1945) and determined by UV-visible spectrophotometry at a wavelength of 665 nm. Potassium (K+) was extracted from the soil using an ammonium acetate solution. It was then determined by UV-visible spectrophotometry at a wavelength of 768 nm (Van Ranst *et al.*, 1992).

Statistical analysis

Statistical analyses were performed using R software. The statistical tests used in this work are as follows: (i) the analysis of variance (ANOVA), (ii) the correlation test (Pearson correlation coefficient) and the Shannon-Weaver biological diversity index was used to characterize the identified cocoa-based agroforestry system.

3. RESULTS

3.1. Density and diversity of trees in agroforests.

The table 1 presents the density, diversity and Shannon indices in the different agroforestry plots studied. Then, the interpretation highlights the names of some dominant species present in all the plots.

Table 1. Density, diversity and Shannon indices in the different agroforestry plots studied

No.	Plots	Diversity/Ha	Density/Ha	Shannon Index
1	Natural forest	54.00 a	477.0 a	3.22
2	Inera-1961	8,000 g	23.00 h	1.41
3	Inera-1989	12.00 e	36.00 d	1.41
4	Inera- 1989 R	10.00 f	25.00 g	0.50
5	Inera-2017	20.00 c	50.00 c	1.89
6	Paysan 1967	6,000 i	32.00 e	0.98
7	Peasant-1967 B	3,000 h	10.00 i	0.95

Numbers in the column followed by the same letters are not significantly different at the 5% level

Table 1 shows that the natural forest has the highest diversity and plant density, with a Shannon index of 3.22, which is the highest value. The latter indicates the presence of exceptional biodiversity. On the other hand, the INERA plots show significant variations, with Shannon indices greater than 1 for some and less than 1 for others. The "Paysan 1967" plot, although low in diversity, has a higher density and a Shannon index less than 1, as does the "Paysan 1967 B" plot. However, it is important to remember that the old INERA plots, including those of the farmers, contain more than 60 % *Terminalia superba*. The most recent plot, that of 2017, has 30 % *Terminalia superba*, 25 % *Celtis mildbraedii* and about 15 % Milicia excelsa. In addition, the natural forest consists of 17*% Trichilia prieureana*, 8 % *Trilepsium madagascariensis*, 8 % *Celtis mildbraedii* and 5 % *Terminalia superba*. The remaining species in the natural forest are less than 1 %.

3.2. Chemical properties of soils

The variations of pH, carbon, nitrogen, phosphorus and potassium contents in different agroforestry plots based on cacao, installed by INERA in different years, as well as in farmers' plots and a natural forest. The box plots with the same letter are not significantly different according to the Tukey test at the 5 % threshold.

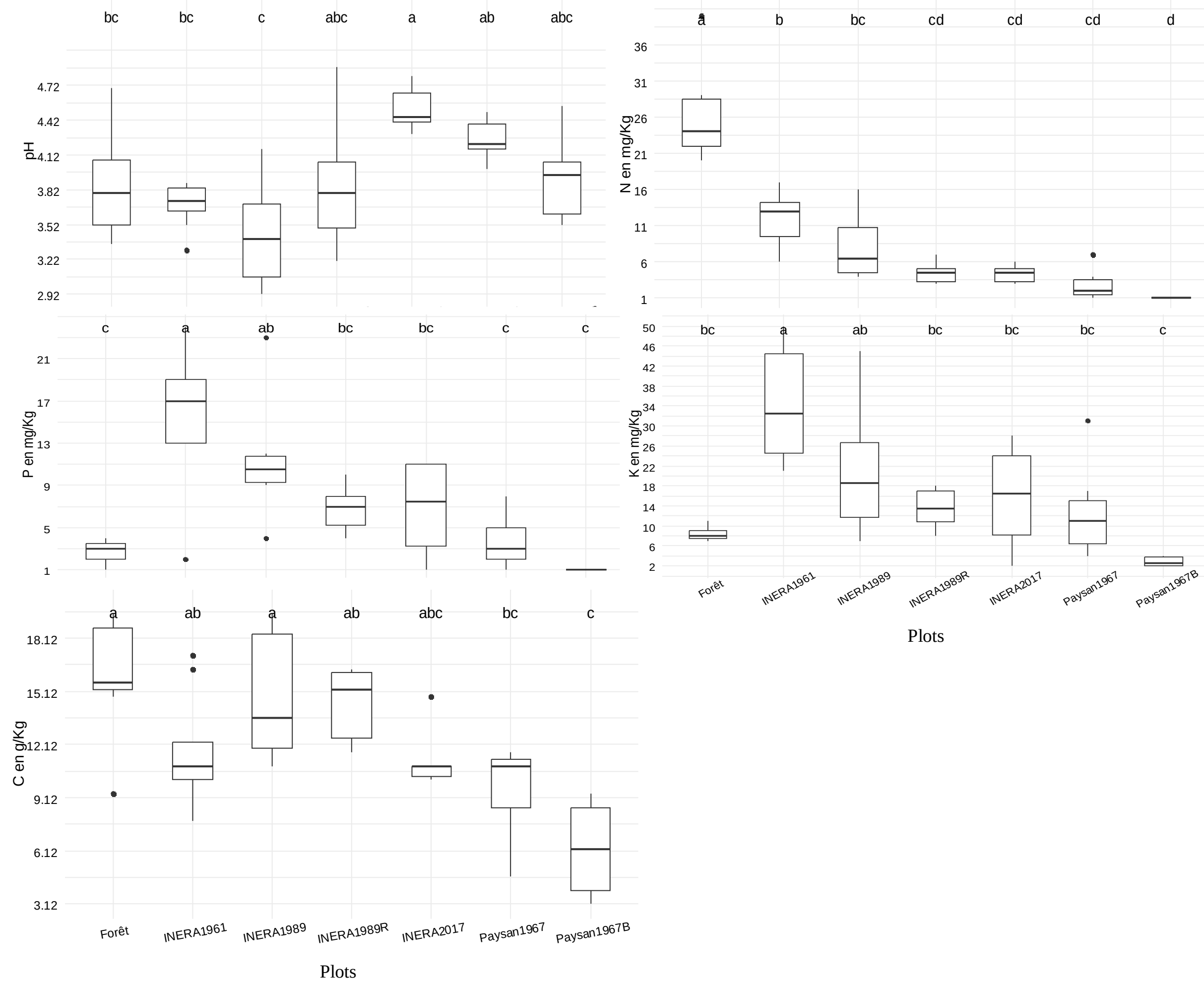

Figure 2. The physical properties of soils under different agroforestry systems and the natural forest

The natural forest has the highest nitrogen content than all other agroforestry plots, followed by the 1961 INERA plot (about 13 mg/kg), higher than other years (1989, 1989R and 2017). The agricultural plots have the lowest content of nitrogen. For phosphorus, the highest concentrations are observed in the INERA plots, while the agricultural plots and the natural forest have less than 5 mg/kg. The potassium concentration is highest in the 1961 INERA plots, followed by the 1989 plots. The 2017 and 1989R INERA plots have a moderate level (16 mg/kg), while the farmers' plots and the natural forest have about 5 mg/kg. Regarding carbon, the natural forest has a higher carbon content, about 18 g/kg.

3.3. Correlation analysis between the studied parameters

This point presents the correlation between the different physicochemical and agroforestry parameters studied, as well as the physicochemical parameters between them, in order to determine the effect of each one on the others. Then, it presents a synthesis of the analysis of variance concerning certain agricultural characteristics or practices and their impact on the physicochemical parameters of the soil.

Correlation between fertility and agroforestry parameters

This table 2 presents the correlation coefficients between soil parameters and agroforestry parameters, as well as the p-values associated with each correlation. Correlation coefficients indicate the strength and direction of the linear relationship between two variables, while p-values indicate the statistical significance of these relationships.

Table 2. Correlation between fertility and agroforestry parameters

Variables	pH	N	P	K +	Da.	Carbon	Clay
Aged SAF	0.05	-0.01	-0.07	0.01	0.24	0.14	-0.11
p-Value	0.68	**0.89**	**0.57**	**0.91**	0.06	0.30	**0.41**
Density Esp.	0.01	-0.25	-0.25	-0.23	**0.49**	**0.52**	-0.17
p-Value	**0.92**	0.06	0.06	0.08	**0.00**	**0.00**	0.20
Diversity Esp.	-0.05	-0.26	-0.24	-0.26	**0.49**	**0.55**	0.20
p-Value	0.69	0.05	0.07	0.04	**0.00**	**0.00**	0.67

With N: Nitrogen, P: Phosphorus, K: Potassium, Da: Apparent density, Esp: species, SAF: agroforestry system. Significant correlations, $p < 0.05$ indicates a significant correlation between the variables.

In the correlation analysis, Table 2 above shows that tree density per hectare is strongly correlated with soil carbon stock and bulk density. Similarly, species diversity per hectare also shows a strong correlation with carbon stock and bulk density. This suggests that higher levels of plant diversity are associated with increased carbon storage.

Correlation between soil fertility parameters

Table 3 below presents the correlation coefficients between the physicochemical parameters, as well as the p-values associated with each correlation.

Table 3. Correlation between soil fertility parameters

Variables	pH	N	P	K	Da.	Carbon
N	-0.236					
p-Value	0.083					
P	-0.211	**0.878**				
p-Value	0.123	**0.00**				
K	-0.121	**0.824**	**0.82**			
p-Value	0.38	**0.00**	**0,00**			
Da.	0,208	**-0,359**	**-0,331**	**-0,324**		
p-Value	0,128	**0,007**	**0,014**	**0,016**		
Carbone	-0,127	-0,056	-0,087	-0,197	**0,302**	
p-Value	0,356	0,683	0,529	0,15	**0,025**	
Argile	-0,237	**0,381**	**0,400**	**0,347**	**-0,611**	0,143
p-Value	0.082	**0.004**	**0.002**	**0.009**	**0.0001**	0.299

With N: Nitrogen, P: Phosphorus, K: Potassium, Da: Apparent density. Significant correlations, $p < 0.05$ indicates a significant correlation between the variables.

Summaries of the analysis of variance

In Table 4 above, the analysis of variables shows significant correlations between several soil parameters. Phosphorus and potassium are highly correlated with nitrogen. This strong correlation indicates that high nitrogen concentrations are often associated with high phosphorus and potassium concentrations in the soil. On the opposite, pH shows a negative but not significant correlation with these elements. Carbon content shows a significant positive correlation with bulk density, indicating that denser soils store more carbon.

Table 4. Summaries of the analysis of variance

Settings	pH	N	P	K	Yes	Carbon
Soil color	**	**	***	*	***	***

Height of trees	**0**	***	***	***	**0**	*
Shading Level	0	***	**	***	**	**
Cultural practice	0	***	***	**	***	***
Degree of slope	0	*	*	*	**	*

Legend: N: Nitrogen, P: Phosphorus, K: Potassium, Da: Apparent density. 0: no influence, ***:** significant influence; ****:** very significant influence; ***** : very highly significant influence.

4. DISCUSSION

4.1. Comparison of soil parameter means

The soil acidity in the different cocoa agroforestry systems is usually low, with a pH between 4.5 and 6, as found by Koffi *et al.* (2023) and Gusli *et al.* (2020). The soil shows great variability from one plot to another; the INERA 2017 plot has the highest pH (4.54), while others have a pH below 4. For Arévalo *et al*. (2015), the acidic pH, around 3,5, is found in the natural forest. However, this variation in pH in agroforestry plots can be attributed to specific soil characteristics or components, such as color, as shown in Table 4. Therefore, the results obtained by Zaia *et al*. (2012) and Koffi *et al.* (2023) showed that the soil under agroforestry systems based on cacao trees older than 20 years can have a nitrogen content of 1,360 mg kg^{-1}. However, the nitrogen values recorded in this study are very low, both for the natural forest and for all the agroforestry systems studied. Moreover, the highest value of nitrogen is recorded in the natural forest, i.e. 23.5 $mg.kg^{-1}$, this value represents a significant difference with all the agroforestry plots studied. The INERA 1961 plot also shows a different average from the other agroforestry plots. This variation in nitrogen content in agroforestry systems can be explained by the diversity of species associated with cacao trees in the different plots (Vroh *et al*., 2019).

These results show that the farmer's plot 1967B and the natural forest have the lowest potassium concentrations, below 10 $mg.kg^{-1}$. This is a very low value in agroforestry systems in general. Koffi et al. (2023), in their studies on the impact of traditional cocoa tree-based agroforestry systems on soil chemical fertility in southwestern Côte d'Ivoire, found a value of 15.64 and 31.28 $mg.kg^{-1}$ in agroforestry systems. According to this study, the highest potassium concentration is recorded in the INERA 1961 plots, reaching approximately 31 $mg.kg^{-1}$, a value similar to that obtained in the previous study. The 1989 plots also show high values, but lower than those of 1961.

According to a study by Gusli *et al.* (2020) comparing a natural forest with an agroforestry system based on cacao tree, the authors noted an increase in the phosphorus content of the soil under agroforestry systems. It even exceeded the threshold required for good cocoa tree growth (Koffi et al., 2023). The results obtained in this study, as shown in Figure 1, show that the 1961 INERA plots have the highest phosphorus concentrations, with averages around 14 $mg.kg^{-1}$, followed by 1989 and 1989 R with averages close to 10 $mg.kg^{-1}$. Moderate phosphorus concentrations are observed for the other years, between 5 and 10 $mg.kg^{-1}$. This trend is the same for the peasant plots and the natural forest, which present the lowest concentrations, less than 5 $mg.kg^{-1}$. These results show the positive effect of this agroforestry system on the assimilable phosphorus content of this soil.

Land use in cocoa-based agroforestry systems results in a reduction in organic matter concentration compared to a neighboring natural forest (Berthrong *et al*., 2009; Bárcena *et al*., 2014; Gusli *et al*., 2020). The carbon stock of the natural forest is significantly higher, with a median of about 16 $g.kg^{-1}$. Although this carbon stock remains low compared to the values found in the aforementioned study, which are about 24.62 $g.kg^{-1}$ in secondary forest and very low in agroforestry systems, ranging from 9.23 $g.kg^{-1}$ to 11.54 $g.kg^{-1}$. It has been found that the carbon content of cocoa tree agroforestry is maintained at about half of that observed in forests (Chatterjee *et al*., 2018; Kimaro *et al*., 2024). According to Nair *et al*. (2011), this decrease in carbon stock in cocoa tree-based agroforestry systems compared to natural forests is due to the low density of trees, their spatial distribution, and the type of plant species present.

Thus, as shown by Koffi *et al*. (2023), most trees in cacao tree agroforestry systems are remnant plantations, meaning they do not cover the entire area. It is possible that the difference in carbon stocks in the systems of almost the same age is due to the difference in the species that make them up. In general, the carbon content found in cocoa tree-based agroforestry systems in this study is not a function of age, as pointed out by Berthrong *et al.* (2009), but depends on the diversity, species density and bulk density of the soil. Berthrong *et al*. (2009) highlighted the fact that organic carbon content decreases with the age of the agroforestry system. According to Mutuku *et al.* (2024), this decrease is much more pronounced for systems with similar characteristics in terms of the management practices used. On the plots managed by INERA, the high carbon value is 14 g.kg^{-1}. On the other hand, the farmers' plots have a low carbon content, less than 10 g.kg $^{-1}$. These are significantly lower than those found by Koko *et al*. (2008), which were 31 g.kg $^{-1}$ in cocoa soils in southwestern Côte d'Ivoire.

4.2. Analysis of correlations between the parameters studied

In their study, Mutuku *et al.* (2023) found a strong positive correlation between carbon, phosphorus, nitrogen and pH; all these elements were however negatively correlated with potassium. However, the correlation analyses performed in this study (Table 3) showed that the correlations between nitrogen, phosphorus and potassium are strong, while these parameters are not correlated with pH or carbon content. Mutuku *et al.* (2023) state that the content of mineral elements such as nitrogen, phosphorus, potassium and organic matter does not depend on any well-defined factor and varies from one soil to another. The same authors also state that the content of organic matter in the soil is not correlated with the content of potassium and phosphorus. No correlation was found between fertility parameters and soil pH. According to a study conducted by Gusli *et al.* (2020), the organic matter content changes in the opposite direction to the bulk density of the soil at the surface. Secondary forest, which had the highest concentration of organic carbon, was the least compacted according to the same author. Conversely, in this study, bulk density is strongly correlated with soil carbon content.

The soil organic carbon content is positively influenced by the diversity and density of trees associated with cacao trees in this study. However, its correlation with the age of the agroforestry system is not demonstrated. These results corroborate those of Berthrong *et al.* (2009), who found that the age of the agroforestry system did not influence the carbon content of the soil under agroforestry systems. Furthermore, the strong correlation between clay and NPK mineral elements observed in this study (Table 3) is largely confirmed by the study of Ben (2006), which shows that the clay content is proportional to the concentration of these elements.

5. CONCLUSION

The natural forest has a very high content of nitrogen, followed by the INERA 1961 plot, while all the other plots have a low content. As for phosphorus, the 1961 INERA plot has the highest concentration, followed by the 1989 and 1989 R plots; the natural forest and some INERA plots have the lowest concentrations. This trend is confirmed for potassium, with the 1961 INERA plots showing the highest concentrations, followed by the 1989 peasant plots, while the other plots and the natural forest show moderate or low levels. The natural forest shows the highest carbon content, while the INERA plots also show significant levels, especially in 1989.

Correlation analyses show that tree density per hectare is strongly related to soil carbon stocks and bulk density, it is the for the species diversity. These results highlight the importance of managing tree density and diversity to optimize carbon storage and soil fertility in agroforestry system.

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References

Adji B. I., Yao K. A. G., Gore bi B. N., Kadio G. A., Gbotto A. A. , Assiri A. A. & Akaffou D. S., (2020). Identification des pratiques et types de systemes agroforestiers a base de cacaoyers (*Theobroma cacao* L.) dans les trois principales zones de production de cacao en Cote d'Ivoire. *Agronomie Africaine*, 32, 323-342.

Asaah E., Degrande A ., Tchoundjeu Z., Biloso A., Habonimana B., Hicintuka C. & Kaboneka S., 2013. *Agroforesterie et domestication des arbres en Afrique centrale*. Ed. OIPR, Université de Kinshasa, RD Congo, pp. 185-195.

Bárcena T.G., Gundersen P. & Vesterdal L., 2014. Afforestation effects on SOC in former cropland: oak and spruce chronosequences resampled after 13 years. *Glob. Change Biol*., 20, 2938-2952. https://doi.org/10.1111/gcb.12608

Ben H. H., 2006. Mineralogical nature and nutritional role of cereal soil clays in subhumid and semi-arid zones (Tunisia). *Comptes Rendus Géoscience*, 355(3), 83-94. https://doi.org/10.1016/j.crte.2006.02.012

Berthrong S.T., Jobbágy E.G. & Jackson R.B., (2009). A global meta-analysis of soil exchangeable cations, pH, carbon, and nitrogen with afforestation. *Ecol. Appl.*, 19, 2228–2241. https://doi.org/10.1890/08-1730.1.

Bray R. H. & Kurtz L. T., 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, 59(1), 39-46.

Camara AA, Dugué P. & de Foresta H., 2012. Transformation des mosaïques de forêt-savane par des pratiques agroforestières en Afrique subsaharienne (Guinée et Cameroun) [Transformation of forest-savanna mosaics by agroforestry practices in sub-Saharan Africa (Guinea and Cameroon)]. *Cybergeo Eur. J. Geogr. Environ*., 26. **doi:10.4000/cybergeo.25588.**

Chatterjee P. N., Ramachandran P.K., Nair, Chakraborty S. & Vimala D. N., (2018). Changes in soil carbon stocks across the Forest-Agroforest-Agriculture/Pasture continuum in various agroecological regions: A meta-analysis. *Agriculture, Ecosystems & Environment*, 266, 55-67. https://doi.org/10.1016/j.agee.2018.07.014

Eblé, A., Falconnier, G., Smoot, J. N. *et al*., 2022. *Mapping cocoa-based agroforestry systems: Assessing land use and ecosystem services in West Africa*. Journal of Land Use Science, 17(3), 412-427.

Kimaro O. D., Desie E., Verbist B., Kimaro D. N., Vancampenhout K. & Feger K.-H., 2024. Soil organic carbon stocks and fertility in smallholder indigenous agroforestry systems of the North-Eastern mountains, Tanzania. *Geoderma Regional*, 36, 14 p. https://doi.org/10.1016/j.geodrs.2024.e00759

Global Soil Laboratory Network (GLOSOLAN), 2019. Standard operating procedure for soil organic carbon Walkley-Black method Titration and colorimetric method and Standard operating procedure for soil nitrogen Kjeldahl method. Food and Agriculture Organization of the United Nations, Glosolan, 21 p.

Gusli S., Sumeni S., Sabodin R., Hadi I. M., Nur M., Mustakim H. M., Useng D. & van Noordwijk M., 2020. *Soil Organic Matter, Mitigation of and Adaptation to Climate Change in Cocoa-Based Agroforestry Systems*. *Land*, 9(323), 2-18. https://doi.org/10.3390/land9090323.

ICF (Initiative Cacao & Forêts), 2019. *Rapport de Progrès du Secteur Privé 2018-2019*. World Cocoa Foundation. Disponible sur : https://www.worldcocoafoundation.org (consulté le 15 septembre 2024)

Koffi K. H., Tièba O. V., Koffi S. K. & Acka Kotaix J. A., 2023. *The Impact of traditional cocoa-based agroforestry systems on chemical soil fertility in southwest of Côte d'Ivoire*. *World Journal of Advanced Research and Reviews*, 19(1), 1300–1309. https://doi.org/10.30574/wjarr.2023.19.1.1448

Mikobi C. & Mitais S., 2021. *Rapport de consultance : Réserve de Biosphère de Luki, diagnostic agraire et étude des mesures de gestion du foncier mises en place par ULB-Coopération, ERAIFT, WWF-RDC*, 113 p.

Mutuku S. N., Nyangito M. M., Kironchi G. & Vivian W. O., 2023. Agroforestry practices impacts on soil properties in the drylands of Eastern Kenya. *Trees, Forests and People*, 8 p.

Nair P.K.R., Saha S.K., Stein T.V., Andreu M.G., Luedeling E., Sileshi G., Beedy T., Dietz J., Ruiz-de-oña-plaza C., Soto-pinto L., Paladino S., Morales F., Esquivel E., Tonucci R.G. & Garcia R., 2011. Carbon sequestration potential of agroforestry systems. *Adv. Agrofor*., 8, 61–83. https://doi.org/10.1007/978-94-007-1630-8.

Nsenga L., 2004. *Études socio-économiques dans les villages riverains de la RBL*. WWF, RDC, 52 p.

Nutriche L. M., 2014. *Evaluation de la contribution de la culture de cacao {Théobroma cacao) sous ombrage dans le maintien des stocks de carbone et la conservation de la biodiversité dans les forêts secondaires exploitées de l'Ituri (Province Orientale, RD Congo*. Université de Kisangani, 48 p.

Nyange N. M., 2014. *Participation des communautés locales et gestion durable des forêts : cas de la RBL en RDC*. Thèse de doctorat en co-tutelle, Université Laval et Université de Kinshasa, 205 p.

Oscar, D. H. (2022). L'importance de l'agroforesterie dans l'économie cacaoyère en Colombie. *Présentation lors de Forest Carbon Partnership, Initiativa Cacao, Bosques et Baz, Abidjan, Côte d'Ivoire, 23 novembre 2022*, 33 p.

Plas B., 2020. *Les cacaoyères agroforestières de la région de Man : un système de culture à l'agonie ou l'émergence d'une stratégie post-forestière ? Gembloux Agro-Bio Tech (GxABT)*, Master en agroécologie, à finalité spécialisée, 86 p. URI/URL : http://hdl.handle.net/2268.2/10678

Van Ranst E. Verloo M. Demeyer A. & Pauwels J.M., 1992. *Manual for the Soil Chemistry and Fertility Laboratory. Analytical Methods for Soils and Plants Equipment and Management of Consumables*. Univesité de Ghent, International Training Centre for post gruaduate Siol Sciences Krisgslaan 281/58, 243 p.

Vroh B. A., 2019. Système agroforestier à cacaoyers en Côte Besse, d’Ivoire : Connaissances existantes et besoins de recherche pour une production durable. *Revue Marocaine des Sciences Agronomiques et Vétérinaires*, 7(1), 99-109.

Zaia F. C., Gama-Rodrigues A. C., Gama-Rodrigues E. F., Moc E. F., Fontes A. G., Machado R. C. R. & Baligar V. C., 2012. Carbon, nitrogen, organic phosphorus, microbial biomass and N mineralization in soils under cacao agroforestry systems in Bahia, Brazil. *Springer Science*, 86, 197–212.