Journal of Agricultural Chemistry and Environment, 2026, 15(4), 422-438
https://www.scirp.org/journal/jacen
ISSN Online: 2325-744X
ISSN Print: 2325-7458

Agroforestry for Improving Physico-Chemical and Biological Properties of Soil under Cocoa Trees in West-Central Côte d'Ivoire

Evelyne Gévère-Marise Assi[1], Acka Jacques Alain Kotaix[1], Kouakou Stanislas Koffi[2], Caudou Trébissou[1], Hervé Kouadio[1]

[1]National Centre for Agricultural Research (CNRA), Divo, Côte d'Ivoire.
[2]Faculty of Agroforestry, Jean Lorougnon Guédé University, Daloa, Côte d'Ivoire
Email: evelynemarise83@gmail.com

How to cite this paper: Assi, E.G.-M., Kotaix, A.J.A., Koffi, K.S., Trébissou, C. and Kiuadio, H. (2026) Agroforestry for Improving Physico-Chemical and Biological Properties of Soil under Cocoa Trees in West-Central Côte d'Ivoire. *Journal of Agricultural Chemistry and Environment*, **15**, 422-438.
https://doi.org/10.4236/jacen.2026.154022

Received: September 19, 2026
Accepted: November 7, 2026
Published: November 10, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/
Open Access

Abstract

Agroforestry is a very common practice in farmers' cultivation methods. It involves growing trees alongside crops on the same plot of land. With the aim of determining the effects of agroforestry trees on cocoa trees, a study was carried out in traditional agroforestry systems in the department of Lakota. To this end, an assessment was carried out of the plant species and the physical, chemical and biological fertility of the soils in these systems. With regard to the physical and chemical indicators of soil fertility, the following analyses were carried out on the soil samples from the various treatments: bulk density, coarse particle content, available water content, and the determination of organic matter (OM), organic carbon (OC), nitrogen (N), the C/N ratio and soil pH. With regard to biological indicators, 12 monoliths were installed in the plots in order to identify the biological organisms in the soil, as well as their abundance and diversity. The results showed that, during the floristic survey, fruit-bearing species (62.49 per cent) were more prevalent than forest species (37.51 per cent). Furthermore, the bulk density and usable water reserve decrease as the density of trees associated with cocoa trees increases; consequently, coarse particles are more abundant in more sparsely spaced stands. As for the chemical indicators, organic matter content was higher in the soils of agroforestry systems (28.52 - 32.16 $g \cdot kg^{-1}$) than in the soils of full-sun plots (25.80 $g \cdot kg^{-1}$). With regard to biological indicators, high organism abundance was observed in treatments T2 (earthworms: 58, molluscs: 9.33, termites: 98.67) and T3 (earthworms: 61.67, molluscs: 8; termites: 43), whilst low values were observed under full sun (earthworms: 9, molluscs: 4.32; termites: 25.33). From our results, we can conclude that densities of between 25 and 50 trees per hectare could be beneficial for the sustainability of cocoa plantations, given

that the physical, chemical and biological indicators of soil fertility showed optimal values.

Keywords

Agroforestry, Cocoa Tree, Density, Fertility, Lakota

1. Introduction

The degradation of natural resources, particularly soil, is now one of the main challenges facing global agriculture. In sub-Saharan Africa, this degradation is a particular cause for concern due to the low intrinsic fertility of the soil, climatic constraints and intensive farming practices, which accelerate the depletion of soil resources [1]-[3]. This situation is leading to a gradual decline in agricultural productivity, jeopardising food security and the sustainability of production systems [4]. In this context, soil quality assessment appears to be an essential tool for evaluating the sustainability of agroecosystems and guiding sustainable management strategies. Soil quality refers to its ability to simultaneously fulfil the biological, physical and chemical functions necessary to maintain crop productivity, to the preservation of the environment and the functioning of ecosystems. It depends not only on its physico-chemical properties, in particular the availability of essential nutrients such as carbon, nitrogen, phosphorus, potassium, calcium and magnesium, but also on its biological component. This biological fertility relies primarily on the activity of soil organisms, which break down organic matter and recycle nutrients, the formation of aggregates and the improvement of soil structure. Among these organisms, soil macrofauna plays a vital role. Consisting mainly of earthworms, termites, ants, millipedes, molluscs and various insect larvae, it comprises the invertebrates visible to the naked eye that spend a significant part of their life cycle in the soil ([5] Bachelier, 1978; [6] Brown *et al*., 2002). These organisms, often referred to as "ecosystem engineers" [7], alter the physical, chemical and biological properties of the soil by promoting the incorporation of organic matter and aeration, water infiltration and the availability of the minerals essential for crop growth. The diversity and abundance of macrofauna are therefore relevant indicators of biological fertility and soil quality. In Côte d'Ivoire, where agriculture is a strategic sector of the national economy, cocoa farming plays a key role. As the world's leading cocoa producer, the country derives a significant proportion of its export earnings from this sector, on which more than a million producers are directly dependent [8] [9]. However, the expansion of cocoa plantations—often in the form of monoculture—has led to a sharp decline in forest cover, a reduction in biodiversity and progressive soil degradation, thereby jeopardising the sustainability of the plantations and cocoa productivity [10]. In light of these challenges, agroforestry appears to be a promising approach that reconciles agricultural production with the conservation of natural resources. By

deliberately combining cocoa trees with forest or fruit trees, agroforestry systems help to improve the microclimate, enrich the soil with organic matter, limit erosion, promote the recycling of nutrients and maintain functional biodiversity, which is essential for the proper functioning of agroecosystems [11]-[13]. These systems have the potential to simultaneously improve the chemical properties of soils and their biological fertility through the development of an abundant and diverse macrofauna. In the Lôh-Djiboua region, particularly in the Lakota department where cocoa farming is the predominant agricultural activity, agroforestry systems are characterised by considerable diversity. However, our understanding of their effects on soil quality remains limited, particularly with regard to the interactions between soil chemical properties, biological fertility and the structure of macrofauna communities. A better understanding of these relationships appears essential for promoting agroforestry practices capable of ensuring sustainable cocoa production whilst preserving the ecological functions of the soil. It is against this backdrop that this study has been conducted, with the aim of assessing the influence of cocoa agroforestry systems on soil quality through a combined analysis of soil chemical properties and soil macrofauna in the plantations of the Lakota department.

2. Materials and Methods

2.1. Selection of Study Sites

For our study, three plots of cocoa trees were selected in each of the two villages in the Lakota district, namely Gogné and Djokolilié, making a total of six plots. The plots were selected on the basis of the presence of associated trees at varying densities within the same plot. In the village, the three plots are situated close by, approximately 2 to 3 km apart. The cocoa plantations are more than 10 years old.

2.2. Experimental Setup and Treatments Applied

2.2.1. Determination of the Density of Associated Trees

The experimental plots covered an area of 2 hectares. The method used is a nested plot sampling scheme. It comprises a main plot measuring 50 m × 50 m, designed to determine the density of the associated trees and to carry out an inventory of them. Within this plot, sub-plots measuring 10 m × 10 m were established to determine cocoa tree density as a function of tree cover. Across the plot, four test plots were established in order to determine different densities within the same plot. Three density ranges were therefore identified in comparison with 'full sun' (no trees growing alongside the cocoa trees). The trial was conducted using a Fischer block design with four treatments (density of trees associated with cocoa trees) and three replicates, with each plot constituting a replicate within the department. Based on the density gradient of trees growing alongside the cocoa trees, four treatments were identified:

T0 (control): cocoa trees in full sun;

T1: cocoa trees with 1 to 25 associated trees per hectare;

T2: cocoa trees with 25 to 50 associated trees per hectare;

T3: cocoa trees with more than 50 associated trees per hectare.

2.2.2. Characterisation of Agroforestry Systems

General information on the various plant species found in these systems—such as their common and scientific names, their family and their role within these systems—was gathered from a field survey [14]. This technique was applied to all the plots studied. The list of woody species identified during the survey was compiled in accordance with the APG IV nomenclature, which involves the taxonomic classification of the plant species surveyed.

2.2.3. Inventory of Associated Trees

For each density of trees associated with cocoa trees, general information on the various plant species found in these systems—such as their common and scientific names, their family and their role within these systems—was collected through a transect survey [14]. This technique was applied to all the plots studied in the two villages. The list of woody species identified during the survey was compiled in accordance with the APG IV nomenclature, which involves the taxonomic classification of the plant species surveyed.

2.2.4. Physico-Chemical Characterisation

The samples taken from the 0 - 20 cm depth layer for the "soil diagnosis" in cocoa cultivation, as described by [15], were collected and homogenised to produce a composite sample. Three replicates were taken from each of the three sites for chemical analysis in the laboratory, with a view to characterising the soil's physico-chemical indicators. Thus, the texture was determined by a particle size analysis using the Robinson method described by [16]. The pH of the water was measured using a pH meter at a soil-to-solution ratio of 1:2.5. Organic carbon (C) was determined using the Walkley & Black method and total nitrogen (N total) using the Kjeldahl method.

The following were derived from these parameters:

Organic matter (OM), using the formula: $OM = 1.724 \times C$;

The carbon-to-nitrogen (C/N) ratio;

The sum of the exchangeable bases (Ca^{2+}, K^{+}, Na^{+} et Mg^{2+}) referred to as (S);

The saturation level of the adsorbent complex (V%) by the relationship: (S/CEC) x100.

2.2.5. Determination of the Bulk Density of the Soil, the Available Water Content and the Coarse Particles

Bulk density

The bulk density (Da) of soil is its weight per unit volume of dry soil *in situ*. The method used is the cylinder method. A cylinder, open at both ends and of known volume, is carefully driven into the ground—taking care not to disturb its structure—to a depth of 20 cm (0 - 10 cm; 10 - 20 cm). The soil sample is weighed (wet) to determine its fresh weight, then placed in a coolant bag and sent to the

laboratory to be dried in an oven (105˚C) for 24 hours. The dry sample is then weighed again to determine its dry weight. The bulk density (g/cm^3) is calculated as the ratio of the mass of the dried soil to the volume of the cylinder.

$$\mathrm{Da}\left(\mathrm{g}/\mathrm{cm}^3\right)=\frac{\text{Dry land mass}\left(\mathrm{g}\right)}{\text{Cylinder volume}\left(\mathrm{cm}^3\right)} \quad (1)$$

$$\text{Cylinder volume}=\pi r^2 h$$

with, r (cm): the radius of the base of the cylinder and h (cm): the height of the cylinder.

Useful water reserve

The recoverable reserves were determined by gravimetric analysis [17]. Samples are taken using a cylindrical tube with a circumference of 340 cm^3 from layers at depths of 0 - 10 cm and 10 - 20 cm. After collection, the samples are placed in pre-tared containers, and then weighed to determine the fresh weight of the soil (Ptf) and the dry weight (Pts) after being dried in an oven at 105˚C for 24 hours. Moisture content by weight, expressed as a percentage, is calculated using the following equation:

$$Hp\left(\%\right)=\left(Ptf-Pts\right)/Pts\,; \quad (2)$$

The available soil water reserve is then determined using the following equation:

$$R\left(\mathrm{mm}\right)=10\times h\times Hp\times Da\,; \quad (3)$$

where R (mm): Water reserves in the relevant aquifer; h: Thickness of the horizon in metres; Da (g/cm^3): Bulk density on the horizon; Hp: Moisture content by weight of dry soil, expressed as a percentage.

Proportion of coarse particles

The soil sample, which has been dried beforehand, is weighed, then sieved and weighed again in order to carry out the following calculation:

$$EG\left(\%\right)=\frac{\text{Mass of material retained on a 2 mm diameter sieve}}{\text{Initial mass of the air-dried sample}}\times 100 \quad (4)$$

The weight percentage was therefore assessed according to three categories: less than 20 per cent; 20 to 50 per cent; and more than 50 per cent [18].

2.2.6. Biological Characterisation of Soil

The study of soil macrofauna was carried out to assess the biodiversity and biological fertility of the soils in the cocoa plantations within these agroforestry systems. The monolith design and the identification of macrofauna were made possible using quadrat and TSBF (Tropical Soil Biology and Fertility) methods, as described in the work of [19]. The study was carried out during the rainy season in order to assess a wide range of soil macrofauna. Quadrats measuring 50 × 50 × 30 cm were set up in each density of trees associated with the cocoa trees, on each plot studied. The aim was to extract a soil layer (monoliths) of this size from each treatment in order to identify and count the macrofauna present in the different

densities of associated trees. In total, four monoliths were designed per for each of the four densities tested that is, 12 monoliths across all three plots studied in each village—in order to assess the biological fertility of the soils in these agroforestry orchards (Figure 1).



Figure 1. Soil monoliths (50 cm × 50 cm × 30 cm) for the study of macrofauna.

Once the monolith has been formed, soil samples are taken at 10 cm intervals throughout each monolith until a depth of 30 cm is reached. A total of three soil samples were therefore collected and placed in a storage bag to prevent any organisms from escaping, before being extracted by direct manual sorting [20] [21]. After sampling, the three soil samples (each 10 cm deep) from each monolith are spread out gradually on a plastic tray so that the soil macrofauna can be extracted by hand. All visible specimens are collected and counted in 10 cm layers using tweezers, and preserved according to their taxonomic group. Earthworms are preserved in a 4 per cent formaldehyde solution, whilst other organisms, including termites, ants and millipedes, etc., are preserved in 70 per cent alcohol. This procedure ensures that specimens are properly preserved for subsequent taxonomic analysis. The jars are labelled according to the plot and the density of the associated trees, and then sent to the laboratory for a detailed analysis of the organisms present. Of the invertebrate macro-organisms collected, only specimens from the major taxonomic groups of earthworms, termites, myriapods, halophilus and molluscs were identified. The other invertebrate macroorganisms that were collected but not identified have been grouped together and will form the "other organisms" group. The "other organisms" group includes: fly larvae, ants, woodlice, mites and spiders. The macrofauna were identified using the FAO's identification key for soil macrofauna.

2.3. Statistical Analyses

Data relating to physical parameters (bulk density, proportion of coarse particles,

usable reserve, etc.), chemical parameters (C, N, V etc.) and soil macrofauna (number of termites, millipedes, molluscs, etc.). Each variable was subjected to an analysis of variance (ANOVA) based on the associated tree densities, using SAS 2016 software, after verifying the homogeneity of variances. Statistically significant differences were examined using post-hoc tests, in particular the Student-Newman-Keuls (SNK) test, at a 5 per cent significance level. Significance levels were expressed as follows: $p < 0.05$ (significant), $p < 0.01$ (highly significant), $p < 0.001$ (very highly significant). Clusters were established amongst all the parameters measured in this study using Principal Component Analysis (PCA) with the XLSTAT software, in order to determine the relationships between the variables under investigation.

3. Results

3.1. Characterisation of Plant Species Associated with Cocoa Trees

3.1.1. Nature of the Associated Trees in Cocoa Plantations

The floristic survey of associated tree species in the three plots revealed a total of 383 trees, comprising 25 species belonging to 21 distinct botanical families. Of these species, 239 are fruit-bearing species, representing 62.49 per cent, compared with 144 forest species, representing 37.51 per cent (Figure 2).

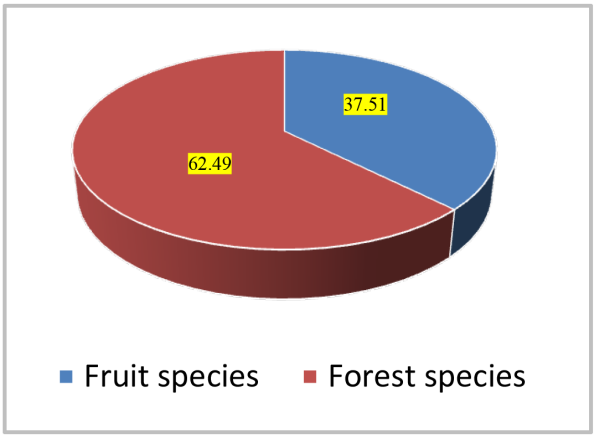


Figure 2. Proportion of plant species associated with cocoa trees.

3.1.2. Characteristics of Fruit Species Associated with Cocoa Trees

There are 11 fruit species recorded in the cocoa plantations. They belong to 9 botanical families. *Citrus sinensis*, *Musa paradisiaca* and *Mangifera indica* were the most common species found in cocoa plantations, with respective proportions of 11.17%, 8.78% and 7.71% (Table 1).

3.1.3. Characteristics of Forest Species Associated with Cocoa Trees

The surveyed areas contained 14 different forest species, belonging to 8 botanical families. The most common species are: *Pycnanthus angolensis*, *Pterygota bequaertii*, *Ricinodendron heudelotii* and *Acacia mangium*, with abundance percentages of 4.26 per cent; 3.72%; 3.46% and 3.46%, respectively (Table 2).

Table 1. Fruit species found in cocoa plantations.

Common name	Species	Family	Proportion of abundance for each species
Avocado tree	*Persea americana*	Lauraceae	6.65
Orange tree	*Citrus sinensis*	Rutaceae	11.17
Mango tree	*Mangifera indica*	Anacardiaceae	7.71
Papaya tree	*Carica papaya*	Caricaceae	5.59
Lemon tree	*Citrus limon*	Rutaceae	2.66
Banana tree	*Musa paradisiaca*	Musaceae	8.78
Mandarin tree	*Citrus reticulata*	Rutaceae	5.05
Gwava	*Psidium guajava*	Myrtaceae	2.93
Coconut tree	*Coco nucifera*	Arecaceae	4.52
Cola	*Cola nitida*	Malvaceae	4.52
Moringa	*Moringa oleifera*	Moringaceae	2.93

Table 2. Forest species found in cocoa plantations.

Common name	Species	Family	Proportion of abundance for each species (%)
Albizzia	*Albizzia lebbeck*	Fabaceae	2.39
Acacia	*Acacia mangium*	Fabaceae	3.46
Iroko	*Milicia excelsa*	Moraceae	3.19
Illomba	*Pycnanthus angolensis*	Myristicaceae	4.26
Fromager	*Ceiba pentandra*	Malvaceae	1.86
Encens	*Aucoumea klaineana*	Burseraceae	2.39
Isope	*Nesogordonia papaverifera*	Malvaceae	1.60
Akpi	*Ricinodendron heudelotii*	Euphorbiaceae	3.46
Fraké	*erminalia superba*	Combretaceae	2.93
Movingui	*Distemonanthus benthamianus*	Fabaceae	1.60
Samba	*Triplochiton scleroxylon*	Malvaceae	2.13
Coto	*Pterygota bequaertii*	Malvaceae	3.72
Acajou	*Khaya ivorensis*	Meliaceae	2.13
Bois bété	*Mansonia altissima*	Malvaceae	2.39

3.2. Effect of Agroforestry Tree Densities on Soil Physico-Chemical Parameters

Analysis of the table revealed a significant difference ($p < 0.05$) between the treatments in terms of bulk density (Da) and available soil water (RU). The highest bulk density was observed for the control (T0), with a value of 1.40 g/cm^3. With

regard to the usable water reserve, treatments T0, T1 and T2 recorded the highest values of 41.57 mm, 39.54 mm and 44.35 mm respectively. However, with regard to the coarse-particle content, no significant difference was observed between the treatments (Table 3).

Table 3. Physical properties of soils under different cocoa cropping systems.

Treatment	Bulk density (Da) (g/cm^3)	Coarse particles (%)	Useful water reserve (RU) (mm)
T0 (Full sun)	1.40 ± 0.03^a	23.22 ± 1.23^a	41.57 ± 0.54^a
T1 (0 - 25 trees per ha)	1.20 ± 0.04^b	15.66 ± 0.53^a	39.54 ± 0.62^a
T2 (25 - 50 trees per ha)	1.26 ± 0.03^b	18.33 ± 2.18^a	44.35 ± 2.54^a
T3 (>50 trees per ha)	1.27 ± 0.03^b	13.33 ± 1.33^a	34.28 ± 0.97^b
Cocoa thresholds	<1.5	<30	<50
Pr	0.002	0.72	0.0002
Mean	1.28	17.63	39.93
Cv	8.03	10.73	10.68

The results of the chemical analyses are set out in Table 4. The highest levels of organic matter, carbon and nitrogen were found in the T2 and T3 density treatments, at 16 - 18.70 g·kg^{-1}, 30.53 - 32.16 g·kg^{-1} and 1.40 - 1.65 g·kg^{-1} respectively. The soil pH fluctuated between 6.43 and 6.7 for all treatments. The cation exchange capacity (CEC) of the soils in the various treatments was higher in treatments T2 and T3 (29.93 and 23.16); even the CEC values for the other treatments, although low, remained within the normal range for cocoa cultivation. However, no significant difference was observed in the saturation rate (Table 4).

Table 4. Chemical properties of soils under different cocoa cropping systems.

Treatment	SOC (g.kg^{-1})	SOM (g.kg^{-1})	N (g.kg^{-1})	pH	C/N	CEC (cmol$^+$/kg)	V (%)
T0 (Full sun)	12.53 ± 0.92^b	25.80 ± 1.58^b	0.70 ± 0.43^b	6.46 ± 0.20^a	17.90 ± 3.50^{ab}	17.21 ± 3.33^a	57.86 ± 2.27^a
T1 (0 - 25 trees/ha)	16 ± 0.61^{ab}	28.52 ± 1.06^{ab}	0.77 ± 0.17^{ab}	6.43 ± 0.10^a	20.77 ± 1.29^a	18.07 ± 2.89^a	60.74 ± 5.98^a
T2 (25 - 50 trees/ha)	17.37 ± 0.53^a	30.53 ± 0.92^a	1.40 ± 0.10^a	6.7 ± 0.08^a	12.40 ± 6.74^b	23.16 ± 0.80^a	71.69 ± 2.22^a
T3 (>50 trees/ha)	18.70 ± 1.48^a	32.16 ± 2.54^a	1.65 ± 0.22^a	6.7 ± 0.11^a	11.33 ± 0.49^b	29.93.10 ± 1.85^a	63.38 ± 1.84^a
Cocoa thresholds	17 - 32	>30	>1.2	5.1 - 7	9 - 15	12 - 30	>60
Pr	0.006	0.006	0.02	0.17	0.006	0.35	0.12
Mean	15.26	26.25	1.08	6.6	24.40	17.40	89.15
Cv	18.46	18.46	5.94	5.16	9.53	36.37	34.87

Mean values marked with the same letter in the same column are not significantly different at the 5 per cent significance level. SOC: soil organic carbon, SOM: soil organic matter, N: nitrogen, C/N: carbon-to-nitrogen ratio, CEC: Cation Exchange Capacity; V: base saturation; Pr: probability; Cv: coefficient of variation.

3.3. Effect of Agroforestry Systems on Indicators of Biological Soil Fertility

Analysis of variance revealed a significant difference between the treatments for all the biological organisms studied. Treatment T2 showed high abundance across all organisms. This was in contrast to treatments T0 and T1, for which the values were lower than those for the other treatments. However, the difference is less pronounced in the case of molluscs, where treatments T1 and T3 are, in principle, identical (Table 5) (Figure 3).

Table 5. Soil fauna identified according to tree density.

Treatments	Earthworms	Termites	Millipedes	Molluscs	Holophilus	Other
T0 (Full sun)	9 ± 1.29^{c}	25.33 ± 1.05^{b}	7.67 ± 260^{b}	4.33 ± 1.23^{b}	4.67 ± 0.78^{c}	20.67 ± 4.59^{b}
T1 (1 - 25 tree /ha)	22.67 ± 2.93^{b}	45.67 ± 2.74^{b}	6.67 ± 0.93^{b}	6.33 ± 1.71^{ab}	8.00 ± 2.77^{bc}	15.00 ± 3.01^{b}
T2 (25 - 50 tree /ha)	58 ± 1.75^{a}	98.67 ± 2.47^{a}	15.89 ± 1.36^{a}	9.33 ± 0.78^{a}	9.33 ± 0.78^{ab}	65.67 ± 2.07^{a}
T3 (>50 tree /ha)	61.67 ± 3.20^{a}	43 ± 1.12^{b}	17.33 ± 1.50^{a}	8.00 ± 1.29^{ab}	16.67 ± 25^{a}	61.33 ± 1.30^{a}
Pr	<0.001	<0.001	<0.001	0.05	0.0007	<0001
Mean	37.83	53.17	11.89	7.00	10.50	40.67
Cv	19.24	4.46	4.27	5.56	5.51	5.29

Means marked with the same letter in the same column are not significantly different at the 5 per cent significance level. Pr: probability; Cv: coefficient of variation.

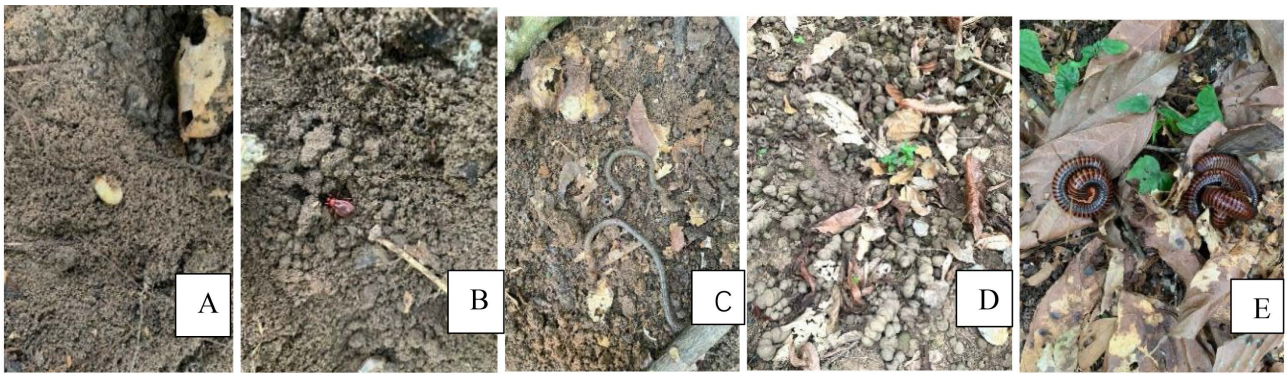


Figure 3. Various organisms observed in the soil of agroforestry systems. A: fly larvae; B: mites; C: earthworms; D: earthworm cuticles; E: millipedes.

3.4. Interaction between Biological, Chemical, Physical Properties of the Soil and Tree Density

The Principal Component Analysis (PCA) carried out using the soil's physico-chemical and biological parameters (Figure 4) showed that axes 1 and 2 accounted for 74.8 per cent and 18.1 per cent of the total variance respectively; this represents 92.9 per cent of the total variance. This information can therefore be analysed easily by focusing on the significant correlations revealed by these axes. Based on the correlation between the axes and the variables, it appears that Axis 1 is positively cor-

related with most soil parameters, such as CEC, MOS, SBE, pH, termites, molluscs, earthworms and myriapods, and negatively correlated with the C/N ratio. As for the vertically oriented variables, they are mainly correlated with the F2 axis. Overlaying the data revealed that the treatments fell into two groups: The first group comprises the T0 treatment (full sun) and the T1 treatment (0 - 25 trees/ha), whilst the second group comprises the T2 and T3 treatments. These treatments (T2 and T3) promoted the production of organic matter (OM), soil nutrients (SBE), good soil moisture saturation (V), a reduction in soil acidity (pH), and the development of soil fauna and macrofauna. In contrast, T0 and T1-weighted images are characterised by a C/N ratio and a low abundance of these parameters.

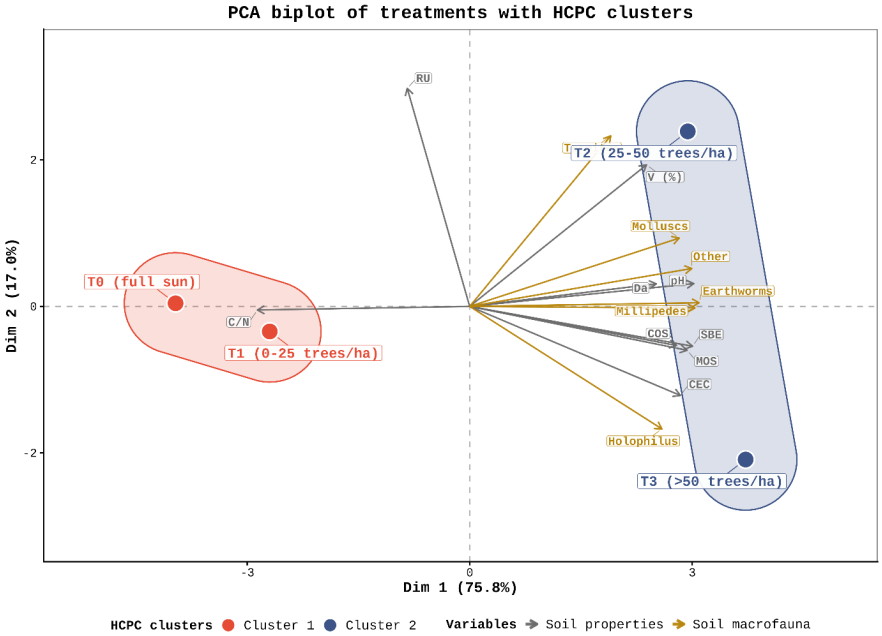


Figure 4. Biplot of the analyses relating tree density, physico-chemical parameters and biological activity.

4. Discussion

Agroforestry systems are recognised as models of sustainable production that combine crops with woody species. The adoption of these systems on cocoa farms could prove significant for producers, as they improve soil quality and productivity. We will explain our findings, give our views on them and relate them to some related research.

The results of the survey of trees associated with cocoa trees revealed that agricultural fruit species were predominant, accounting for 62.40 per cent in the traditional agrosystems of the Lakota area. These species, including *Citrus sinensis* (orange tree), *Musa paradisiaca* (banana tree) and *Mangifera indica* (mango tree), are mostly grown for food, whilst others, such as *Cola nitida* (cola tree), are planted to diversify farmers' incomes [22]. Following the floristic survey of our agroforestry systems, a complete system was identified, comprising the three as-

sociated tree strata. Trees in stratum 3 stood out (39 per cent) from those in strata 2 and 1, which accounted for 36 per cent and 25 per cent respectively. Indeed, the prevalence of associated trees that are considerably larger than the cocoa trees (strata 3) would appear to indicate that the agroforestry orchards found in the area are ageing. This was revealed by [21] who showed that no new cocoa plantations are being established in Côte d'Ivoire's main cocoa-producing areas and that all of them are existing plantations that have been in production for more than five years. However, some producers retain certain tree species in their plantations in order to use them as timber, which is sold to logging companies [23]. As for the species comprising strata 2 and 3 consisting of *Citrus sinensis* (orange tree), *Musa paradisiaca* (banana tree) and *Mangifera indica* (mango tree), their presence is thought to be due to dietary requirements [22].

Furthermore, analysis of the physical properties of the soil has shown that the bulk density of the soil decreases as the density of trees growing alongside the cocoa trees increases. In fact, the value was 1.20 g/cm^3 for treatment T1 (0 - 25 associated trees), 1.26 g/cm^3 for treatment T2 with a medium density (25 - 50 associated trees) and 1.27 g/cm^3 for more than 50 associated trees (T3). These results confirm that these plots are indeed cultivated systems, as described by [24]. They maintain that the bulk density of cultivated systems generally ranges between 1.2 and 1.5 g/cm^3. Furthermore, the decrease in bulk density associated with tree density is thought to be due to good soil structure and improved aeration, resulting from the seamless interaction between the soil components. This idea is supported by [25], who demonstrates that agroforestry, through the continuous addition of plant litter and the development of the root system, reduces the bulk density of the soil whilst improving its porosity. As for the usable water reserve, the results indicated that this decreases as tree density increases. Indeed, the T1 (0 - 25 associated trees) and T2 (25 - 50 associated trees) treatments recorded higher values than the high-density treatment (>50 associated trees), with values of 39 mm, 44 mm and 34 mm respectively. This finding could be explained by competition between trees and cocoa plants for access to water in the soil. [25] explain that if the trees growing alongside cocoa trees do not complement this crop, competition may arise for the available water in the soil. These results highlight the importance of selecting an appropriate density of trees to be planted alongside cocoa trees within modern agroforestry systems, which are now recommended in Côte d'Ivoire. The proportion of coarse particles does not vary from one treatment to another. Furthermore, regardless of the associated tree density, the proportion of coarse material remains within the range of values for cocoa cultivation reported by [26]. Indeed, soils with a low content of coarse particles have a good usable water-holding capacity. However, an abundance of coarse particles reduces the soil's ability to retain water.

From a chemical perspective, the research focused on organic matter, the rate of mineralisation, cation exchange capacity (CEC), total exchangeable bases, base saturation and nutrients. The results relating to soil organic matter content

showed that the values obtained were higher in agroforestry systems than in full-sun systems, but remained within the normal range for cocoa cultivation [27]. However, the optimal values were observed for T2 (30.53 $g.kg^{-1}$) and T3 (32.16 $g.kg^{-1}$). These values represent the optimum MO levels for cocoa cultivation. They are thought to be linked to a high availability and diversity of litter debris. Furthermore, the presence of trees in a plantation is thought to increase the soil's organic carbon content through the permanent presence of plant litter and the microclimatic conditions essential for the development of organisms that break down plant matter, which is then returned to the soil. These findings are consistent with those of [28] [29], who argue that agroforestry increases carbon and organic matter stocks compared with agricultural systems without associated trees. Furthermore, the C/N ratio, which indicates the rate of organic matter mineralisation, showed normal values for treatments T2 (25 - 50 trees/ha) and T3 (>50 trees/ha), at 12.40 and 11.33 respectively. These values indicate good mineralisation of the organic matter. The optimal range ($9 < C/N < 15$) ensures a balance between mineralisation and immobilisation, beneficial for the nutrition of cocoa trees [30]. Indeed, [31] established threshold values for nitrogen uptake by plants. If the C/N ratio is less than 9, mineralisation is too rapid (nitrogen loss), and if the ratio is greater than 15, mineralisation is too slow (nitrogen deficiency). The nitrogen input observed in treatments T2 and T3 may be due to the presence of associated trees capable of fixing atmospheric nitrogen in the soil, as mentioned in the survey of trees associated with cocoa trees. Indeed, the results showed that in these two densities (T2 and T3), there is a good supply of nitrogen, at 1.40 and 1.65 mg/kg respectively.

As for the adsorbent complex, the results of this study revealed identical CEC values in soils of all tree densities associated with cocoa trees. These rates ranged from 17.21 at the control level (T0) to 29.93 for the high-density treatment ($cmol.kg^{-1}$). These values fall within the standards for cocoa cultivation. Indeed, soils that receive a daily supply of organic matter from associated trees will develop a well-formed clay-humus complex [32]. This is the "reservoir" for basic cations in the soil, which explains why systems with increasingly high tree densities exhibit higher CEC values as density increases. Furthermore, the soil pH was statistically identical across all cropping systems (6.4 to 6.7), with values close to neutrality (7). These results show that agroforestry systems have helped to maintain, or even improve, soil pH. Indeed, the ideal pH for growing cocoa is 7 [27] [33] [34]. The same authors had confirmed that this plant can still grow in slightly acidic (pH 4.5 - 6) or slightly alkaline (pH 6.5 - 7.5) soils. The near-neutral pH levels found in the various soils are thought to promote the effective decomposition of organic matter and the optimal structuring of soil components. In agroforestry systems, soil chemical properties are strongly influenced by daily litter inputs and nutrient recycling [35]. Furthermore, the base saturation (V %) showed statistically identical values in the soils of the different cropping systems. However, the tree-based system yielded acceptable values of 57.86 per cent, 71.69 per cent and 63.38 per cent re-

spectively for treatments T1, T2 and T3, compared with the 60 per cent benchmark set by [36]. Furthermore, these slightly elevated saturation values confirm that the soils are slightly neutral, with a pH of around 6.7; indeed, the base saturation is closely linked to soil pH [37]. Thus, when the pH is low, the saturation level is low (<60 per cent), and when the pH is around neutral, the base saturation level is high (>60 per cent). Furthermore, the presence of trees in plantations helps to maintain the base saturation level through nutrient recycling and the transfer of exchangeable bases from deeper soil layers to surface layers [38]. With regard to the sum of exchangeable bases, the results showed the highest values in the T2 (16.62 cmol/kg) and T3 (18.97 cmol/kg) treatments compared with the other treatments. These values are consistent with those reported by [39] which defines an optimal value for cocoa cultivation of more than 15 cmol/kg. These normal values are thought to be due to the well-structured clay-humus complex of the soils studied.

Following the assessment of the soils' physico-chemical properties, the biological characterisation of the soil is then addressed. Indeed, the results of the biological characterisation revealed an abundance of biological organisms at medium (25 to 50 associated trees) and high (more than 50 associated trees) densities, compared with the lower associated tree densities (0 and 25 associated trees) and the "full sun" system. These results suggest that an increase in the density of associated trees is correlated with a higher abundance of soil macrofauna, thus reflecting an increase in biological activity within the ecosystem. Indeed, the presence of trees in cropping systems appears to promote the establishment, survival and activity of beneficial soil organisms, in particular by improving microclimatic conditions, the continuous supply of organic matter. These findings are consistent with those of [9] who reported that agroforestry systems promote high levels of biological activity thanks to the microclimatic conditions they create. Principal component analysis (PCA) yielded the same results as those from the analysis of variance, which shows that systems with increasing levels of cover are rich in biological organisms in terms of both abundance and diversity.

The findings of this study indicate that traditional cocoa-based agroforestry systems have a positive impact on cocoa plantations. However, densities of between 25 and 50 trees per hectare and those with more than 50 trees per hectare could be beneficial for the sustainability of cocoa plantations, given that the physical, chemical and biological indicators of soil fertility have reached optimal levels at these densities. But further studies are needed on the effect of these densities on the growth and yield of cocoa trees in order to draw definitive conclusions regarding the recommended density.

Conflicts of Interest

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

References

[1] Oldeman, L.R. (1992) Global Extent of Soil Degradation. In: *Bi-Annual Report* 1991-

1992, ISRIC, 19-36. https://edepot.wur.nl/299739

[2] Bationo, A., Koala, S. and Ayuk, E. (1998) Fertilité des sols pour la production céréalière en zone sahélo-soudanienne et valorisation des phosphates naturels. *Cahiers Agricultures*, **7**, 365-371.

[3] Mafongoya, P., Kuntashula, E. and Sileshi, G. (2006) Managing Soil Fertility and Nutrient Cycles through Fertilizer Trees in Southern Africa. In: Uphoff, N., Ed., *Biological Approaches to Sustainable Soil Systems*, CRC Press, 273-289. https://doi.org/10.1201/9781420017113.ch19

[4] Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.-M.N., *et al*. (1997) Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital. In: Buresh, R.J., *et al*., Eds., *Replenishing Soil Fertility in Africa*, Soil Science Society of America Special Publication 51, SSSA, 1-46.

[5] Bachelier, G. (1978) La faune des sols. Son écologie et son action. Initiations—Documentations techniques N° 38, O.R.S.T.O.M., 391 p.

[6] Brown, G.G., Pasini, A., Benito, N.P., De Aquino, A.M. and Correia, M.E.F. (2002) Diversity and Functional Role of Soil Macrofauna Communities in Brazilian No-Tillage Agroecosystems: A Preliminary Analysis. *International Symposium on Managing Biodiversity in Agricultural Ecosystems*, Montreal, 8-10 Novembre 2001, 8 p.

[7] Jones, C.G., Lawton, J.H. and Shachak, M. (1994) Organisms as Ecosystem Engineers. *Oikos*, **69**, 373-386. https://doi.org/10.2307/3545850

[8] FAO (2021) Importance du cacao dans le développement économique et social de la Côte d'Ivoire. FAO.

[9] Konaté, N., Ouattara, Y., Kouakou, A.K. and Barima, Y.S.S. (2024) Effects of Traditional Agroforestry Practices on Cocoa Yields in Côte D'ivoire. *Sustainability*, **16**, Article No. 9927. https://doi.org/10.3390/su16229927

[10] Kouassi, J.-L., Diby, L., Konan, D., Kouassi, A., Bene, Y. and Kouamé, C. (2023) Drivers of Cocoa Agroforestry Adoption by Smallholder Farmers Around the Taï National Park in Southwestern Côte d'Ivoire. *Scientific Reports*, **13**, Article No. 14309. https://doi.org/10.1038/s41598-023-41593-5

[11] Isaac, M.E. and Kimaro, A.A. (2011) Diagnosis of Nutrient Imbalances with Vector Analysis in Agroforestry Systems. *Journal of Environmental Quality*, **40**, 860-866. https://doi.org/10.2134/jeq2010.0144

[12] Kouassi, J., Kouassi, A., Bene, Y., Konan, D., Tondoh, E.J. and Kouame, C. (2022) Exploring Barriers to Agroforestry Adoption by Cocoa Farmers in South-Western Côte D'ivoire. *Sustainability*, **13**, Article No. 13075. https://doi.org/10.3390/su132313075

[13] Assi, E.G.M., Kotaix, A.J.A., Koffi, S. and Guiraud, B.S.B. (2025) Structural and Functional Characteristics of Cocoa Agroforestry Systems in Côte d'Ivoire. *International Journal of Environmental Sciences*, **11**, 471-480.

[14] Aké-Assi, L. (2002) Flora of Ivory Coast 2, Catalog, Systematics, Biogeography and Ecology. Conservatoire et Jardin Botanique de Genève.

[15] Snoeck, D., Abekoe, M.K., Afrifa, A.A. and Appiah, M.R. (2006) The Soil Diagnostic Method for Formulating Fertilizer Requirements on Cocoa in Ghana. *Proceedings of the 15th International Cocoa Research Conference*, San José, 9-14 October 2006, 387-394.

[16] Baize, D. and Jabiol, B. (1995) Guide de description des sols. Edition Quae, 430 p.

[17] Vilain, M. (1997) La production végétale: La maîtrise technique de la production. Vol. 1, Lavoisier TEC et DOC.

[18] Koko, L., Yoro, R., N'Goran, K. and Assa, A. (2009) Évaluation de la fertilité des sols sous cacaoyers dans le Sud-Ouest de la Côte d'Ivoire. *Agronomie Africaine*, **20**, 82-95. https://doi.org/10.4314/aga.v20i1.1738

[19] Anderson, J.M. and Ingram, J.S.I. (1994) Tropical Soil Biology and Fertility: A Handbook of Methods. *Soil Science*, **157**, Article No. 265. https://doi.org/10.1097/00010694-199404000-00012

[20] Lavelle, P. (1978) Les vers de terre de la savane de Lamto (Cote d'Ivoire): Peuplements, populations et fonctions dans l'écosystème. Publication du Laboratoire de Zoologie, Ecole Normale Supérieure 12, 1-301. https://catalogue.civa.brussels/index.php/Detail/objects/138428/lang/en_US

[21] Guéi, A.M., N'Dri, J.K., Zro, F.G.B., Bakayoko, S. and Tondoh, J.E. (2019) Relationships between Soil Morpho-Chemical Parameters and Earthworm Community Attributes in Tropical Agro-Ecosystems in the Centre-West Region of Côte D'ivoire, Africa. *Tropical Ecology*, **60**, 209-218. https://doi.org/10.1007/s42965-019-00021-4

[22] Smith Dumont, E., Gnahoua, G.M., Ohouo, L., Sinclair, F.L. and Vaast, P. (2014) Farmers in Côte D'ivoire Value Integrating Tree Diversity in Cocoa for the Provision of Ecosystem Services. *Agroforestry Systems*, **88**, 1047-1066. https://doi.org/10.1007/s10457-014-9679-4

[23] Ruf, F. and Konan, A. (2001) Les Difficultés De La Replantation. Quel Avenir Pour Le Cacao En Côte D'ivoire? *Oléagineux, Corps Gras, Lipides*, **8**, 593-598. https://doi.org/10.1051/ocl.2001.0593

[24] N'Guessan, A.E., Hérault, B., Zo-Bi, I.C., Aussenac, R., Dago, M., Konan, I.K., *et al*. (2026) Repenser L'agroforesterie Cacaoyère: Vers Une Coexistence Durable Entre Arbres Rémanents, Spontanés et Plantés. *Perspective*, **63**, 1-4. https://doi.org/10.19182/perspective/38075

[25] Brady, N.C. and Weil, R.R. (2002) The Nature and Properties of Soils. 13th Edition, Prentice Hall, 249 p.

[26] Rajan, K., *et al*. (2024) Agroforestry for Improving Soil Physical, Chemical, and Biological Properties. *Indian Journal of Agroforestry*, **26**, 61-69.

[27] Smith, A.J. (1980) Soils Classification and the Cocoa Grower. *Cocoa Growers' Bulletin*, **30**, 5-10.

[28] Nair, P.K., Kumar, B.M. and Nair, V.D. (2009) Agroforestry as a Strategy for Carbon Sequestration. *Journal of Plant Nutrition and Soil Science*, **172**, 10-23. https://doi.org/10.1002/jpln.200800030

[29] Agbotui, D.K., Ingold, M. and Buerkert, A. (2024) Carbon and Nutrient Cycling in Cocoa Agroforests under Organic and Conventional Management. *Nutrient Cycling in Agroecosystems*, **129**, 7-20. https://doi.org/10.1007/s10705-024-10349-6

[30] Kimetu, J.M., Lehmann, J., Kinyangi, J.M., Cheng, C.H., Thies, J., Mugendi, D.N., *et al*. (2009) Soil Organic C Stabilization and Thresholds in C Saturation. *Soil Biology and Biochemistry*, **41**, 2100-2104. https://doi.org/10.1016/j.soilbio.2009.07.022

[31] Podwojewski, P. (1986) Étude morpho-pédologique de la station Metenesel de la baie Lambubu Malakula-Vanuatu. ORSTOM, 101-104.

[32] Chenu, C. (2001) Le complexe argilo-humique des sols: État des connaissances actuelles. *Comptes Rendus de l'Académie d'Agriculture de France*, **87**, 3-12.

[33] Appiah, M.R.K., Ofori-Frimpon, A.A., Afrifa, M.K., Abekoe and Snoeck, D. (2006) Improvement of Soil Fertility Management in Cocoa Plantations in Ghana. FSP Regional Cacao Scientific and Technical Final Report. Rapport Technique N°22, CRIG (Cocoa Research Institute of Ghana).

[34] Tossah, B.K., Koudjega, T. and Snoeck, D. (2006) Amélioration de la gestion de la fertilité des sols dans les plantations de cacaoyers au Togo. Rapport final scientifique et technique du FSP Régional Cacao. Vol. 43, ITRA/CRAF.

[35] Nair, P.K.R. (1993) State-of-the-Art of Agroforestry Research and Education. *Agroforestry Systems*, **23**, 95-119. https://doi.org/10.1007/bf00704909

[36] Weil, R.R. and Brady, N.C. (2017) The Nature and Properties of Soils. 15th Edition, Pearson. https://doi.org/10.2136/sssaj2016.0005br

[37] Havlin, J.L., Beaton, J.D., Tisdale, S.L. and Nelson, W.L. (2005) Soil Fertility and Fertilizers: An Introduction to Nutrient Management. 7th Edition, Pearson Prentice Hall.

[38] Vanlauwe, B., Aihou, K., Tossah, B.K., Diels, J., Sanginga, N. and Merckx, R. (2005) *Senna siamea* Trees Recycle Ca from a Ca-Rich Subsoil and Increase the Topsoil pH in Agroforestry Systems in the West African Derived Savanna Zone. *Plant and Soil*, **269**, 285-296. https://doi.org/10.1007/s11104-004-0599-3

[39] Landon, J.R. (1991) Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural land Evaluation in the Tropics and Subtropics. Booker Agriculture Internatinal.