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Impacts of Calcium and Magnesium Amendment on Soil Macrofauna Under Cocoa Trees in the South-West and Central-South of Ivory Coast

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The production of cocoa in Ivory Coast faces major challenges, particularly soil acidification, which leads to a significant decrease in yields. To reduce soil acidity under cocoa trees in order to maintain cocoa production, a study was conducted to test the effect of a mineral amendment containing calcium and magnesium (TerraCalco) in two agroecological zones (South-West and Central-South) of cocoa production in Ivory Coast. The study was carried out according to a split-split plot experimental design with 4 repetitions taking into account three factors; the first factor is the region represented by 2 levels (South-West and Centre-South), the second by soil depth with 3 levels, and the third factor, by the formulation of the input with 6 levels representing treatments T0, T1, T2, T3, T4, and T5. The results obtained showed that the localities of Méagui (South-West) and Guitry (Central-South) have the highest densities of macrofauna with the highest density of earthworms (20.67±2.65 individuals/m²) and termites (30.83±4.65 individuals/m²) at Méagui. The locality of Guitry exhibits the highest densities of ants (8.25±2.17 individuals/m²), beetles (5.22±2.10 individuals/m²), and myriapods (42.68±11.03 individuals/m²). The 0-10 cm depth contains the highest density of macrofauna per m², consisting mainly of earthworms (28.48±2.55), ants (12.81±1.82), termites (36.12±3.58), beetles (6.55±1.55), and myriapods (43.00±8.30). Treatment T5 achieved the highest densities per m² for all macrofauna groups, namely earthworms (17.69±3.81), ants (14.02±3.43), termites (24.42±5.63), beetles (7.71±3.10), and myriapods (40.79±19.10). In contrast, the control treatment T0 (without amendment) had the lowest densities for all the macrofauna groups, namely earthworms (17.69±3.81), ants (14.02±3.43), termites (24.42±5.63), beetles (7.71±3.10), and myriapods (40.79±19.10). In contrast, the control treatment T0 (without amendment) had the lowest densities for all the studied macrofauna groups.

1. Introduction

Crop productivity is closely dependent on soil fertility and quality, which are themselves influenced by biotic and abiotic factors. These factors can be grouped into three main categories: ecological, pedological, and human, each playing an essential role in the balance of agricultural ecosystems. They particularly affect the distribution of soil macrofauna, a group of organisms of which about 90% of species are visible to the naked eye and live in the soil or litter.

The diversity of this macrofauna is crucial, as it supports key ecological processes in agricultural landscapes, such as the decomposition of organic matter, nutrient recycling, improvement of soil structure, and moisture regulation. These processes are essential for plant development and the maintenance of life in the soil.

In Côte d'Ivoire, the soils of cocoa plantations are undergoing progressive acidification, reducing the availability of nutrients for the plants (Sanchez & Logan, 1992). This acidification is exacerbated by the intensification of agricultural practices, particularly the excessive use of chemical inputs. This phenomenon leads to a significant decrease in the diversity and abundance of soil fauna emphasizes that excessive soil acidity has a negative impact on macrofauna, reducing its biological activity and its role in ecological processes. Among the main causes of this acidity is the anarchic use of chemical fertilizers.

Soil acidity not only reduces the abundance of soil macrofauna but also disrupts the bioavailability and assimilation of essential nutrients, promoting their precipitation with iron, aluminum, and calcium hydroxides. To counter this acidification and preserve soil macrofauna, the use of amendments is recommended, especially in aging and impoverished plantations.

Recent studies show that the addition of organic or inorganic amendments to acidic soils increases pH, improves nutrient bioavailability, and promotes the growth of cocoa trees (Alain et al., 2021). In this context, the present study aims to evaluate the effect of a calcium and magnesium amendment on macrofauna populations in acidic pH soils under cocoa trees, in the localities of Guitry, Lakota, Soubré, and Méagui in Ivory coast.

2. Materials and Methods

2.1. Study Area

The study covers two regions of Côte d'Ivoire: the South-West Region (5°35'32" to 5°58'44"N; 6°34'24" to 6°36'00"W) in the localities of Soubré and Méagui (figure 1), characterized by a subequatorial climate with two rainy seasons (March-July and September-November) and two dry seasons (December-February and August).

The average annual rainfall is 1392 mm, with an average temperature of 25.8 °C (Evi et al., 2007). The vegetation is characterized by dense, humid, evergreen forests partially converted into cacao agroecosystems. The soils are primarily Acrisols, Eutric Ferralsols, Eutric Cambisols, Dystric plinthic Ferralsols, and Arenosols derived from various geological materials (Kassin et al., 2016; N'Guessan, 2017).

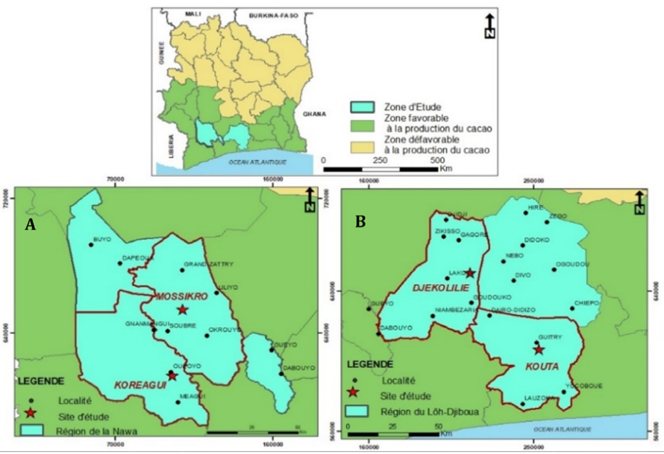

Figure 1: Map Showing the Location of the Study Sites (A: South-West; B: Central-South).

The Central-South Region (5°20'00" to 6°08'22" N; 5°22'00" to 5°57'15" W) in the localities of Lakota and Guitry (figure 1). The climate is of the humid tropical type with two wet seasons and two dry seasons. The average annual rainfall reaches 1320 mm with an average temperature of 27 °C. The vegetation is a mosaic of forest relics and agricultural plots resulting from the expansion of agricultural activities and logging (FAO, 2010; Kouadio, 2016). The soils in this region are similar to those in the South-west, exhibiting physico-chemical properties favorable to cocoa cultivation (Kassin et al., 2016; N'Guessan, 2017).

2.2. Material

2.2.1. Material Plant

The plant material consisted of cocoa trees from unselected or heterogeneous varieties in the exploitation phase, aged 10 to 15 years.

2.2.2. Inputs

The fertilization system consisted of a calcium and magnesium mineral amendment (TerraCalco) combined with an NPK 0-23-19 type fertilizer at varying doses.

2.3. Method

2.3.1. Experimental Setup

The experiment was conducted using a split-split plot design with 4 repetitions, allowing for a hierarchical analysis of the different factors. The first factor corresponded to the regions, with two levels: South-West and Central-South. The second factor concerned soil depth, with three levels: 0-10 cm, 10-20 cm, and 20-30 cm. The third factor corresponded to 6 combinations of fertilizers, constituting the different treatments: T0, T1, T2, T3, T4, and T5. The South-West included the localities of Soubré and Méagui, while Central-South included Lakota and Guitry. The formulations of the six treatment levels are detailed in Table I.

2.3.2. Test Set-up

Each trial consisted of a plot of 1 hectare per site, subdivided into 4 blocks, each containing 6 elementary plots of 15 m × 15 m. Thus, each site contained a total of 24 elementary plots.

2.3.3. Treatment Application Mode

The calcium and magnesium mineral amendment (TerraCalco) was associated with the NPK fertilizer type 0-23-19 and applied twice a year (March-April and September-October) according to the recommendations of the IDH project. The NPK was applied according to the region-specific doses defined for each cocoa production area in Côte d'Ivoire. Thus, the annual doses of 300 g/cocoa tree for the Central-South (Lakota and Guitry) and 400 g/cocoa tree for the South-West (Soubré and Méagui) were combined with the TerraCalco amendment at the recommended annual dose of 750.19 g/cocoa tree in each locality. These fertilizers were applied in a crown around the cocoa trees, after outlining, within a radius of 80 cm around the collar (Kébé et al., 2009).

Table 1: Formulations and Doses of Fertilizers Applied to the Soil of Cocoa Plantations in the Central-South and South-West.

Treatments	Fertilizer Formulations	Doses (g/cocoa tree/year)		
		TerraCalco	NPK 0-23-19 (Central-South)	NPK 0-23-19 (South-West)
T0	Absolute Witness	0	0	0
T1	NPK (0-23-19)	0	300	400
T2	Terracalco + 100 % NPK	750,19	300	400
T3	Terracalco + 80% NPK	750,19	240	320
T4	Terracalco + 70% NPK	750,19	210	280
T5	Terracalco + 50% NPK	750,19	150	200

2.3.4. Collection of Soil Macrofauna

The collection of soil macrofauna was carried out in three distinct soil layers in each of the 24 plots per site, totaling 72 samples per locality. The samples were taken using a metal quadrat measuring 25 cm on each side and 30 cm deep, following the method of the Tropical Soil Biology and Fertility (TSBF) study (Anderson & Ingram, 1993). To do this, the soil monoliths corresponding to the dimensions of the quadrat were divided into three layers (0-10 cm, 10-20 cm, and 20-30 cm), in which the organisms were collected manually, then preserved in 70% alcohol to ensure proper conservation (Anderson & Ingram, 1993). These specimens were then identified and classified into functional categories, based on the classifications proposed by Turbé et al. (2010) and Ratnadass et al. (2012), in order to better understand their ecological role in the soil.

The identification of organisms was carried out using specific guides. Thus, earthworms were identified using the OPVT key (2014), while ants, termites, beetles, and myriapods were examined with a binocular loupe equipped with a camera, connected to a computer for detailed observation. The specimens were compared to reference samples from the collection of the Laboratory of Terrestrial Invertebrate Zoology of the Fundamental Institute of Black Africa (IFAN).

2.3.5. Statistical Analysis

The obtained data were subjected to an analysis of variance (ANOVA) using SAS 9.4 software. The means were compared using the Newman-Keuls test, at a threshold of 5% (Gomez & Gomez, 1984).

3. Results

3.1.1. Morphological Characteristics of Soils Under Cocoa Trees in the Central-South

3.1.1.1. Morphological Characteristics of Soils in Lakota

The superficial layers (A11, A12, and A13) with a thickness of 50 cm (0-50 cm) are very rich in organic matter. These horizons have a loamy-clay texture, are porous, and feature numerous roots with preferential sub-horizontal directions of varying sizes. They exhibit a very low rate of coarse elements, with a few rare iron concretions. The underlying layers A14 and B2t have a thickness of 70 cm (50-120 cm). These horizons are very low in humus, compact, with a clay-loam texture, a low rate of coarse elements, and poor internal drainage (drainage class 4). However, deeper down, the last horizon B2t contains about 85% iron elements forming a rigid crust with traces of ancient hydromorphism. The soil of Lakota is an Endo Duric Manganiferric Plinthic Ferralsol (Figure 2.a).

3.1.1.2. Morphological Characteristics of Soils in Guitry

The upper layers (A11, A12, and A13), very rich in organic matter over a thickness of 38 cm (0-38 cm), exhibit a sandy-loamy texture with a granular structure. They are very crumbly with good porosity and contain numerous roots of various sizes, preferentially oriented horizontally. These surface layers have excellent drainage, corresponding to a drainage class of 1.2 to 2, with no trace of hydromorphism. The lower layers (A14 and B2gtC), rich in clay, extend over a thickness of 82 cm (38-120 cm). In these underlying horizons, the soil becomes more compact, with a high content of coarse elements, mainly consisting of iron concretions (80%). Many spots are also observed in these layers, indicating the presence of an ancient temporary hydromorphism. The soil thus described in Guitry is an Albic Ferric Arenosol (Figure 2.b).

3.1.2. Morphological Characteristics of Soils Under Cocoa Trees in the South-west

3.1.2.1. Morphological Characteristics of Soils in Méagui

The superficial horizons (A11, A12), with a thickness of 14 cm (0-14 cm), have a clayey-loamy texture. They are porous and very rich in organic matter, with many roots of varying sizes, preferentially sub-horizontal direction, as well as a few rare ferruginous concretions. The horizon A13, with a thickness of 9 cm, is, on the other hand, compact, poorly porous, with a massive structure tending towards polyhedral, and rich in coarse elements (60%). The lower horizons (A14 and B2gt) exhibit a massive structure, with a clayey-loamy texture that becomes more clayey in depth. They are devoid of roots, organic matter, and coarse elements, and show poor internal drainage (drainage class 6), along with traces of ancient hydromorphism, indicating past periods of water saturation. In Méagui, the described soil is an Argic Gleyic Ferralsol (Figure 2.c).

3.1.2.2. Morphological Characteristics of Soils in Soubré

The upper layers (A11, A12, and A13), with a thickness of 65 cm (0-65 cm) present a sandy-silt texture with a granular structure. These horizons, rich in organic matter, are porous and crumbly, with numerous preferential sub-horizontal roots of varying sizes. They have good internal drainage (drainage class 1.2) with a gradual transition without signs of hydromorphism. The lower layers, with a thickness of 55 cm (65-120 cm), with textures varying from sandy-silt (A14) to clayey-silt (BCgt), have a massive structure. These horizons become more compact, with high rates of coarse elements (80%) consisting mainly of nodules, ferruginous concretions, and some quartz fragments. In these horizons, there are signs of temporary hydromorphism at depth. The soil described in Soubré is an Endo-Manganiferic Albic Arenosol (Figure 2.d).

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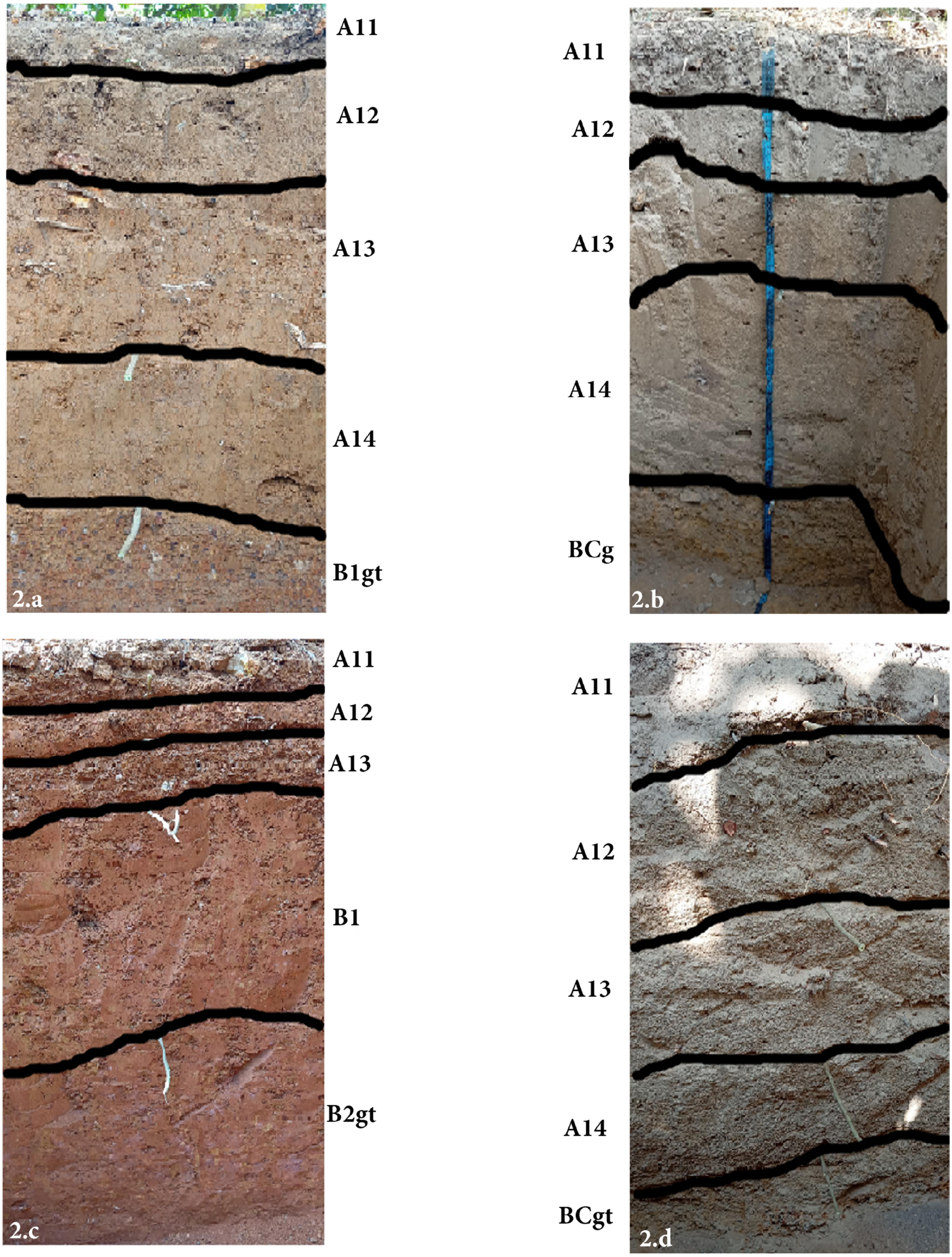

Figure 2: (2.a) Endo-Duric Manganiferric Plinthic Ferralsol, (2.b) Albic Ferric Arenosol, (2.c) Argic Gleyic Ferralsol, (2.d): Endo Manganiferric Albic.

3.1.3. Evaluation of the Diversity and Density of Macrofauna in Locations, Depths and Treatments

- **Analysis by Locality**

The results obtained showed significant differences in the distribution of macrofauna between the studied areas. Regarding earthworms, Méagui exhibits the highest density with 20.67±2.65 individuals/m², while Soubré presents moderate values of 15.45±2.20 individuals/m². The highest densities of ants were observed in Guitry with 8.25±2.17 individuals/m². As for termites, they were abundant in Méagui (30.83±4.65 individuals/m²). The highest densities of beetles and millipedes were observed in Guitry, with 5.22±2.10 and 42.68±11.03 individuals/m², respectively.

Table 2: Distribution of Macrofauna According to Treatments in the Locations of Lakota, Guitry, Méagui, and Soubré.

Locality	Worms	Ants	Termites	Beetles	Myriapods
Lakota	2,05±0,46d	2,75±0,25c	7,19±1,32d	1,92±0,22b	18,28±2,44b
Guitry	7,24±2,40c	8,25±2,17a	9,80±3,03c	5,22±2,10a	42,68±11,03a
Soubré	15,45±2,20b	6,72±1,46b	11,50±2,47b	2,14±0,32b	2,07±0,29c
Méagui	20,67±2,65a	3,05±0,65c	30,8 ±4,65a	0,83±0,17c	2,03±0,37c
P < 5%	0,0017	0,0001	0,0001	0,001	0,0005
The letters (a, b, c, d, e, f) indicate significant differences between the means (Newman-Keuls test, 5% threshold).					

- **Analysis by Soil Depth**

The statistical analysis showed significant variations based on depth. The density of all the studied groups of organisms decreases with soil depth. The 0-10 cm layer has the highest density of macrofauna per m².

Table 3: Macrofauna Distribution According to Treatments at Depths of 10, 20 and 30cm.

Profondeur Du Sol	Worms	Ants	Termites	Beetles	Myriapods
0-10	28,48±2,55**a**	12,81±1,82**a**	36,12±3,58**a**	6,55±1,55**a**	43,00±8,30**a**
10-20	4,69±0,60**b**	1,97±0,23**b**	8,26±2,04**b**	0,70±0,10**b**	4,29±0,42**b**
20-30	0,89±0,22**c**	0,80±0,11**c**	0,11±0,03**c**	0,33±0,06**c**	1,50±0,20**c**
P < 5%	0,0001	0,0001	0,0001	0,0001	0,0005
The letters (a, b, c, d, e, f) indicate significant differences between the means (Newman-Keuls test, 5% threshold). 0-10: depth of 0 to 10 cm of soil, 10-20: depth of 10 to 20 cm of soil, and 20-30: depth of 20 to 30 cm of soil.					

- **Analysis by Treatment**

The effects of the various treatments applied revealed significant differences. Treatment T5 shows the highest values in the studied macrofauna with 17.69±3.81 earthworms, 14.02±3.43 ants, 24.42±5.63 termites, 7.71±3.10 beetles, and 40.79±19.10 myriapods per square meter (m²).

Table 4: Distribution of Macrofauna According to Treatments at Depths of 10, 20 and 30 cm in the Localities of Lakota, Guitry, Méagui and Soubré.

Treatments	Worms	Ants	Termites	Beetles	Myriapods
T0	9,67±2,47d	1,79±0,27e	17,98±4,18b	1,27±0,22cd	15,39±4,55b
T1	14,83±2,82b	3,12±0,46d	10,58±2,64e	1,71±0,26bc	15,00±4,08b
T2	11,96±2,91c	4,00±0,69c	15,75±4,68c	1,67±0,34bc	8,19±1,96d
T3	5,04±1,24e	4,94±1,56b	6,48±1,78f	0,92±0,15d	10,69±2,32c
T4	8,94±2,50d	3,29±0,52d	13,79±3,71d	1,89±0,42b	7,52±1,65d
T5	17,69±3,81a	14,02±3,43a	24,42±5,63a	7,71±3,10a	40,79±19,10a
average	11,35	5,19	14,83	2,53	16,26
CV (%)	25,74	24,05	22,13	40,44	11,6
P < 5%	0,0001	0,0001	0,0001	0,0001	0,0001
P: Probability value for the effect of each factor. CV: Coefficient of variation in percentage for each group. The letters (a, b, c, d, e, f) indicate significant differences between the means (Newman-Keuls test, threshold of 5%). T0: control without terracalco or NPK, T1: 100% NPK, T2: 100% terracalco + 100% NPK, T3: 100% terracalco + 80% NPK, T4: 100% terracalco + 70% NPK, T5: 100% terracalco + 50% NPK.					

4. Discussion

The application of calcium and magnesium-based amendments, combined with NPK fertilizer 0-23-19, on acidic soils has significantly altered soil macrofauna biodiversity. Data collected from various regions and under different treatments enhance our understanding of the interactions between agricultural practices, biodiversity, and soil quality. These organisms participate in a complex trophic network, ensuring the cycle of energy and nutrients from microorganisms to epigeal organisms (FAO et al., 2021).

4.1. Influence of Locality on Macrofauna

The differences in density and diversity of macrofauna between localities are linked to the environmental characteristics of the habitat, such as texture, structure, organic matter content, drainage, and compaction, which constitute favorable conditions for the survival of this macrofauna. In Lakota, the Plinthic Ferralsol, characterized by a rigid crust and poor drainage, limits the ecological niche of macrofauna to the surface horizons, thus restricting bioturbation (Edwards & Bohlen, 1996). Low porosity affects the formation of stable aggregates. In contrast, in Guitry, the Albic Ferric Arenosol, with its optimal drainage and light texture, allows for a more homogeneous colonization of macrofauna across the entire profile, promoting aggregate formation and structural stability (Six et al., 2004). In Méagui, although the A13 horizon is compact, the surface layer, rich in organic matter, remains a suitable habitat for soil macrofauna. In the locality of Soubré, despite the richness of the surface horizons in organic matter, the greater presence of coarse elements in the lower horizons affects the mobility and formation of the macrofauna habitat. These results are consistent with those of Six et al. (2004), who highlighted the importance of local environmental conditions in the distribution and abundance of soil biodiversity. The application of calcium and magnesium amendments to previously acidic soils aims to correct acidity and promote the development of macrofauna. This observation is confirmed by the study results, highlighting a variation in macrofauna density from one region to another. According to prior literature, the reduction of acidity stimulates microbial activity and bioturbation, promoting the formation of aggregates.

4.2. Influence of Soil Depth

The observed trend of a reduction in macrofauna density with depth aligns with global conclusions on soil ecology. Anderson & Ingram (1993) demonstrated that over 80% of soil organisms are concentrated in the top 10 to 20 centimeters, where organic matter, oxygen, and roots are most abundant. This ecological stratification is also corroborated by Wardle (2002), and Rillig et al. (2015), who emphasize that biological activity decreases exponentially with depth due to the scarcity of energy resources and physico-chemical constraints. Prior literature specifies that this vertical distribution is modulated by soil structure, agricultural practices, and biotic interactions. According to Petersen & Luxton (1982), this decline in macrofauna density is related to the decrease in oxygen at depth.

In this study, treatments combining calcium/magnesium amendments and NPK 0-23-19 fertilizer at variable doses likely improved the physical structure of the surface horizons (0-20 cm) by reducing acidity and promoting aggregation, creating a habitat conducive to macrofauna. These results are consistent with the observations of Brussaard (1997), which links the abundance of earthworms and arthropods to the availability of calcium and structural stability.

4.3. Effects of Treatments on Soil Biodiversity

The use of NPK 0-23-19 type fertilizers at variable rates, combined with a calcium and magnesium amendment, had significant effects on soil biodiversity. The increase in macrofauna density observed under treatment T5, consisting of 100% calcium and magnesium amendment and 50% NPK 0-23-19 type fertilizer. These studies showed that the application of mineral or organic fertilizers can enhance soil biodiversity by providing essential nutrients. This also suggest that soil enrichment practices can improve not only crop productivity but also the diversity and abundance of soil organisms.

The soil macrofauna such as earthworms, ants, termites, and others acts as engineers of the ecosystem by modifying soil porosity, the transport of water and gases, and by binding soil particles into stable aggregates. These aggregates keep the soil in place, thereby reducing erosion. The results obtained show that earthworms, ants, and termites were more numerous in the amended plots. The addition of organic or mineral nutrients increases the biomass of macrofauna in treated soils, strengthening the role of these organisms in the decomposition of organic matter and soil fertility.

In contrast, the low density observed with treatment T0 (without amendment or fertilizer) is consistent with the results of Bulluck et al. (2002). These authors demonstrated that unfertilized soils exhibit significantly reduced biodiversity, which negatively impacts soil health and long-term productivity by limiting key processes such as the decomposition of organic matter and the formation of stable aggregates.

4.4. Interaction between soil Improver, Nutrients and Soil pH

Soil acidity is a crucial factor that influences the availability of nutrients and, consequently, the composition of macrofauna. In acidic soils, certain nutrients, like phosphorus, become less available to plants. Calcium and magnesium amendments work by releasing these nutrients and reducing acidity. Duddigan et al. (2021) demonstrated that soil pH plays a key role in regulating the diversity and abundance of macrofauna. These results support this assertion, showing a positive response of macrofauna in amended soils.

5. Conclusion

This study makes a significant contribution to the understanding and sustainable management of cocoa soils in Ivory Coast, particularly in the South-West and Central-South regions. The calcium and magnesium amendment notably improves the fertility of acidic soils by increasing the pH, which neutralizes the toxicity of exchangeable aluminum and free iron, while increasing the availability of phosphorus, an essential element for cocoa tree nutrition. This chemical restoration also promotes a better ionic balance (Ca/Mg, Mg/K), which is essential for the growth and productivity of cocoa trees.

Moreover, the study is distinguished by the integration of the impact of this amendment on soil macrofauna, an aspect often neglected in previous research focused on soil chemistry and yields. By improving the chemical and physical conditions of the soil, the amendment promotes the diversity and abundance of macrofauna, which plays a key role in the decomposition of organic matter and soil structuring, thus contributing to the biological and functional fertility of cocoa systems.

By targeting two regions with distinct agricultural practices and soil characteristics (cocoa trees in full sun versus under shade), this study provides a localized and contextualized understanding of the effects of calcium and magnesium amendments. It complements previous research, which has often been more generalized, by highlighting the importance of adapting agronomic recommendations to local production systems and the specificities of Ferralsols typical of cocoa-growing areas in Africa.

The results show that each site reacts differently to the treatments: a low overall density of macrofauna was observed at Lakota (Central-South), compared to higher densities for certain groups at Méagui and Soubré (South-West), as well as at Guitry (Central-South). These observations demonstrate that calcium and magnesium amendment, combined with reduced doses of NPK fertilizer 0-23-19, has a positive effect on the density and diversity of macrofauna in acidic soils.

These results highlight the importance of adequate soil management to improve biodiversity and soil health, which are crucial factors for the sustainability of agricultural systems, especially in the cocoa-growing regions of Côte d'Ivoire. The integrated approach of mineral amendment and fertilization could serve as a model for other regions facing similar issues related to soil acidity. Finally, it would be beneficial to conduct long-term studies to observe the evolution of macrofauna over several seasons, as well as to explore the interactions between different groups of macrofauna and their impact on soil health and crop productivity. Further research could also evaluate the effect of different types of organic and inorganic fertilizers on soil biodiversity and functionality.

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