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Influence of the topographic gradient on the physico-chemical properties of soils in a tropical agroecosystem in southern Côte d'Ivoire

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Abstract

This study aims to analyze the influence of the topographic gradient on the variability of soil physicochemical properties in a tropical agroecosystem in southern Côte d'Ivoire. Three soil profiles were described along a projected toposequence in the village of Ahoué, respectively at the upper, middle, and lower slopes. Soil samples were collected at different depths and analyzed in the laboratory to assess pH, cation exchange capacity (CEC), and organic matter (OM) content. The results show a marked variability in soil characteristics depending on the topographic position. Soils at the lower slopes have hydromorphic horizons rich in OM and CEC, while those at the upper slopes are more impoverished, acidic, and susceptible to erosion. This differentiation reflects a redistribution of elements linked to erosion, runoff, and deposition dynamics. Topography thus appears to be a determining factor in soil fertility and their cultural suitability. These results highlight the interest of differentiated land management based on pedotopographic conditions, with a view to more sustainable agriculture.

Keywords: Toposequence; Soil Fertility; Organic Matter; Ph; CEC; Côte d'Ivoire

1. Introduction

The spatial variability of soils is a major constraint on the implementation of effective and sustainable agricultural practices, particularly in tropical environments where landscapes are heavily shaped by relief. In these contexts, topography influences not only the distribution of water and nutrients but also the processes of erosion, leaching, and accumulation, leading to marked contrasts in soil morphology and fertility [1, 2].

Recent work in West Africa has highlighted the importance of topographic position in structuring soil profiles and the distribution of chemical properties such as pH, cation exchange capacity (CEC), or organic matter content [3, 4]. These variations, often ignored in land management, are crucial for optimizing agricultural practices and conserving soils [5, 6]. In the southern region of Côte d'Ivoire, extensive farming systems rely on heterogeneous soils, but local knowledge remains fragmented regarding their organization according to relief. The village of Ahoué, located in an agroecological zone characterized by desaturated soils with low water retention, provides a favorable ground for analyzing the interactions between topography and pedogenetic dynamics.

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The present study aims to characterize the influence of the topographic gradient on the variability of soil physico-chemical properties along a toposequence. More specifically, it aims to: (i) describe the morphopedological profiles at different positions on the slope, (ii) quantify the variations in pH, CEC, and organic matter, and (iii) evaluate the agronomic and environmental implications of such differentiation. The results are expected to lay the groundwork for recommendations for efficient and sustainable management of agricultural lands in humid tropical environments.

2. Material and methods

2.1. Study site localisation

The study site is located in the village of Ahoué (between 5° 26' and 5° 29' north latitude, and 3° 50' and 3° 56' west longitude). It covers an area of 1.3 hectares, situated along the highway connecting Abidjan to Alépé, in the northern part of the autonomous district of Abidjan, in the south of Côte d'Ivoire (figure 1). The average monthly temperatures range between 25 and 30 °C, accompanied by a high humidity rate (80 to 90%). Annual rainfall exceeds 1200 mm [7]. The site vegetation corresponds to psammophilic forests, characterized by highly desaturated soils with low water retention capacity and poor clay content. These soils exhibit a thick clay horizon marked by patches that reflect often poor or sometimes imperfect drainage at depth [8].

2.2. Morphopédology charactérization

A toposequence was established on study site, with three pedological pits. The location of the three open pedological pits was based on an unequal probability sampling device [9]. The pedological pits, spaced at least 200 m apart, have a maximum depth of 1.2 m, in the absence of natural constraints. Each profile was identified by its topographical position (Figure 1) following the model described by [10]. The scientific classification used is that adopted by [11]. Geographic coordinates were recorded at the locations of the pits. These pedological pits were described, horizon by horizon, and samples were taken for analysis at the Soil and Plant Laboratory of Félix Houphouët Boigny National Polytechnic Institute (INP-HB) in Yamoussoukro, Côte d'Ivoire according to standard methods [12].

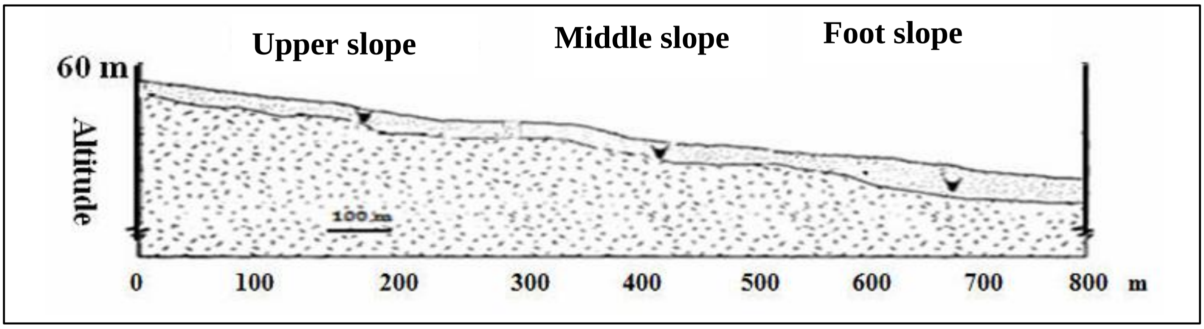

Figure 1 Structuring of Study site toposéquence

3. Result

3.1. Variation of soil profiles along a slope: Influence of topography on soil differentiation

The figure 2 highlights the variability of soil profiles according to the topographic position on the slope. At the top of the slope, the soils are dominated by red clay and exhibit a sequence of well-differentiated horizons. This configuration suggests a strong pedogenetic evolution marked by significant leaching of soluble elements. Towards the middle part of the slope (MV), the texture evolves to yellow clay, indicating a certain degree of remobilization of materials from the upper areas. The structuring of the horizons remains relatively similar, although their depth is more pronounced, which reflects a moderate accumulation of fine particles resulting from upstream erosion processes. In the Foot slope zone (FS), soil characteristics change considerably with the presence of a peaty horizon, indicating pronounced hydromorphism, and the development of reducing conditions. All of these observations highlight the predominant role of topography in pedogenetic dynamics and the spatial organization of horizons.

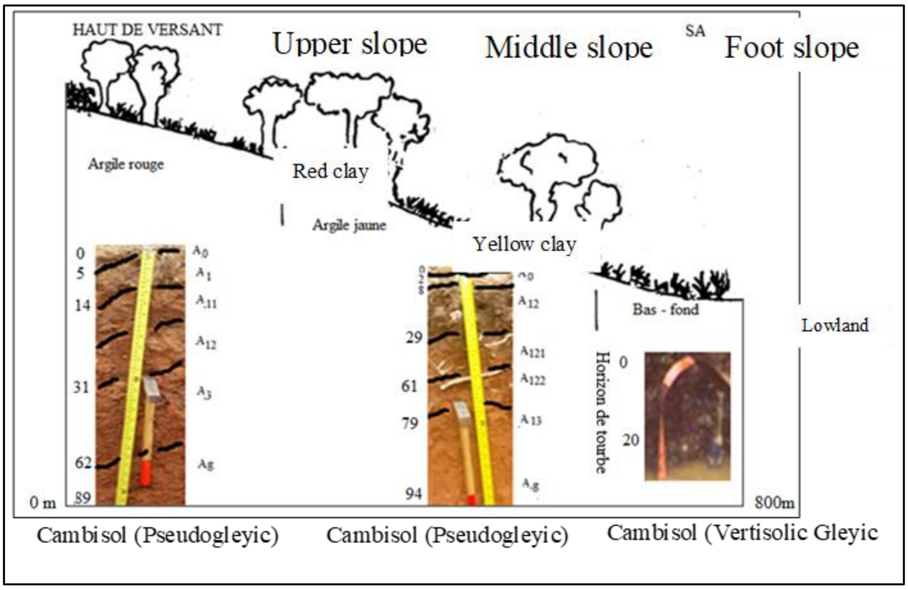

Figure 2 Influence of topography on soil differentiation along a slope

3.2. Influence of topography on the physico-chemical properties of soil

The graphs (Figure 3) illustrate the evolution of the physico-chemical properties of soils (pH, CEC, and organic matter content) according to topography. At the Upper slope, the soils are characterized by a low organic matter content, with values ranging from 2.3 to 9.9 g.kg^{-1}. The CEC is relatively low to moderate, varying between 7.63 and 14.5 cmol.kg^{-1}, while the pH remains generally acidic (4.2 to 5.6). These characteristics explain an overall low to medium cultivation suitability. At the middle slope, the soils show better apparent fertility, with more abundant organic matter (4.4 to 14.9 g.kg^{-1}) and a CEC reaching 21.4 cmol.kg^{-1} at the surface. However, the pH remains acidic (3.87 to 4.1), which limits the cultivation suitability of deep horizons. The sum of ratings indicates an overall average fertility. Finally, at the Foot slope, the organic matter is higher at the surface (21 g.kg^{-1}), while the CEC is moderate (12.98 cmol.kg^{-1}) and the pH is slightly less acidic (5.5). These characteristics give these soils a moderate agricultural suitability.

These variations suggest a more pronounced acidification at middle-position, likely due to the leaching of exchangeable bases. At the same time, the CEC shows a regular decrease along the topographic gradient, indicating a progressive loss of soil colloids, linked to the dynamics of weathering and material transport. Organic matter exhibits a marked decrease in US towards the lower positions (MS and FS), which reflects a gradual depletion of organic carbon, likely due to conditions favoring the mineralization and mobilization of organic matter. However, the differences between US, MS, and FS reveal an interaction between erosion, deposition, and organic degradation processes. Overall, these results highlight the determining influence of topography on the physicochemical properties of soil, with significant implications for the quality and management of agricultural ecosystems.

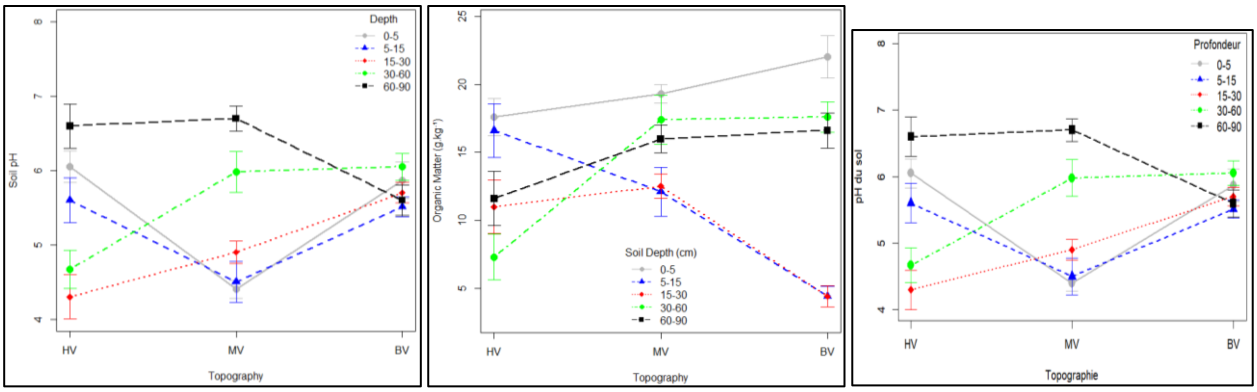

Figure 3 Variations of pH, CEC, and organic matter according to topography

4. Discussion

Understanding the variability of soil quality indicators based on different soil depths across topographic positions (toposequence) is essential for improving soil fertility, agricultural productivity, and ensuring environmental sustainability. This study analyzes the variations in soil quality indicators according to different soil depths (0 to 5 cm, 5 to 15 cm, 15 to 30 cm, 30 to 60 cm, and 60 to 80 cm) within three topographic positions along a toposequence (lower slope, mid-slope, and upper slope).

4.1. Impact of topography on soil reaction variability (pH-water)

The analysis of pH-water fluctuations according to topographic gradients highlights notable divergences between studies; thus suggests that soil acidity results from a complex interaction among climatic factors, pedogenetic processes, and management practices. According to [13], the studied soils exhibit variable acidity, ranging from acidic to very acidic (5.6 to 4.2). This heterogeneity is often attributed to management practices and local environmental conditions. In this regard, [14] demonstrated, through a study along a toposequence, that pH variation is influenced by topographic position, with ridge tops and mid-slopes being subjected to distinct dynamics compared to valley bottoms.

The toposequence influence on soil acidity is reflected in statistically significant differences between topographic positions, particularly between the footslopes and the mid-slopes, as well as between the footslopes and the upper slopes. This trend suggests a progressive decrease of pH with increasing gradient, likely due to runoff and the redistribution of organic and mineral materials. This redistribution thus promotes greater acidification at lower positions. In line with these observations, soils located on Upper slope (US) exhibit higher pH values than those at mid-slope (MS) and foot slope (FS), corroborating the findings of [15], who reported greater alkalinity in the summit portion of the catenas.

However, several studies suggest opposing trends. [16, 17, 18] report that the highest pH values are generally found at the bottom of slopes, where the accumulation of sediments and organic matter tends to buffer soil acidity. In contrast, [19] found no significant variation of pH based on topographic positions, thus highlighting the potential influence of other environmental parameters on soil acidity regulation. These discrepancies between studies may be attributed to differences in climatic conditions, erosive dynamics, and agricultural practices specific to each ecosystem.

In the face of these uncertainties, it appears essential to implement suitable soil conservation and water management strategies in order to mitigate the effects of acidity and limit the degradation of agricultural lands. Without these interventions, the intensification of acidification could permanently alter soil quality and compromise long-term agricultural productivity. An integration of this knowledge into agricultural policies is necessary to preserve the resilience of ecosystems to climate change and increasing anthropogenic pressures.

4.2. Dynamics of soil organic matter and implications for soil quality

In this study, variations in organic matter (OM) were examined based on topography, distinguishing three positions : foot slope (FS), mid-slope (MS), and upper slope (US). The results reveal a more pronounced accumulation of OM at depth in the soils of the foot slope and mid-slope, compared to those of upper slope. This differentiated distribution appears closely linked to the textural properties and water retention capacity of the soils, which influence the storage and stability of OM. Indeed, the interaction between OM and soil texture promotes a significant improvement in soil structure, enhancing the stability of aggregates and optimizing water retention, particularly in soils with high clay content, in accordance with the observations of [20].

The comparative analysis of soils according to topography highlights the determining influence of hydrological and textural conditions specific to each landscape position. The soils of foot slope, characterized by a high clay content and better water retention capacity, show a more pronounced accumulation of organic matter (OM) and greater stability of aggregates. These results corroborate previous studies indicating that water retention favors the decomposition and stabilization of organic compounds, thus contributing to the long-term structural improvement of soils [20]. In contrast, the soils of upper slope, generally more sandy and prone to erosion, exhibit a more limited accumulation of OM. This response can be attributed to their lower capacity to retain moisture and nutrients, thus reducing the potential for stabilizing organic matter in the soil profile. Appropriate management of these soils could include the integration of conservation practices, such as organic amendment combined with the establishment of vegetation hedges and cover crops, in order to limit erosion and maximize organic matter storage. These results highlight the importance of a differentiated approach to soil management based on topographical variations, in order to optimize their quality and resilience to environmental constraints. This dynamic is amplified in clay-rich soils, where phosphate ions are more easily retained and available for plants [21]. However, in sandier soils, such as those observed on the upper slopes, rapid phosphorus loss can occur, reducing soil quality in the long term. The increase in organic matter is a key indicator of soil quality improvement, and its increase in the upper horizons above 30 cm always results in a proportional improvement in crop yields.

4.3. Topographic variability on cation exchange capacity and implications for soil management

In this study, variations of cation exchange capacity (CEC) were examined based on topography, distinguishing three positions: foot slope (FS), mid-slope (MS), and upper slope (US). The distribution analysis of cation exchange capacity (CEC) reveals significant differences depending on the topographic position. Soils located at the foot slope exhibit higher CEC values, particularly in the upper horizons at a depth of 30 cm. This accumulation may be attributed to better water retention and reduced exposure to erosion losses, thus limiting the leaching of exchangeable cations. These results align with the work of [22] which demonstrated that topography significantly influences pedogenetic processes and the distribution of soil properties.

According to [23], these topographical variations create distinct pedological microsites that influence not only the CEC but also the biogeochemical cycles as a whole. Research by [24] confirmed that these interactions between water properties and erosion processes are essential for understanding nutrient dynamics in the soil. [25] further highlighted the importance of a three-dimensional approach in soil studies, integrating the vertical dimension (profile) and horizontal dimension (toposequence). From an agronomic perspective, this differential distribution of CEC is strategically important for soil management in topographically complex environments. [2] emphasized the importance of these areas as natural "wells" of fertility in agricultural landscapes. Furthermore, in areas more exposed to erosion, such as high and mid-slopes, targeted interventions, such as the establishment of cover crops and the improvement of soil structure through organic amendments, could prove essential. These approaches are supported by [5] work on the conservation management of water and soil, and by [26], who developed differentiated intervention strategies based on topographical positions. These findings thus highlight the need for differentiated soil management based on their position in the landscape, integrating conservation strategies tailored to the hydrological constraints and erosion dynamics specific to each area. As [6] notes, understanding these topographical variations is essential for developing sustainable agricultural practices that are resilient to soil conservation challenges.

5. Conclusion

The study conducted in the village of Ahoué highlighted a strong variability in the physico-chemical properties of soils depending on topographic position. The soils at the foot slope stand out due to a better accumulation of organic matter, a higher cation exchange capacity, and a more neutral pH, indicating more favorable conditions for fertility. In contrast, the soils located upstream appear to be poorer, more acidic, and susceptible to erosion, due to their exposure to runoff and leaching processes. These results confirm the structuring role of the relief in the distribution of nutrients and in the evolution of pedological profiles in humid tropical environments. They emphasize the need to adopt differentiated agricultural practices according to topographical units, in order to optimize yields while preserving soil sustainability. Taking into account pedotopographical conditions in agricultural planning policies is a promising avenue for improving land management, particularly in rural areas where knowledge about soil quality remains limited. This study thus provides a useful scientific basis for guiding strategies for rational fertilization, soil conservation, and agroecological planning in tropical agroecosystems.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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