

Bioindicator plants of soil quality in an agro-ecological zone in Ahoué (Southern Ivory Coast): Application to peanut cultivation

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Abstract

In a context of soil degradation, this study examines the relationship between floristic composition and soil properties in the agro-ecological zone of Ahoué, southern Côte d'Ivoire, using a methodological approach combining the Indicator Value Index (IndVal), multivariate analysis (heatmap and hierarchical clustering) and environmental gradient mapping. The main objective is to identify and characterize bioindicator plant species of soil quality in this area. Our results highlight significant and robust correlations between some species and specific edaphic conditions. *Mallotus oppositifolius* and *Centrosema pubescens* were found to be strongly associated with soils characterized by high organic matter (OM) and high cation exchange capacity (CEC), suggesting favorable fertility conditions. Conversely, *Xylopiya aethiopica* and *Usteria guineensis* were identified as indicators of acidic and potentially degraded soils, with low CEC and lower nutrient retention, which could negatively impact the growth of sensitive crops. Multivariate analysis confirmed the high spatial variability of edaphic parameters along the topographic gradient, highlighting the heterogeneity of crop growth conditions within the study area. These results highlight the importance of plant bioindicators for characterizing soils and anticipating their evolution under the effect of pedogenetic processes and anthropogenic disturbances. The integration of spatial models and species functional diversity would help refine ecological diagnoses and optimize soil conservation and sustainable management strategies.

Keywords: Bioindicator Plants; Indicator Value Index; Soil Quality; Sustainable Soil Management; Organic Matter; Côte d'Ivoire

1. Introduction

Peanut (*Arachis hypogaea*) cultivation is of strategic importance to agricultural systems in many regions, particularly in West Africa. Soil quality, which directly influences crop productivity and sustainability, is a crucial factor for farm success. Traditionally, stakeholders in the agricultural sector (farmers, agronomists, soil engineers) assess soil quality based on criteria such as texture, depth, color, or coarse element content, which, however, only provide an approximate assessment of actual soil conditions ([1]; [2]; [3]). Soil analyses, which are more precise, are often expensive, limiting their access to farmers, particularly in rural areas of Africa [4].

Faced with this problem, the use of floristic bioindicators appears to be a relevant alternative for assessing soil quality quickly and economically [5]. Indeed, the local flora, through its diversity and dynamics, directly reflects the soil and

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ecological conditions of the environment. Certain plant species, sensitive to variations in soil properties, can thus serve as reliable indicators of its quality ([6]; [7]). In Africa, this approach is widely used by rural communities, who have learned to identify soil bioindicator plants to adapt their agricultural practices ([8]; [9]; [10]).

In this context, this study proposes to identify and analyze bioindicator plants in the agro-ecological zone of Ahoué, in southern Côte d'Ivoire, with a particular focus on their application in peanut cultivation. The local flora, particularly plants considered weeds, could offer valuable clues on soil characteristics, influencing peanut growth and health. By identifying these species and linking them to soil properties, the objective is to provide farmers with practical and accessible tools to assess the quality of their soils, without having to resort to costly analyses.

This work is based on quantitative data on plant species abundance, allowing the study of the relationships between vegetation and soils in this region. The results could open new perspectives for sustainable soil management in agriculture, particularly for sensitive crops such as peanuts. By facilitating the rapid assessment of soil quality, this study could contribute to improving farm productivity, while reducing the costs associated with soil analysis, particularly in regions where resources are limited [11].

2. Materials and methods

2.1. Study Site Location

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, located along the road linking Abidjan to Alépé, north of the autonomous district of Abidjan, in southern Côte d'Ivoire. Average monthly temperatures range between 25 and 30°C, accompanied by high humidity (80 to 90%). Annual precipitation exceeds 1200 mm [12]. The site's vegetation consists of psammophilous forests, characterized by highly desaturated soils with low water retention capacity and low clay content. These soils have a thick clayey horizon, marked by spots which reflect drainage which is often poor or sometimes imperfect in depth [13].

2.2. Study of floristic composition through toposequences and soil pits

To analyze the floristic composition of the study area, three toposequences were established, each comprising three soil pits (A, B, and C) located along each transect (Figure 1). The pits, spaced at least 200 m apart, have a maximum depth of 1.2 m, except in areas with natural constraints. Each soil profile was classified according to its topographic position as upper slope (HS), mid-slope (MS), and lower slope (LS), in accordance with the Yao-Kouamé model [14].

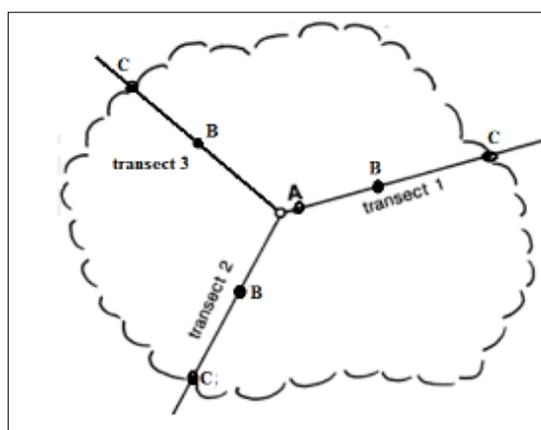


Figure 1 Structure of the toposequences produced in the landscape of the site studied

This approach allows capturing agro-pedological and plant variations according to topographic gradients (1 m² plots for perennial herbaceous plants and 5 m² plots for woody species), in accordance with the method described by Dibong and Ndjouondo [15]. This method allows for an accurate assessment of species dominance and distribution, while providing a suitable framework for comparison between different topographic profiles.

2.3. Soil quality levels and their assessment using the FAO-based approach

Soil quality assessment is based on the FAO classification [16], which considers soil as a physical resource integrated into agricultural production systems. This approach takes into account various factors, including agronomic potential, economic constraints, and the inputs required for production. Each soil unit is thus categorized according to its suitability for a specific use, distinguishing two main levels: S (suitable) and N (unsuitable).

Soil suitability for peanut cultivation is classified into five categories based on economic and agronomic criteria

- S1 (very suitable): Highly productive soils, with optimal conditions for peanut cultivation. These soils allow economically profitable production without requiring significant improvements.
- S2 (moderately suitable): Soils suitable for peanut cultivation but with certain limitations that reduce potential yield. The operation remains economically viable, although adjustments may be required.
- S3 (marginally suitable): Soils with significant constraints limiting productivity. Agricultural use is possible but at a significantly lower yield, requiring increased investment to maintain profitability.
- N1 (not suitable for economic reasons, but marginally suitable): Soils where the profitability of peanut cultivation is compromised by excessively high production costs (e.g., high input or labor requirements). However, these soils could be exploited under certain conditions with appropriate cultural practices.
- N2 (unsuitable for physical reasons): Soils with irreversible constraints that make cultivation impossible in the context of the intended use. This category includes soils with very shallow depths (< 20 cm), poor drainage, or exposure to recurring flooding risks.

The parameters considered include soil pH, depth, water retention capacity, and drainage. Soils best suited to peanut cultivation are characterized by sufficient depth and a pH between 6 and 7.5. Conversely, soil units prone to waterlogging, with a thin layer (< 20 cm), or poor drainage are classified as unsuitable for cultivation (N2).

This assessment framework provides a baseline for planning agricultural uses and implementing land management strategies aimed at optimizing productivity while minimizing economic and environmental constraints (Table I).

Table 1 Soil quality assessment grid according to pedological factors

| Soil Suitability Class | Very fit: S1 | Moderately fit: S2 | Little fit: S3 | Unfit: N |
|--------------------------|--------------|----------------------|--------------------|--------------|
| Effective Depth (cm) | > 100 | 60 - 100 | 30 - 60 | < 30 |
| Internal Drainage Class | 4 | 3 et 5 | 2 et 6 | 0 et 1 |
| Acidity (pH) | 6 - 7.5 | 5.5 - 6 7.5 - 7.8 | 5 - 5.5 7.8 - 8 | < 4.5 > 8 |
| Total Exchangeable Bases | > 10 | 5 - 10 | 2 - 5 | < 2 |
| Consistency | Soft | Friable | Hard | Very Hard |
| Gravel Load (p.c.) | < 10 | 10 - 30 | 30 - 50 | > 50 |
| Soil Quality Class | High | middle | Poor | Low |

Adapted from FAO [16] in <http://p-case.iata.fi.cnr.it/ap3a/>

2.4. Identification of bioindicator species of edaphic and agronomic conditions

2.4.1. IndVal calculation methodology

The IndVal index is obtained using the `multipatt()` algorithm from the `indicpecies` package in R ([17]; [18]). This approach allows indicator species to be identified based on their frequency of occurrence within the different groups studied. The statistical significance of species-group associations is assessed using a permutation test (`how(nperm = 1999)`) to obtain robust p-values [19]. A species is considered a significant indicator when it has a high IndVal and a p-value < 0.05 after permutation.

2.4.2. Identification of Bioindicator Species and Ecological Interpretation

Species with a significant IndVal were selected as bioindicators because they reflect agroecological conditions and the dynamics of soil management practices. The results were visualized using bar plots, where each species is represented

by its IndVal and statistical significance. This representation facilitates the interpretation of ecological trends and species-soil associations.

In addition to the statistical analysis, a literature review was conducted to contextualize the results by integrating the ecological requirements of the identified species and their role in the studied ecosystems ([19]; [20]).

2.5. Multivariate Analysis of Soil Properties Using Heatmaps and Hierarchical Clustering

The analysis of soil properties is based on a dataset comprising measurements from several locations, characterized by physicochemical parameters such as pH, cation exchange capacity (CEC), organic matter (OM), and available phosphorus (P_2O_5) levels. To optimally exploit this information, the data are transformed into a numerical matrix, excluding the Location column, which serves as an identifier, thus focusing the analysis on the relationships between quantitative variables [21]. A custom color palette is applied to improve the readability of the values: a gradient from white (low values) to red (high values) is used to enhance the visual interpretation of the observed variations; which facilitates the detection of underlying patterns and highlights soil quality gradients [22].

To identify structural relationships between topographical positions and their physicochemical properties, a correlation-based distance measure (cor.dist) is used to optimize the assessment of similarities and dissimilarities between study sites [23].

The hierarchical clustering algorithm (hclust) is then used to group localities and variables based on their statistical proximities. This method visualizes the data structure in the form of dendrograms, facilitating the identification of natural clusters [24].

To enhance the interpretation of the results, colored annotations are added to the rows and columns of the heatmap to indicate the groups defined during the hierarchical clustering [25]. This approach facilitates the detection of associations between localities and soil properties based on fertility classes and interactions between variables.

Finally, the last heatmap simultaneously integrates hierarchical clusters and group annotations to provide a synthetic view of the identified environmental trends. This method is particularly effective in revealing complex relationships and hidden patterns in multivariate data, a key issue in environmental and agroecological studies [26]. All analyses are carried out using the pheatmap package, which allows joint clustering of rows (sites) and columns (variables) for optimal reading of the relationships between the different dimensions of the dataset.

3. Results

3.1. Study of floristic composition through toposequences and soil pits

A total of 22 dominant species were selected based on surveys conducted in the three toposequences studied. All abundant plant species were identified in the field.

3.2. Unifactorial analysis of correlations between bioindicator species and soil quality according to the Indicator Value Index (IndVal)

The correlation between indicators and soil quality is demonstrated by the ability of certain species to distinctly characterize soil conditions, according to their suitability level and the statistical significance of their IndVal. A summary analysis is illustrated in Table II.

3.2.1. Species strongly associated with high-quality or high-suitability soils

The analysis of Table II indicates that the species *Mallotus oppositifolius* and *Centrosema pubescens* have high IndVals (1.00 and 0.95, respectively) and very low p-values (0.001 and 0.005). These species exhibit characteristics favorable to soil fertility. In contrast, species such as *Chromolaena odorata* (IndVal = 0.88, $p = 0.043$), *Cecropia peltata* (IndVal = 0.87, $p = 0.029$), and *Funtumia africana* (IndVal = 0.86, $p = 0.036$) are found in groups corresponding to intermediate (or transitional) suitability soils, reflecting environments where soil degradation or improvement processes are in balance. They are indicators of moderately fertile soils, suggesting an efficient nutrient recycling capacity. These results suggest that these species are good bioindicators of favorable soils (often characterized by better structure, adequate fertility or optimized management practices) because their presence is strongly correlated with optimal soil conditions.

3.2.2. Species indicating low suitability or degraded soil quality

The species with high IndVal and significant p-values in this group are *Xylopia aethiopica* (IndVal = 1.00, p = 0.001) and *Usteria guineensis* (IndVal = 0.94, p = 0.005). Their presence is correlated with soils with low nutrient retention capacity, often associated with erosion processes and low organic matter. The species *Oplismenus hirtellus* (IndVal = 0.87, p = 0.050) is also significant for these poor soils, suggesting adaptation to low fertility conditions. These results indicate that the presence of these species suggests unfavorable soil conditions.

3.2.3. Non-significant species

Newbouldia laevis (IndVal = 0.84, p = 0.097) is known to occur on poor soils, but its statistical values suggest that it is not an exclusive bioindicator of soil degradation. For many other species, relatively high p-values (p > 0.05) indicate that their IndVal does not reliably distinguish soil quality. Their presence is less correlated with specific fertility gradients, suggesting that they are not good bioindicators of soil quality, even though they may be ecologically important in other contexts.

Table 2 Soil fertility indicators according to the Indicator Value Index (IndVal) and their statistical significance [F: frequencies of occurrence; A: relative abundances, P-value = Probability, Significance codes: 0 **** 0.001 *** 0.01 ** 0.05 * 0.1 ns 1

| Soil fertility group | F | A | Indicator species | IndVal | p-value |
|---|------|-----|--------------------------------|--------|---------------------|
| High, fit + poor, fit + average, fit | 100 | 29 | <i>Chromolaena odorata</i> | 0.88 | 0.043* |
| | 35 | 0.1 | <i>Cecropia peltata</i> | 0.87 | 0.029* |
| | 33 | 0.1 | <i>Funtumia africana</i> | 0.86 | 0.036* |
| High, unfit + low, unfit + medium, unfit | 33.3 | 0.1 | <i>Usteria guineensis</i> | 0.94 | 0.005** |
| Weak, unfit + poor, unfit + average, unfit | 33 | 20 | <i>Oplismenus hirtellus</i> | 0.87 | 0.050* |
| High, fit + low, fit + poor, fit + average, fit | 100 | 7 | <i>Mallotus oppositifolius</i> | 1.00 | 0.001*** |
| | | | <i>Centrosema pubescens</i> | 0.95 | 0.005** |
| High, unfit + low, unfit + poor, unfit + average, unfit | 33 | 0.2 | <i>Xylopia aethiopica</i> | 1.00 | 0.001*** |
| Other indicator species | 33 | 0.7 | <i>Amphimas pterocarpoides</i> | 0.84 | 0.093. |
| | 100 | 7 | <i>Aspilia africana</i> | 0.90 | 0.337 ^{ns} |
| | 70 | 20 | <i>Alchornea cordifolia</i> | 0.75 | 0.297 ^{ns} |
| | 100 | 29 | <i>Alchornea cordifolia2</i> | 0.71 | 0.310 ^{ns} |
| | 70 | 7 | <i>Panicum repens</i> | 0.75 | 0.299 ^{ns} |
| | 33 | 20 | <i>Macaranga heudelotii</i> | 0.82 | 0.092. |
| | 55 | 0.3 | <i>Microdesmis keayana</i> | 0.84 | 0.072. |
| | 33 | 0.1 | <i>Ouratea flava</i> | 0.82 | 0.126 ^{ns} |
| | 33,3 | 0.2 | <i>Myrianthus libericus</i> | 0.84 | 0.402 ^{ns} |
| | 33 | 0.1 | <i>Scleria depressa</i> | 0.81 | 0.143 ^{ns} |
| | 33.3 | 0.2 | <i>Morinda lucida</i> | 0.84 | 0.087 |
| | 33 | 0.7 | <i>Aspilia africana 2</i> | 0.84 | 0.408 ^{ns} |
| | 70 | 0.2 | <i>Streptogyna crinita</i> | 0.84 | 0.077 |
| | 33 | 0.2 | <i>Newbouldia laevis</i> | 0.84 | 0.097 |

3.3. Multivariate Analysis of Soil Properties Using Heatmaps and Hierarchical Clustering

3.3.1. Data Structuring and Ecological Interpretation

The hierarchical analysis shows an organization into three distinct groups (indicated by the grayscale color code) defining soil fertility gradients related to the distribution of plant species.

Group 1 (High Phosphorus Affinity and Fertile Soils)

Species such as *P. repens*, *A. africana*, *M. oppositifolius*, and *N. laevis* show a strong correlation with high P_2O_5 concentrations, as evidenced by the high intensity (bright red) areas in the heatmap. These species are characteristic of soils enriched in available phosphorus, generally associated with increased mineralization of organic matter and active nutrient turnover. It is worth highlighting the absence of *P. repens* and *N. laevis* among the bioindicator plants identified by the indicator value index (IndVal), while they are highlighted by the heatmap analysis.

Group 2 (Affinity with Moderately Fertile Soils)

A subgroup includes species such as *Chromolaena odorata*, *Macaranga heudelotii*, and *Centrosema pubescens*, which exhibit an intermediate relationship with CEC and organic matter. These species are often found in soils undergoing ecological transition, demonstrating moderate fertility and a partial balance between mineralization and nutrient storage.

Group 3 (Indicators of Poor and Degraded Soils)

The species *Xylopia aethiopica*, *Cecropia peltata*, *Funtumia africana*, and *Usteria guineensis* are strongly correlated with low CEC and OM values (deep blue areas). These species are indicators of heavily leached soils, with reduced nutrient retention capacity and lower biological activity. Their presence suggests environments subject to advanced erosion and degradation processes.

A grouping can be identified in which *Myrianthus libericus* and *Oplismenus hirtellus* show an affinity for soils rich in OM and CEC. These species are often present in soils with active organic dynamics, characterized by efficient retention of nutrient cations. *Ouratea flava*, on the other hand, is associated with more acidic soils, characterized by a lower availability of exchangeable bases. This species could thus be an indicator of soils subject to intense leaching processes, often associated with advanced degradation of chemical fertility in tropical soils. The presence of *Scleria depressa* in areas characterized by variable P_2O_5 contents suggests tolerance to contrasting edaphic conditions. The absence of a strictly linear relationship with phosphorus highlights the complexity of the interactions between vegetation and biogeochemical processes influencing P bioavailability in these ecosystems.

3.3.2. Correlations and Implications for Soil Quality

The interaction between physicochemical variables and bioindicator species highlights several ecological dynamics:

- Phosphorus (P_2O_5) is the most discriminating factor, strongly correlated with certain nitrophilous species such as *P. repens* and *Mallotus oppositifolius*, suggesting a direct relationship between P availability and plant structure.
- Organic matter (OM) and CEC play a central role in group differentiation, with a notable influence on the distribution of secondary forest species such as *Macaranga heudelotii* and *C. pubescens*.
- Low pH values are associated with pioneer and acid-tolerant species such as *X. aethiopica* and *C. peltata*, suggesting that acidity is a limiting factor in certain soil systems.

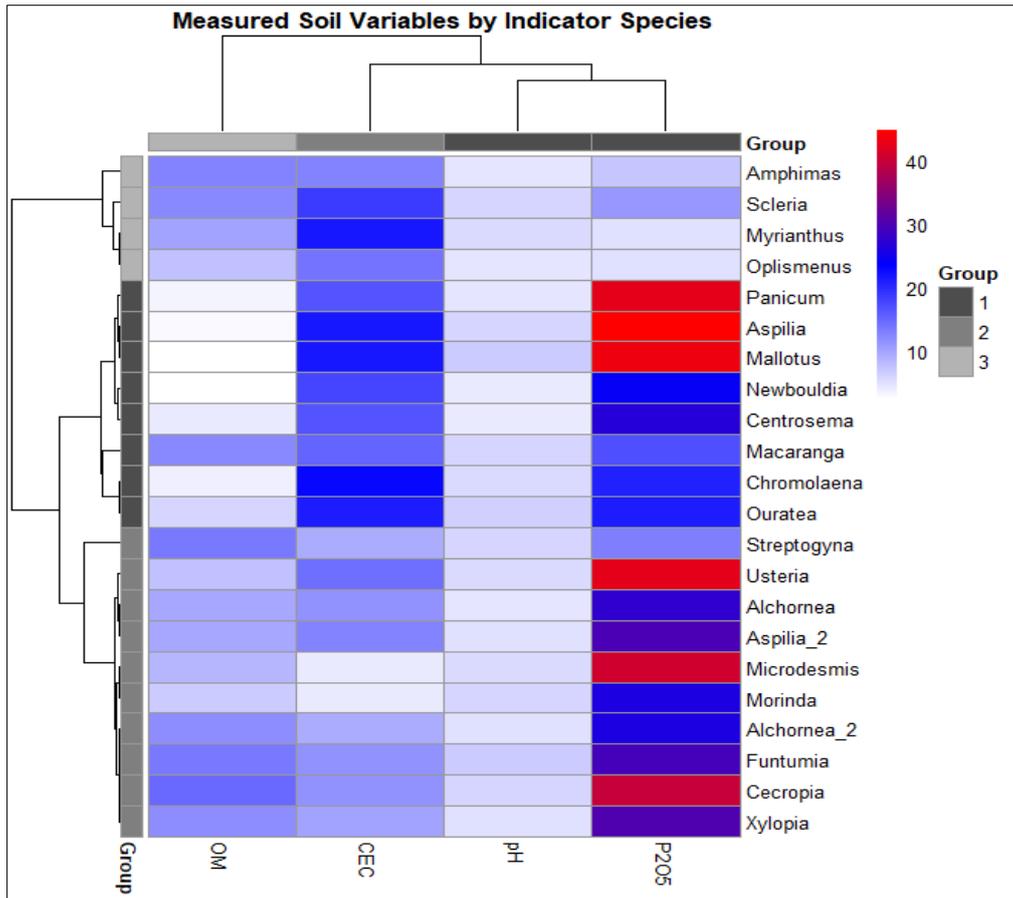


Figure 2 Heatmap and hierarchical clustering dendrogram depicting the grouping of edaphic variables with similar distribution patterns across plant species

The heatmap was generated using an optimized R script implementing the `cor2.dist` function, which utilizes the squared Pearson correlation coefficient (R^2) as a distance metric for hierarchical clustering. The color gradient represents the relative magnitude of each variable: blue indicates values below the mean, white corresponds to values near the mean, and red signifies values above the mean. Darker shades denote higher absolute values.

4. Discussion

Analysis of correlations between bioindicator species and soil quality, based on the Indicator Value Index (IndVal), highlights differential associations between floristic composition and soil characteristics. The results obtained confirm that some species are reliable markers of soil fertility conditions, while others reflect more constrained environments, characterized by lower nutrient availability and altered soil physicochemical properties. These observations corroborate the work of Dufrêne and Legendre [27], who initially developed the IndVal Index as a robust tool for identifying indicator species across environmental gradients.

Species such as *Mallotus oppositifolius* and *Centrosema pubescens* display high IndVal values, suggesting their strong affinity for soils with a stable structure and higher organic matter content. This correlation is in agreement with the work of De Cáceres and Legendre [18], who demonstrated the usefulness of IndVal to link the presence of plant species to specific edaphic conditions.

The absence of *P. repens* and *N. laevis* among the bioindicator plants identified by the indicator value index (IndVal), while they are highlighted by the heatmap analysis, is explained by the categorical nature of IndVal, which favors species strictly associated with a specific soil group. In contrast, multivariate analysis reveals ecological gradients and co-occurrences between plant communities and soil properties, thus highlighting more nuanced relationships. Therefore, *P. repens* and *N. laevis* can be considered as potential bioindicator species of soil quality, although their association is not exclusive enough to be detected by the IndVal approach alone.

Furthermore, the species *Chromolaena odorata*, *Cecropia peltata* and *Funtumia africana* are also associated with intermediate quality soils, demonstrating their role in the regeneration processes of disturbed soils [28]. On the other hand, some species, notably *Xylopia aethiopica* and *Usteria guineensis*, are strongly indicative of degraded soils, characterized by low nutrient retention capacity and increased susceptibility to erosion phenomena. These results are in line with the research of Barrios [29], who highlighted the importance of plant bioindicators in the assessment of tropical soil degradation. Furthermore, the presence of *Oplismenus hirtellus* in a constrained environment suggests tolerance to edaphic stress conditions, which corroborates the observations of Herrick et al. [30] on the use of indicator plants to characterize soil resilience to anthropogenic disturbances.

Other species, however, do not show a statistically significant correlation with soil quality gradients. *Newbouldia laevis*, although associated with poor soils, displays a relatively moderate IndVal value and a non-significant p-value, which limits its use as a reliable indicator. This lack of a strong relationship between some species and soil properties was also noted by Gillison and Brewer [31], who noted that some plants, although ecologically relevant, may not respond directly to the parameters measured in a quantitative assessment framework.

The observed discrepancies between indicator species can be attributed to the complex interactions between soil dynamics, cultivation practices and local microclimatic conditions. These results highlight the importance of continuing investigations on plant bioindicators to better understand their role in sustainable soil management and ecosystem conservation. In this context, the integration of complementary methods, such as the analysis of species functional diversity and spatial modeling of edaphic properties, could improve the accuracy of ecological diagnoses and guide restoration strategies for degraded soils.

Multivariate analysis of soil properties using heatmaps and hierarchical clustering highlights distinct groupings of indicator plant species according to topographic gradients and associated soil characteristics. These results suggest a determining influence of pedogenetic processes on species distribution, notably due to variations in soil fertility induced by differential erosion and nutrient redistribution. This spatial structuring was described by Borůvka et al. [32], who demonstrated that associations between plant composition and soil properties result from the superposition of natural and anthropogenic processes influencing nutrient dynamics.

Panicum repens, *Aspilia africana*, and *Mallotus oppositifolius* are predominantly found in soils characterized by very low OM content and moderate CEC. This distribution indicates rapid OM mineralization, leading to accelerated nutrient release, particularly phosphorus. These observations align with the work of Ryzhova et al. [33], who showed that in OM-poor soils, intensified biological activity promotes rapid decomposition and thus reduces the soil's capacity to store carbon and retain nutrients. Similarly, the findings of Garcia-Pausas and Paterson [34] indicate that accelerated OM cycling in these soils could be attributed to a dominance of microorganisms specialized in the rapid degradation of organic compounds.

The establishment of these species in the surface horizons (0-20 cm) reflects an active dynamic of decomposition and recycling of OM, characteristic of systems subject to frequent disturbances such as erosion and leaching. This dynamic is confirmed by the studies of Berhe et al. [35], who highlight that erosion accelerates the decomposition of organic matter by modifying its chemical and physical stability, and by Bonfanti et al. [36], who demonstrated that the surface soils of eroded areas present more intense biogeochemical cycles, favoring the rapid release of nutrients. Thus, these results highlight the importance of interactions between soil properties and indicator vegetation in understanding soil quality dynamics.

5. Conclusion

This study highlights the fundamental role of bioindicator plant species in assessing and monitoring soil quality. The integration of the Indicator Value Index (IndVal) and multivariate analyses identified specific associations between floristic composition and soil parameters, revealing structuring environmental gradients that influence plant species distribution. The results show that *Mallotus oppositifolius* and *Centrosema pubescens* are reliable indicators of soils rich in organic matter and with a high cation exchange capacity (CEC), reflecting a relatively stable ecosystem with nutrient retention dynamics favorable to fertility. In contrast, the presence of *Xylopia aethiopica*, *Cecropia peltata*, and *Usteria guineensis* indicates acidic and depleted soils, characterized by a low CEC and increased vulnerability to erosion and nutrient leaching. The integration of spatial models and functional diversity of bioindicator plants could improve the accuracy of ecological diagnoses and guide conservation and restoration strategies for degraded soils. Adapted management, integrating soil conservation and OM maintenance practices, could contribute to improving the resilience of these ecosystems in the face of environmental constraints and increasing anthropogenic pressures.

Compliance with ethical standards

Disclosure of conflict of interest

There are no conflicts of interest.

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