

Evaluation and diagnosis of the rice-growing potential of the Pronou and Bodokro lowlands (Central Côte d'Ivoire): A multi-criteria approach based on the physico-chemical properties of the soil

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Abstract

In Côte d'Ivoire, the underutilization of lowland rice-growing areas stems from limited knowledge of their agronomic potential, often assessed uniformly without considering their soil heterogeneity. This study aimed to develop an integrated and spatially differentiated method for evaluating rice-growing potential, based on the physicochemical properties of the soil, in order to formulate appropriate management recommendations. A multi-criteria approach was implemented through detailed soil characterization (texture, pH, phosphorus, drainage) at two contrasting sites (Pronou and Bodokro). It utilized soil analyses, fertility indices (physical fertility index, corrected acidity index, rice-growing potential index), and multivariate statistical tools, with a view to the sustainable intensification of rice cultivation. The results reveal that the Pronou site has a very high overall rice-growing potential (mean IPR = 78.6), with homogeneous, well-drained clay soils and an optimal pH. In contrast, Bodokro, which is more heterogeneous, has a medium to low potential (mean IPR = 63.2), characterized by acidic, sandy soils and drainage constraints. This analysis identified four classes of agronomic potential (very high to low) through a functional typology validated by PCA and CHA. The regression model explains 89.3% of the variance in rice-growing potential with a correct classification rate of 94.8%, thus confirming the robustness of the approach. These results demonstrate that this method allows for the differentiation of lowland management strategies based on their actual potential, optimizing inputs, investments, and farming practices. It therefore constitutes a decision-making tool for policies aimed at developing rice-growing land.

Keywords: Rice-growing potential; Lowlands; Multi-criteria assessment; Soil typology; Composite indices; Multivariate analysis; Ivory Coast

1. Introduction

In Côte d'Ivoire, rice is the third most consumed cereal after yams and cassava (Ngaresseum, 2010; Ouédraogo *et al.*, 2021). Its cultivation is a major strategic issue for food security (Kouassi *et al.*, 2023). Despite the existence of vast lowland areas estimated at over 1.2 million hectares (Souberou *et al.*, 2016; DGE, 2018), national rice productivity remains well below its theoretical potential, fluctuating around 2.5 t/ha compared to 6-8 t/ha in optimized systems (MINADER, 2020). This chronic under-exploitation of lowland ecosystems is mainly due to a lack of detailed knowledge of the agronomic potential of the soils, which are often assessed in a uniform manner without consideration of their intrinsic pedological heterogeneity (Samlaba, 2001; Worou, 2003).

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Conventional approaches to rice-growing land assessment, based on generic criteria and point observations, prove inadequate for capturing the spatial and temporal complexity of lowland soil systems (Becker and Johnson, 2001). This methodological gap leads to poorly differentiated management strategies, resulting in suboptimal investments and disappointing yields (Windmeijer and Andriessse, 1993). Faced with these challenges, research proposes a scientific method for optimizing national rice production. This major sustainable development issue reconciles economic imperatives (reduced imports, food security), methodological innovation (multi-criteria composite indices), and the environmental preservation of lowland ecosystems.

The scientific question to be addressed therefore concerns the precise evaluation of the agronomic potential of soils, which is an essential prerequisite for any coherent and sustainable management strategy for lowland ecosystems (FAO, 2007; Pretty et al., 2011). The objective of this study is to develop an integrated and spatially differentiated method for evaluating the rice-growing potential of lowland areas, based on a multi-criteria approach that utilizes the physico-chemical properties of the soil.

This approach aims to formulate targeted and optimized land management recommendations, enabling the rational use of rice-growing land. To this end, a detailed soil characterization was carried out on two contrasting sites in the central region of Côte d'Ivoire: Pronou and Bodokro, to identify functional soil typologies and predictively model rice-growing potential. The results of this research will contribute to advancing knowledge in soil science applied to Ivorian rice cultivation.

2. Materials and methods

2.1. Study Sites

This study was conducted in the Gbêkè region (North-Central Côte d'Ivoire), approximately 330 km north of Abidjan. Its geographical area extends between the 6th and 8th parallels of north latitude. The investigations focused on two representative sites of the lowlands in this region: Pronou (5°18'00" and 5°12'00" west longitude, and between 7°18'00" and 7°24'00" north latitude), located in the sub-prefecture of Bocanda, while Bodokro (5°48'00"-5°42'00"W, and 7°48'00"-7°54'00"N), falls within the department of Béoumi.

The choice of these two sites is based on their contrasting soil characteristics, their accessibility, their representativeness of the region's geological and edaphic units, their strong agroecological representativeness, and their potential use for lowland rainfed rice cultivation. They thus constitute relevant sites for assessing the rice-growing potential of lowland areas in the humid Sudanian zone.

2.2. Methods

2.2.1. Sampling device and soil description

No cultivation treatments were applied. The study focused exclusively on the agropedological characterization of the lowlands through systematic soil sampling. Samples were taken during the dry season, at the scale of the morphopedological unit, from the surface horizon (0-20 cm), considered the most representative of root processes and nutritional dynamics for rice (*Oryza sativa* L.). Sampling was carried out using a regular staggered grid, with a density varying from 8 to 12 samples/ha depending on the apparent heterogeneity of the soil facies. Each composite sample was obtained by homogenizing five subsamples collected in a cross pattern over a 25 m² area.

2.2.2. Physico-chemical analyses

Physico-chemical analyses were performed on 63 composite samples from the target horizon. They were carried out at the Laboratory for the Analysis of Plants and Soils (LAVESO) of the Félix Houphouët-Boigny National Polytechnic Institute of Yamoussoukro (Table 1).

Table 1 Soil physico-chemical parameters and methods of determination

Setting	Method of determination
pH (H ₂ O) (soil:water = 1:2.5)	Glass electrode pH meter (Diack and Loum, 2014)
Organic carbon (C)	Walkley and Black method (Hilhorst and Balendonck, 1999)
Organic matter (OM)	Calculated using the formula: MO = 1.72 × C
Total nitrogen (Nt)	Modified Kjeldahl method (Diack and Loum, 2014)
Assimilable phosphorus (Assimilable P)	Modified Olsen method (Hilhorst and Balendonck, 1999)
Calcium (Ca ²⁺)	Atomic absorption spectrometry (Pansu and Gautheyrou, 2003)
Magnesium (Mg ²⁺)	
Potassium (K ⁺)	
Sodium (Na ⁺)	
Sum of exchangeable bases (SBE)	$SBE = Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}$
Base saturation rate (V)	$V = SBE / CEC$
Cation exchange capacity (CEC)	Modified Kjeldahl method (Diack and Loum, 2014)
Iron (Fe ²⁺)	Mass spectrometry (Lund et al., 1999)
Copper (Cu ²⁺)	
Manganese (Mn ³⁺)	
Zinc (Zn ³⁺)	
Sand	Particle size analysis using a Robinson pipette (Douzals, 2000)
Silt	
Clay	

2.2.3. Analysis of potential agronomic of the lowland soils

Rice Potential Index (RPI)

The assessment of agronomic potential was conducted using a composite fertility index, developed according to a multi-criteria approach inspired by the FAO assessment framework (1976) and the recommendations of Sys et al. (1993) for rice cultivation in hydromorphic environments. Four major components were selected:

- Soil texture (30%): favouring clay-loam soils which are favorable to water retention ;
- Acid-base status (25%): based on the optimal pH values for rice cultivation (5.5-6.5) ;
- Drainage conditions (25%): differentiating between hydromorphic, intermediate and well-drained positions;
- Topographic position (20%): integrating the upstream, middle and downstream positions of the toposequence.

A weighted score out of 100 was assigned to each site based on the agronomic thresholds selected for each parameter. The classification of rice-growing potential was established as follows:

- Very high (≥ 80 points): optimal soils for intensive rice cultivation;
- High (60–79 points): favorable soils with minor constraints;
- Medium (40–59 points): moderately favorable soils requiring amendments;
- Low (20–39 points): soils with major constraints;
- Very low (< 20 points): soils unsuitable for rice cultivation.

This quantitative approach allows for an objective ranking of spatial units, with a view to differentiated recommendations regarding hydro-agricultural development.

2.3. Statistical processing and multivariate analyses

2.3.1. Analysis of variance and multivariate tests

The data were subjected to two-way analyses of variance (ANOVA) to evaluate the effect of the factors Locality (Bodokro vs. Pronou) and Topographic Position (Upstream, Middle, Downstream) on each physicochemical parameter. The statistical models used follow the form:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \epsilon_{ijkl}$$

where: Y_{ijkl} represents the dependent variable (pH, texture, etc.), μ is the overall mean, α_i is the effect of locality i , β_j is the effect of topographic position j , $(\alpha\beta)_{ij}$ is the interaction between locality and position, and ϵ_{ijkl} is the residual error

A multivariate analysis of variance (ANOVA) was conducted to simultaneously test the effect of the factors on all physicochemical variables: [water pH, KCl pH, clay, silt, sand, pH Δ , texture sum] ~ Locality + Position + Locality: Position

2.3.2. Analysis according to effect sizes

Effect sizes were quantified by calculating the eta-squared (η^2) according to Cohen (1988), using the effectsize package in R. The eta-squared represents the proportion of variance explained by each factor according to the formula: $\eta^2 = SS_{\text{effect}} / SS_{\text{total}}$

with SS_{effect} : sum of squares explained by the factor (Locality, Position, or their interaction), SS_{total} : total sum of squares (includes effects and residual error). The value of η^2 varies between 0 and 1. The interpretation thresholds used are:

- Small effect: $\eta^2 \approx 0.01$ (1% of variance explained)
- Average effect: $\eta^2 \approx 0.06$ (6% of variance explained)
- Strong effect: $\eta^2 \approx 0.14$ (14% of variance explained)

2.3.3. Exploratory multivariate analyses

The data were analyzed using principal component analysis (PCA) to identify dominant axes of soil variation and correlations between variables. A hierarchical ascending classification (HAC) was then applied to the factorial coordinates to establish a functional typology of soils, linked to their suitability for rice cultivation.

2.3.4. Composite Fertility Indices

Secondary indices were calculated to synthesize the soil information:

Physical Fertility Index (PFI): $PFI = (\text{Clay} \times 0.4) + (\text{Silt} \times 0.3) + ((100 - \text{Sands}) \times 0.3)$

Corrected Acidity Index (CAI): $CAI = 100 - |\text{optimal pH} - \text{measured pH}| \times 20$, with optimal pH = 6.0 for irrigated rice cultivation

Rice Potential Index (IPR): $IPR = (\text{IFP} \times 0.40) + (\text{IAC} \times 0.30) + (\text{Drainage Score} \times 0.30)$

2.3.5. Analysis of spatial variability

Intra-site and inter-site variability was quantified by calculating the coefficients of variation (CV) for each parameter: $CV = (\sigma / \mu) \times 100$

The selected variability classes are:

- Low variability: $CV < 15\%$
- Moderate variability: $15\% \leq CV < 35\%$
- High variability: $CV \geq 35\%$

This approach makes it possible to identify the most discriminating parameters for the characterization of soil units and the evaluation of their rice-growing potential.

2.3.6. Statistical validation and robustness tests

The normality of the residuals was verified using the Shapiro-Wilk test, and homoscedasticity using the Levene test. In cases where the conditions for applying ANOVA were not met, logarithmic transformations or non-parametric tests (Kruskal-Wallis) were applied. Statistical analyses were performed using R version 4.4.3, with the packages stats, effectsize, FactoMineR, and cluster. The significance level was set at $\alpha = 0.05$ for all statistical tests.

3. Results

3.1. Analysis of the soil distributions of the lowlands

3.1.1. Acid-base status of soils

The results (Figure 1) show that the soils of the Pronou lowlands exhibit greater chemical homogeneity, with an optimized mean pH (6.5 ± 0.4). Conversely, the soils of the Bodokro lowlands show a more variable pH (5.0 to 7.0) and a bimodal distribution. Analysis of variance indicates that the "Location" factor significantly influences pH ($p = 0.004$). In contrast, neither topographic position ($p = 0.276$) nor its interaction with location ($p = 0.127$) has a significant effect. In other words, intra-site variations are less pronounced than those observed between the two sites.

The corrected acidity index (CAI) reinforces this differentiation: the average value observed at Pronou (88.3) appears to be close chemically to the optimum, reflecting an agronomic requirement for rice cultivation, while that measured at Bodokro (76.4) reflects greater chemical instability and a distance from the optimal threshold, with potential consequences for nutrient bioavailability and crop productivity.

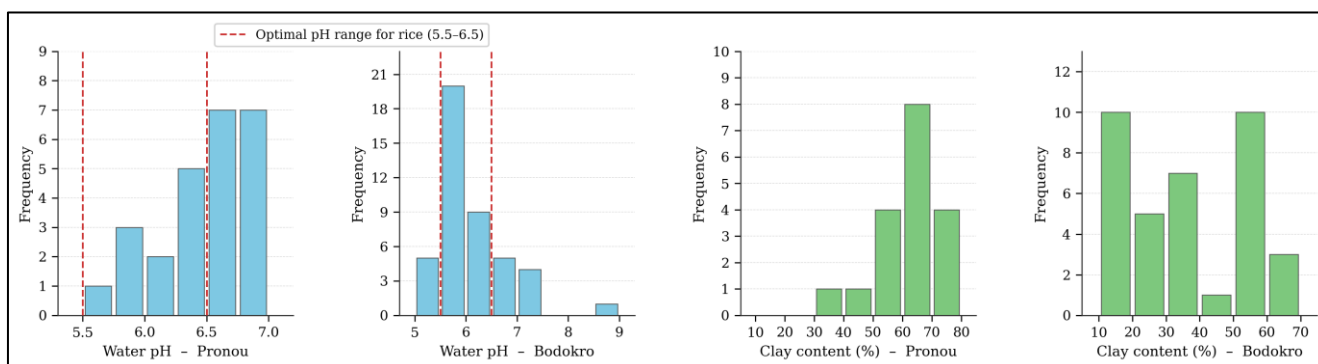


Figure 1 Histograms of the distribution of acid-base status and clay in the Pronou lowlands and Bodokro lowlands. Left panels (blue): water pH at Pronou (unimodal, mean 6.5 ± 0.4) and Bodokro (bimodal, range 5.0-7.0). Right panels (green): clay content (%) at Pronou (dominant fraction 60-80%) and Bodokro (trimodal distribution, 10-70%). Red dashed lines indicate the optimal pH range for irrigated rice cultivation (5.5-6.5). $n = 63$ composite samples (Pronou: $n = 18$; Bodokro: $n = 35$)

3.1.2. Organic and nutritional status

The soils of Pronou (Figure 2) are distinguished by high natural fertility (CEC of 30-40), a high organic matter (OM) content of 3-4%, and total nitrogen (N) of 0.25-0.30%, with good OM stability (C/N ratio balanced between 10 and 12). In contrast, available phosphorus remains moderate (5-10 ppm). At Bodokro, the lowland soils are characterized by more heterogeneous fertility, with a more moderate OM content (1.5-2.0%) and rapid mineralization (C/N ratio varying between 6 and 8). Phosphorus is generally low to medium, and the CEC is more variable (0-20).

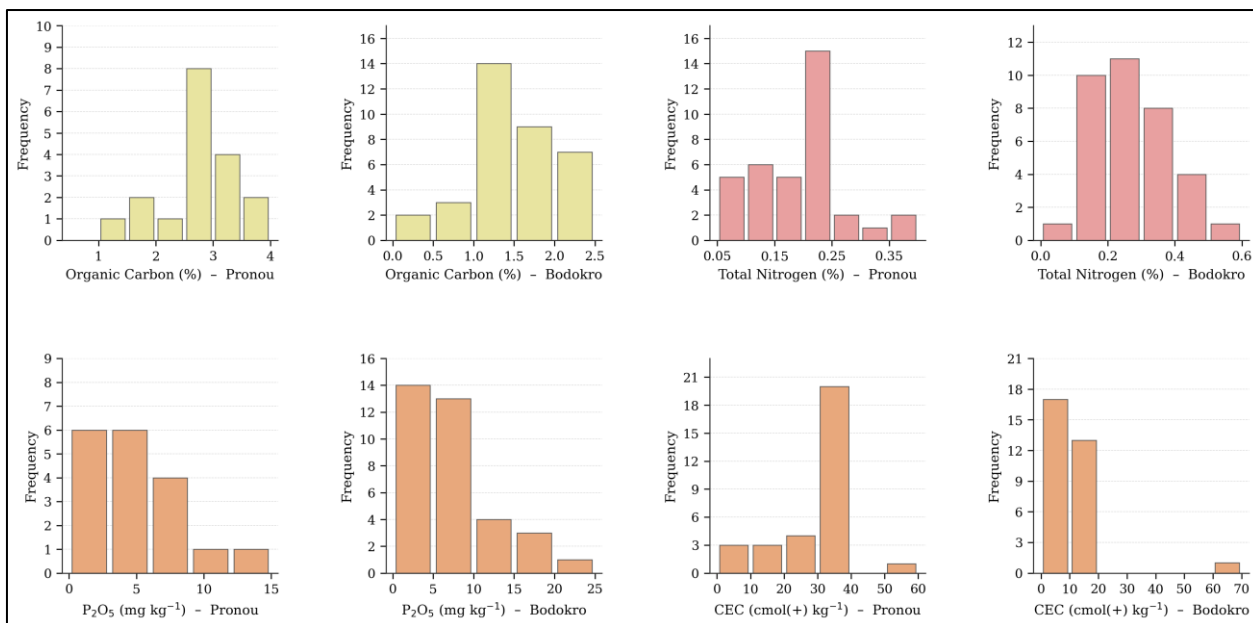


Figure 2 Histograms of the distribution of organic and nutritional status in the Pronou lowlands and Bodokro lowlands. Upper row (cream/pink): organic carbon (%) and total nitrogen (%) for Pronou and Bodokro. Lower row (salmon): available phosphorus P₂O₅ (mg kg⁻¹) and cation exchange capacity CEC (cmol(+) kg⁻¹) for Pronou and Bodokro. Pronou soils are characterised by higher and more uniform organic carbon (2.5-4.0%), nitrogen (0.20–0.30%), and CEC (30-40 cmol(+) kg⁻¹) relative to Bodokro (organic carbon 1.0-2.5%; CEC 0-20 cmol(+) kg⁻¹). n = 63 composite samples

3.1.3. Textural contrast between the two sites

Analysis of variance (Table 2) reveals that the silty fractions are significantly influenced by location (p = 0.008), topographic position (p = 0.0002), and their interaction (p = 0.001). For the sandy fraction, only location has a significant effect (p = 0.012), while position and its interaction with location are not significant. For the clayey fraction, the effect of location is highly significant (p < 0.001), indicating a clear difference between Bodokro and Pronou. Topographic position also has a significant effect (p = 0.015), reflecting a vertical structuring of the textural profile, while the Location × Position interaction is not significant: the position is relatively similar between the two sites.

Table 2 Comparison of the major textural properties of the sampled lowlands according to locality and topographic position (± standard deviation)

Position	Bodokro (± sd) (%)			Pronou (± sd) (%)		
	Clay	Silt	Sand	Clay	Silt	Sand
Upstream	26.3 ± 8.86	47.7 ± 6.52	24.1 ± 9.22	53.0 ± 25.5	30.3 ± 10.6	14.6 ± 21.0
Medium	41.4 ± 20.8	30.7 ± 7.13	24.4 ± 16.5	54.2 ± 23.1	32.9 ± 10.7	11.3 ± 13.6
Downstream	50.8 ± 9.83	33.5 ± 6.43	13.1 ± 5.34	57.8 ± 21.9	30.6 ± 11.5	9.51 ± 12.1

sd: standard deviation.

At Pronou, 78% of the samples studied exhibit a "Clay" texture (Table 3) . Conversely, at Bodokro, the textures are more diverse, with a trimodal distribution: "Clay" (34%), "Clay-loam" (31%), and "Silty-sandy" (20%). This textural dichotomy illustrates the contrast between the uniformity of the soils at Pronou and the marked heterogeneity of those at Bodokro.

Table 3 Distribution of soil textural classes in the localities of Bodokro and Pronou.

soil texture	Bodokro	Pronou
Clayey	34.29	77.78
Clay-loam	31.43	0.00
Silty	11.43	11.11
Silty-clay	2.86	0.00
Silty-sandy	20.00	11.11

3.2. Variability of edaphic indicators according to localities and topographic positions

3.2.1. Physical Fertility Index

A Pronou l' The Physical Fertility Index (PFI) had a mean value of 72.8 ± 12.4 , significantly higher than that of Bodokro (58.3 ± 15.7 , $p < 0.001$). These results confirm the advantage of homogeneous clay textures for water and nutrient retention.

3.2.2. Rice potential index

The IPR, which incorporates physical fertility (40%), corrected acidity (30%), and drainage conditions (30%), constitutes a comprehensive indicator of agronomic potential. Pronou displayed a mean IPR of 78.6 ± 8.9 , a highly significant difference ($p < 0.001$), compared to 63.2 ± 14.3 for Bodokro.

3.2.3. Effect of location

Analysis of variance revealed that the localities of Bodokro and Pronou exert a structuring effect on several edaphic variables essential to agricultural productivity, with effect sizes often large ($\eta^2 > 0.14$). This geographical differentiation reflects distinct soil dynamics. These differences are detailed in Table 4, with the corresponding effect sizes (η^2):

Table 4 Summary of discriminating edaphic parameters between Bodokro and Pronou

Variable	p-value	η^2	Intensity of the effect
Total nitrogen	0.016	0.119	AVERAGE
Organic carbon	0.00	0.579	Strong
pH in water	0.004	0.165	Strong
pH KCl	0.005	0.162	Strong
Cation exchange capacity (CEC)	0.00	0.340	Strong
Exchangeable bases (SB)	0.00	0.340	Strong
Sand content (Sands)	0.004	0.168	Strong
Silt content (Silt)	0.0028	0.178	Strong
Clay content (Clay)	0.0007	0.222	Strong
Exchangeable calcium (Ca^{2+})	0.0000	0.508	Strong
Exchangeable magnesium (Mg^{2+})	0.0000	0.513	Strong

3.2.4. Effect of topographic position

Analysis of variance highlights the crucial role of terrain morphology in soil textural differentiation. The topographic effect on soil texture cannot be overlooked in agroecological assessments. The structuring effect of topographic position on soil texture at the landscape scale is summarized in Table 5).

Table 5 Summary of discriminating edaphic parameters according to topography

Variable	p-value	η^2	Intensity of the effect
Sand (%)	0.0244	0.149	Strong
Silt (%)	0.0004	0.288	Strong
Clay (%)	0.0178	0.161	Strong

3.2.5. Effects of interaction between locality and topographic position on edaphic properties

Analysis of variance reveals that the effect of topographic position varies according to locality, and vice versa. Two key variables (silt content and ΔpH) show statistically significant interactions. with large effect sizes (Table 6).

Table 6 Summary of edaphic parameters with significant locality \times topographic position interaction effects

Variable	p-value	η^2	Intensity of the interaction
Silt (%)	0.0063	0.198	Marked interaction
ΔpH (pH water – pH KCl)	0.0030	0.224	Marked interaction

3.3. Multivariate analysis and structuring of soil data

3.3.1. Hierarchical classification and soil typology

Principal component analysis (Figure 3) reveals a more balanced structuring of the Pronou site (cumulative variance: 71%), while Bodokro shows a more dispersed variance (55.8%). With a slight dominance of cluster 1 (52%), followed by cluster 2 (48%) and a marginal representation of cluster 3 (19%), the Pronou lowlands indicate moderate soil variability. As for the Bodokro site, spatial heterogeneity is pronounced, with dominant areas of high fertility but also sectors with localized constraints, with a marked concentration in cluster 1 (72%), a reduced concentration in cluster 2 (26%), and a marginal concentration in cluster 3 (3%).

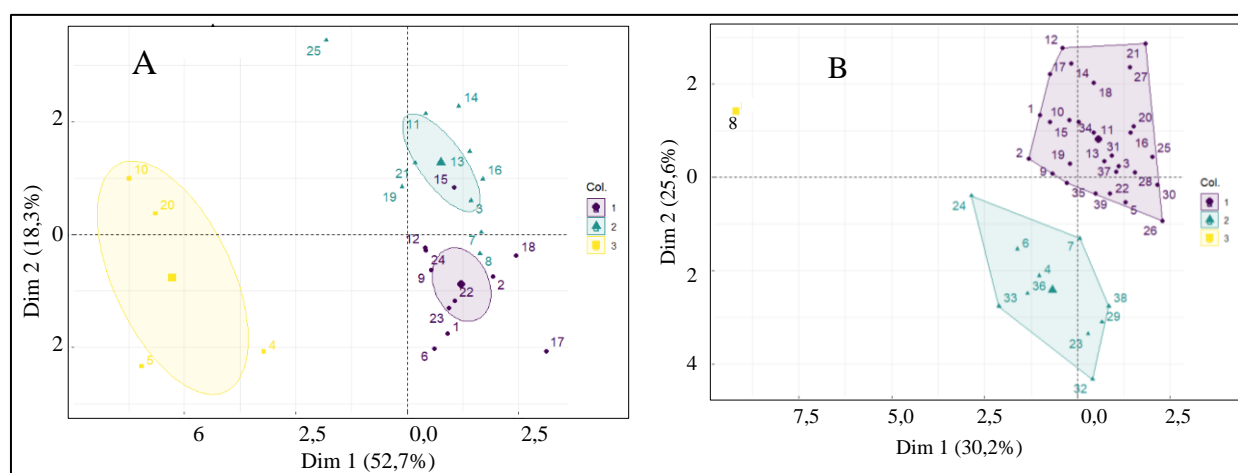


Figure 3 Diagram of the Principal Component Analysis, morphopedological classification and agronomic potential of the lowland soils of Pronou (A) and Bodokro (B)

3.3.2. Analysis of the morphopedological classification of soils

Cluster 1 comprises the most fertile soils, rich in nitrogen (0.18-0.38%), organic carbon (>1.5%), and exchangeable bases (>8 meq/100g), primarily located upstream and downstream, with medium to high rice-growing potential in 79% of cases. Cluster 2, located in mid- and downstream positions, is distinguished by intermediate fertility, with moderate nitrogen (0.08–0.21%) and carbon (<1.4%) content, associated with low exchangeable base reserves (<6 meq/100g), which limits its rice-growing potential. Cluster 3, concentrated upstream and in mid-water positions, comprises the most degraded soils, characterized by severe nutrient depletion (N = 0.11%, C = 0.36%, available P = 1 mg/kg), resulting in a uniformly low rice-growing potential (Table 7).

Table 7 Detailed edaphic characteristics by cluster

Setting	Cluster 1	Cluster 2	Cluster 3
Fertility index	Optimized	Intermediate	-1.68
Total nitrogen (%)	0.18 - 0.38	0.08 - 0.21	0.11
Organic carbon (%)	> 1.5	< 1.4	0.36
SBE (meq/100g)	> 8	< 6 (generally)	Very low
Absorbable phosphorus (mg/kg)	3-22	1 - 10	1
Topographic position	Upstream and downstream	Median and downstream	Upstream and mid-level
Low potential	21% soils	100% soils	100% soil
Average potential	43% soils	0 soil	0 soil
High potential	36% soils	0 soil	0 soil

3.4. Comparative evaluation of soil functional characteristics

The functional assessment (Table 8) reveals that Pronou exhibits edaphic characteristics exceeding established critical thresholds for high cation exchange capacity (30-40 cmol(+)/kg), optimal organic matter stock (>3.0%), and nitrogen content (>0.2%). The balanced C/N ratio (10-12) indicates optimal organic matter mineralization, despite moderate phosphate availability (5-10 ppm). Conversely, Bodokro displays nutritional constraints, with limited cation exchange capacity (0-20 cmol(+)/kg), intermediate organic matter stock (1.5-2.0%), accelerated mineralization (C/N of 6-8), and generally deficient phosphate availability.

This comparative analysis confirms the superior agronomic potential of Pronou, characterized by high and homogeneous fertility which contrasts with the functional heterogeneity of Bodokro whose lowlands require differentiated interventions.

Table 8 Strategic diagnosis – Constraints, strengths and priorities according to Landon's frameworks (1991)

Edaphic parameter	Critical threshold	Pronou	Bodokro
CEC (cmol(+)/kg)	> 15	30-40	0 - 20
Organic matter (%)	> 2.0	> 3.0	1.5 - 2.0
Total nitrogen (%)	> 0.15	> 0.2	Variable
C/N ratio	8-15	10-12	6-8
Available phosphorus (ppm)	10-15	5-10	Generally < 10
Overall rating	-	High fertility	Heterogeneous fertility

4. Discussion

4.1. Spatial differentiation of the acid-base properties of shallow waters

Analysis of the acid-base status reveals a marked difference between the two study sites, with greater chemical homogeneity at Pronou (mean pH: 6.5 ± 0.4) compared to the variability at Bodokro (pH: 5.0 to 7.0). These results corroborate the observations of Landon (1991), which highlight the influence of local pedoclimatic conditions on the pH stability of tropical soils. The corrected acidity index (CAI) of Pronou (88.3) indicates close proximity to the agronomic optimum required for rice cultivation, while that of Bodokro (76.4) reflects more pronounced chemical instability, consistent with the work of Raunet (1984) on lowland soils in Côte d'Ivoire.

The significant effect of the "Location" factor on pH ($p = 0.004$) confirms the importance of intrinsic site characteristics in regulating acidity, thus aligning with the findings of Teferi et al. (2016), who demonstrated the predominant influence

of geomorphology on the chemical properties of lowland soils. The lack of a significant effect of topographic position contrasts with some studies (Miheretu and Yimer, 2018), but can be explained by the hydromorphic specificity of lowlands, where water redistribution processes attenuate classic topographic gradients.

4.2. Textural heterogeneity and agronomic implications

The textural dichotomy observed between Pronou (78% clay soils) and Bodokro (trimodal distribution) illustrates contrasting pedogenetic processes. This textural uniformity of Pronou, promoting superior water and nutrient retention capacity, results in a significantly higher physical fertility index (PFI) (72.8 ± 12.4 vs. 58.3 ± 15.7). These results are consistent with the work of Becker and Johnson (2001), who associate homogeneous clay textures with optimal rice-growing potential in humid tropical zones.

The textural heterogeneity of Bodokro, characterized by the coexistence of clayey (34%), clayey-silty (31%), and silty-sandy (20%) textures, reflects a complex sedimentary dynamic typical of lowland areas with contrasting geomorphology (Windmeijer and Andriessse, 1993). This spatial variability necessitates a differentiated approach to rice management, in accordance with the recommendations of Audebert et al. (2000) and Adoukpe et al. (2021) for the optimization of lowland rice systems.

4.3. Multivariate structuring and soil typology

Principal component analysis reveals contrasting spatial distribution patterns, with a more balanced cumulative variance at Pronou (71%) than at Bodokro (55.8%). This differentiation confirms the hypothesis of greater soil stability at Pronou, facilitating consistent management of farming practices. The cluster distribution at Bodokro, with a marked concentration in cluster 1 (72%), reflects a pronounced spatial heterogeneity characteristic of lowlands with differentiated soil evolution (Raunet, 1985). The established typology reveals a decreasing fertility gradient from cluster 1 (optimized fertility) to cluster 3 (severe constraints). This structure aligns with the observations of Keita *et al.* (2013) on the intrinsic variability of tropical lowland soils, where hydromorphic processes and nutrient redistribution generate complex soil mosaics.

4.4. Implications for rice farming management

The Rice Potential Index (RPI) confirms the agronomic superiority of Pronou (78.6 ± 8.9) over Bodokro (63.2 ± 14.3). These findings justify differentiated management strategies. For Pronou, the homogeneity of its soil properties allows for direct rice intensification, while Bodokro requires a zonal approach adapted to its significant spatial heterogeneity. These results align with the recommendations of Segda et al. (2004) for differentiated management of lowland areas according to their agronomic potential. The widespread phosphate deficiency observed at both sites (5–10 ppm at Pronou, <10 ppm at Bodokro) constitutes a major constraint requiring appropriate phosphate inputs, in accordance with the recommendations of Sahrawat et al. (2010) for tropical rice soils. This nutritional limitation, common to the ferrallitic soils of the studied climatic zone, requires a phosphate fertilization strategy prior to any sustainable rice intensification.

5. Conclusion

This comparative study of the soil properties of the Pronou and Bodokro lowlands has allowed for the characterization of two distinct soil models with major agronomic implications for the sustainable development of rice cultivation in central Côte d'Ivoire. Multifactorial analysis reveals a significant spatial differentiation between the sites. Pronou exhibits remarkable soil homogeneity characterized by a stable pH, a predominantly clayey texture, and a high rice-growing potential index. Bodokro, on the other hand, is distinguished by strong spatial heterogeneity marked by significant pH variability, a trimodal textural distribution, and a more moderate agronomic potential. This soil dichotomy, confirmed by principal component analysis and cluster typology, reflects contrasting pedogenetic processes directly linked to local geomorphological and hydroclimatic conditions.

The remarkable homogeneity of Pronou, reflected in its optimal corrected acidity index and superior physical fertility index, gives this site a comparative advantage for direct rice intensification with uniform cultivation practices. Conversely, Bodokro, illustrated, absolutely requires a differentiated management approach that takes into account its complex soil mosaic. This spatial differentiation necessitates management strategies adapted to the intrinsic specificities of each identified soil unit.

However, beyond these contrasts, the widespread phosphate deficiency observed at both sites constitutes a major shared nutritional constraint. This limitation necessitates a prior and tailored phosphate fertilization strategy as an

essential prerequisite for any sustainable rice intensification. This differentiated approach, integrating spatial specificities and common constraints, paves the way for a more efficient and sustainable use of these ecosystems, which are strategic for food security in Côte d'Ivoire, while respecting their ecological integrity and intrinsic agronomic potential.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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