Journal of Agricultural Chemistry and Environment, 2026, 15(3), 297-322
https://www.scirp.org/journal/jacen
ISSN Online: 2325-744X
ISSN Print: 2325-7458

Agronomic Potential of First-Order Inland Valleys for Rice Production under Climatic Variability in Pronou, Central Côte d'Ivoire

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How to cite this paper: Pitta, A.M.C., Bolou-Bi, B.E., Sehi, Z., Guety, T.P. and Kone, B. (2026) Agronomic Potential of First-Order Inland Valleys for Rice Production under Climatic Variability in Pronou, Central Côte d'Ivoire. *Journal of Agricultural Chemistry and Environment*, **15**, 297-322.
https://doi.org/10.4236/jacen.2026.153016

Received: April 10, 2026
Accepted: July 26, 2026
Published: July 29, 2026

Abstract

This study was carried out in the first-order inland valleys of Pronou, Gbêkê region, central Côte d'Ivoire. It investigated the agronomic potential of these ecosystems for optimized rice production under conditions of interannual climatic variability. For the first time in this production system, a prospective modeling approach was adopted using the APSIMX R package interface, within which crop yields were simulated via a process-informed empirical model calibrated against published dose-response relationships for improved inland valley rice varieties in West Africa. This integrative framework combined soil physico-chemical, hydrological, and climatic data (2020-2023) with three rice varieties: NERICA-L19, WAB 56-50, and a local ecotype, simulated under six nitrogen application rates (0, 40, 80, 120, 160, 200 kg N/ha) across three topographic positions. Results demonstrated consistent agronomic stability of the studied inland valleys (feasibility indices ≥ 0.80) despite interannual climatic fluctuations. The optimal planting window spanned April to June, with yield potential peaking in May for all tested varieties. Among the tested varieties, NERICA-L19 consistently outperformed WAB 56-50 and the local ecotype, with predicted yields reaching 6860 kg/ha at 200 kg N/ha and a nitrogen use efficiency exceeding that of the local variety by 18%. Nitrogen fertilization exerted significant and dose-dependent effects on grain yield, predominantly during the climatically favorable period ($p < 0.01$). A multiple linear regression model ($R^2 = 0.87$; $F = 62.4$; $p < 0.001$) corroborated the superiority of an integrated management strategy combining optimized variety selection, sowing date adjustment, and calibrated nitrogen fertilization. At the recommended rate of 200 kg N/ha, net economic benefits reached 2,174,000 FCFA/ha for NERICA-L19, with a negligible risk of economic loss across all simulated price and yield scenarios. These results provide a robust, evidence-based framework for adaptive nitrogen management in first-order inland valley rice systems, with direct implications for enhancing the resilience and sustainability of smallholder rice production under increasing climatic variability in West Africa.

Keywords

Inland Valley Agroecology, Climatic Variability, Empirical Yield Modeling, Nitrogen Management, Resilient Rice Systems, Côte d'Ivoire

1. Introduction

Rice (*Oryza sativa* L.) constitutes the most widely consumed cereal staple globally, cultivated across more than 100 countries and providing the primary caloric intake for over three billion people, with dietary significance across Asia and Sub-Saharan Africa [1]. Global production remains heavily concentrated in Asian countries, which account for approximately 90% of total output and 85% of cultivated area [1]. Against this backdrop, Sub-Saharan Africa faces a deepening structural food dependency: according to OECD-FAO projections for the 2024-2033 agricultural outlook, Africa is projected to account for 41% of global rice imports by 2033 corresponding to approximately 17 million tonnes annually [2]. Bridging this supply-demand gap represents one of the most pressing agricultural development imperatives on the continent.

West Africa accounts for approximately 60% of Sub-Saharan Africa's rice cultivation area, positioning it as the continent's principal lever for production expansion. AfricaRice [3] estimates that this region harbors considerable untapped yield potential, particularly through the development of water-controlled cropping systems. This opportunity is rendered more critical by the fact that nearly 80% of current West African rice systems rely exclusively on rainfall, exposing smallholder farmers to chronic yield instability under increasingly erratic precipitation regimes. First-order inland valleys, topographically defined depressions characterized by gentle longitudinal slopes and capacity for seasonal or permanent water accumulation, offer biophysical conditions particularly conducive to lowland rice cultivation. However, in Côte d'Ivoire, the agronomic valorization of these environments remains systematically suboptimal, constrained by a confluence of agroecological, technological, and socio-economic barriers [4].

In the Pronou area of the Gbêkê region, where rice production constitutes a cornerstone of the local agricultural economy, farming practices remain predominantly empirical and unintensified, yielding irregular and economically insufficient harvests. Compounding these structural limitations, progressive intensification of rainfall variability and recurrent drought episodes further erode production stability, elevating the strategic urgency of evidence-based inland valley management [5]. Despite the widely acknowledged productive potential of West African first-order inland valleys, critical knowledge gaps persist regarding the interactive effects of topographic position, soil physico-chemical properties, interannual climatic variability, and rice varietal response under contrasting nitrogen management regimes [6] [7]. This knowledge deficit constitutes a major obstacle to the formulation of differentiated, site-specific agronomic recommendations capable of unlocking the full productive capacity of these ecosystems.

The present study addresses this gap through a systematic, multi-scale evaluation of the agronomic potential of first-order inland valleys in Pronou, deploying an integrative analytical framework articulated around three complementary methodological pillars: i) rigorous field-based pedological characterization stratified by toposequential position; ii) prospective yield simulation using the APSIMX R package interface, within which a process-informed empirical model was implemented, encompassing a full factorial combination of three varieties, six nitrogen application rates, and three agroecological zones; and iii) integrated net benefit and stochastic risk assessment across contrasting price and yield scenarios. This integrative framework was designed to characterize and quantify the respective contributions of topographic position, edaphic properties, varietal performance, and nitrogen management to rice yield determination under interannual climatic variability. Ultimately, this study aims to deliver science-based agronomic recommendations directly applicable to smallholder rice producers and agricultural extension services operating in the inland valley systems of Côte d'Ivoire.

2. Materials and Methods

2.1. Study Area

The study was carried out in the Gbêkê region, central Côte d'Ivoire (7˚48'00"N - 7˚54'00"N; 5˚48'00"W - 5˚42'00"W; approximately 330 km north of Abidjan). The region is bordered to the north by the Hambol region, to the south by the Bélier region, to the east by the Iffou region, and to the west by the Béré and Marahoué regions. The climate is sub-humid tropical with a bimodal rainfall pattern (annual average 857 - 1020 mm over the study period). The inland valleys of Pronou, selected for this study, represent first-order systems with seasonally variable hydrological regimes and a predominantly subsistence farming system centered on rice, maize (**Figure 1**).

2.2. Plant Material

Three rice varieties with contrasting agronomic profiles were selected: NERICA-L19 (115-day cycle; yield potential 6.5 t/ha), WAB 56-50 (105-day cycle; yield potential 5.8 t/ha), and a traditional local ecotype (125-day cycle; yield potential 5.2 t/ha). NERICA-L19 was selected for its widely documented high yield potential and nitrogen responsiveness in West African inland valley conditions; WAB 56-50 was included as a reference improved variety of intermediate productivity commonly promoted by AfricaRice extension programs in Côte d'Ivoire; and the local ecotype was retained as a benchmark representative of farmers' current practice and a proxy for genetic adaptation to local agroecological constraints. Both improved varieties were developed by Africa Rice [8].

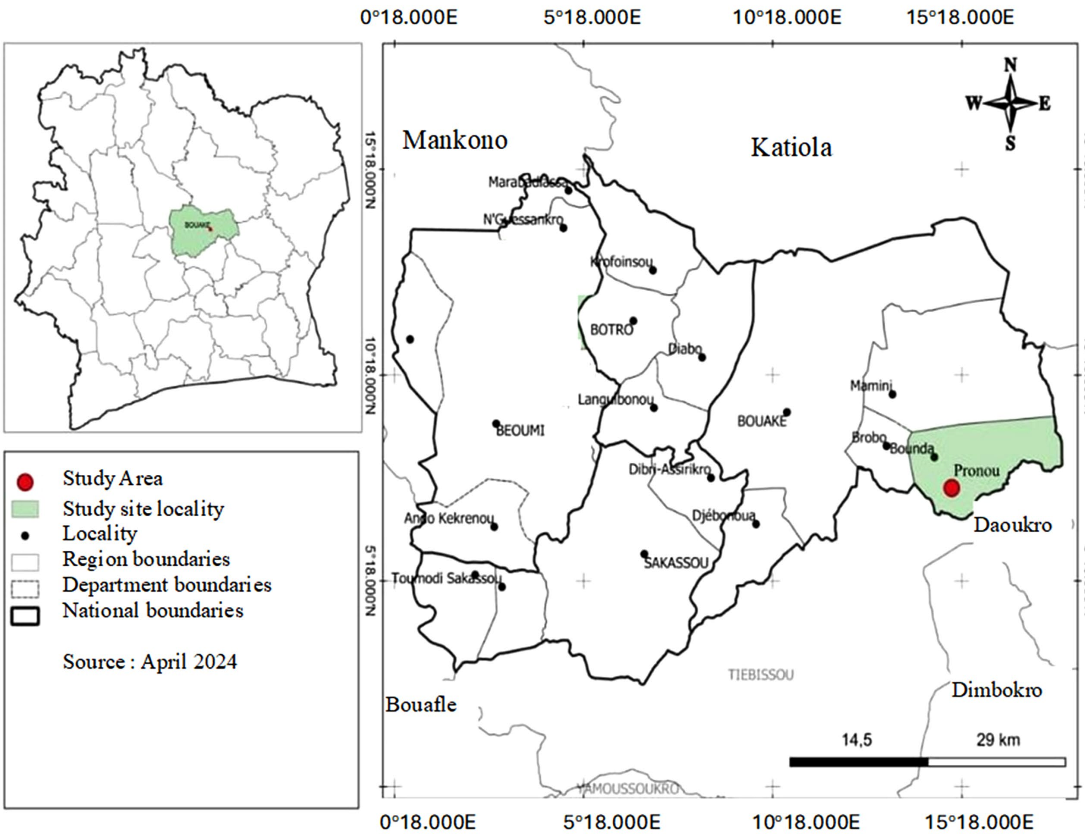

Figure 1. Map of the Pronou study area in North-East Gbêkê region.

2.3. Soil Sampling and Physico-Chemical Analysis

Soil data collection covered three principal soil types (clay, clay-loam, loam-clay), with sampling stratified across three longitudinal zones of the inland valley (upstream, downstream, middle) and three transverse topographic positions (hydromorphic, median, flat), following the protocol of Becker *et al.* [9] recommended by AfricaRice for inland valley soil characterization in Sub-Saharan Africa [10]. The 0–20 cm depth was selected as it corresponds to the primary rooting zone and nutrient-active layer in lowland rice systems, where the majority of nitrogen uptake, organic matter decomposition, and biogeochemical transformations occur [9] [10]. For each zone-position combination, three composite samples were collected at 0 - 20 cm depth, yielding 75 samples in total.

Samples were air-dried, crushed, and sieved to 2 mm prior to analysis following standardized methods [11]. Texture was determined by Robinson pipette; pH (water and KCl) at a 1:2.5 soil:solution ratio; organic carbon by Walkley-Black oxidimetry; total nitrogen by Kjeldahl; available phosphorus by Bray-1; exchangeable bases (Ca, Mg, K, Na) by ammonium acetate extraction and atomic absorption spectrometry; and extractable iron by the dithionite-citrate-bicarbonate method. The C:N ratio and sum of exchangeable bases (SEB) were calculated accordingly. Textural classes were assigned following the USDA triangle [12].

2.4. Climatic Data

Monthly meteorological records spanning 2020-2023 (49 months), encompassing minimum and maximum air temperatures, relative humidity, cumulative precipitation, and solar radiation, were retrieved through the QBMS R package interfacing with standardized BrAPI protocols [13]. Monthly meteorological records were downscaled to daily time steps using a stochastic temporal disaggregation procedure that conserves the first- and second-order statistical moments of the original monthly distributions [14], with precipitation allocated such that 20% of rain days received 80% of monthly totals [15]. Solar radiation was estimated from site latitude and seasonality, ranging 15 - 25 MJ/m^2/day [16].

2.5. Crop Yield Modeling

2.5.1. Predictive Yield Model

To clarify the modeling framework: the APSIMX R package was used as a simulation environment, but given the absence of locally calibrated APSIM crop parameter files for these specific varieties and sites, grain yields were simulated using a process-informed empirical model implemented within R and calibrated against published dose-response relationships for improved inland valley rice varieties in West Africa [17] [18], incorporating nitrogen application rate, annual precipitation, initial soil nitrogen content, and varietal characteristics as predictive variables.

The model was structured around five components: a variety-specific potential yield under zero nitrogen input (Y_0), a variety-dependent agronomic nitrogen use efficiency coefficient (NUE, kg grain kg^{-1} N), a soil fertility modifier derived from initial soil nitrogen content, a unimodal precipitation response function peaking at 1200 mm·year^{-1} and a nitrogen saturation function reflecting the law of diminishing returns above 120 kg·N·ha^{-1}. The complete predictive equation is expressed as: $Y = Y_0 \times f(P) \times f(N_s) + NUE \times N \times g(N)$, where Y is the predicted grain yield (kg·ha^{-1}); Y_0 is the variety-specific baseline yield at zero nitrogen input (NERICA-L19: 3860 kg·ha^{-1}; WAB 56 - 50: 3560 kg·ha^{-1}; local ecotype: 3160 kg·ha^{-1}); $f(P) = 1 - 0.0002 \times (P - 1200)^2$ is the unimodal precipitation response function (P: annual precipitation in mm), peaking at P = 1200 mm; $f(N_s) = 1 + 0.5 \times N_s$ is the soil fertility modifier (N_s: initial soil nitrogen content in %); NUE is the variety-specific agronomic nitrogen use efficiency coefficient (NERICA-L19: 19.8 kg·grain·kg^{-1} N at 40 kg·N·ha^{-1}, declining to 15.0 at 200 kg·N·ha^{-1}); and $g(N) = 1 - \exp(-N/120)$ is the nitrogen saturation function modeling diminishing returns above the 120 kg N ha^{-1} inflection threshold. This empirical model was parameterized using published dose-response data [17] [18] and validated internally by verifying that simulated baseline yields and nitrogen response slopes fell within the confidence intervals reported for analogous inland valley systems in West Africa.

2.5.2. Simulation Scenarios

A full factorial simulation design was implemented, combining four observed years (2020-2023) and one projected year (2024), six nitrogen application rates (0, 40, 80, 120, 160, and 200 kg·N·ha^{-1}), three rice varieties, and three inland valley zones, yielding 270 distinct production scenarios. The 2024 projected climate year was generated by applying the mean inter-annual trend observed over 2020-2023 to extrapolate the five meteorological variables forward by one year; this approach provides a near-term exploratory scenario rather than a formal climate projection, and its outputs are interpreted accordingly. For each scenario, grain yield was predicted using the calibrated empirical model, enabling systematic quantification of the individual and combined effects of nitrogen management, varietal choice, and agroecological context on rice productivity [19].

2.6. Economic Analysis and Risk Assessment

2.6.1. Profitability Analysis

The economic performance of each production scenario was evaluated using locally referenced input-output prices and cost parameters [20]: paddy rice farm-gate price (400 FCFA·kg^{-1}; ~0.61 €·kg^{-1}), nitrogen fertilizer unit cost (600 FCFA·kg^{-1}·N; ~0.91 €·kg^{-1}·N), fixed labor cost (150,000 FCFA·ha^{-1}; ~229 €·ha^{-1}), variable labor cost associated with nitrogen application (500 FCFA·kg^{-1} N applied; ~0.76 €·kg^{-1}·N), and other fixed production costs encompassing seed, land preparation, and crop management (200,000 FCFA·ha^{-1}; ~305 €·ha^{-1}), yielding a total production cost of 570,000 FCFA·ha^{-1} (~869 €·ha^{-1}) at the recommended rate of 200 kg·N·ha^{-1}. All euro conversions are based on the fixed FCFA/EUR parity of 655.96 XOF EUR^{-1} established under the West African Economic and Monetary Union (UEMOA) framework. For each scenario, four economic performance indicators were computed: gross revenue (predicted yield x paddy farm-gate price), total production cost (nitrogen cost + total labor cost + fixed costs), net benefit (gross revenue - total production cost), benefit-cost ratio (gross revenue/total production cost), and return on investment (net benefit/total production cost × 100, %).

2.6.2. Sensitivity and Risk Analysis

A multi-scenario robustness analysis was conducted to assess the stability of agronomic recommendations under combined price and yield uncertainty, following the methodological framework of Baudron *et al.* [21]. Three paddy price levels were considered: low (300 FCFA·kg^{-1}; ~0.46 €·kg^{-1}), baseline (400 FCFA·kg^{-1}; ~0.61 €·kg^{-1}), and high (500 FCFA·kg^{-1}; ~0.76 €·kg^{-1}), crossed with three yield performance levels: unfavorable (70% of predicted yield), baseline (100%), and favorable (120%), generating nine combined scenarios per variety-zone-nitrogen rate combination. For each of the resulting scenario sets, net benefit distributions were characterized by their minimum, mean, maximum, and standard deviation, and the probability of economic loss was computed as the proportion of scenarios yielding a negative net benefit, formally: $P(\text{loss}) = n(NB < 0)/N_{total}$, where n(NB <

0) is the number of combined price-yield scenarios with net benefit (NB) below zero and $N_{total} = 9$ is the total number of combined scenarios per treatment combination. A P(loss) of 0 indicates that no combination of the three price levels and three yield multipliers generates a negative net benefit [22].

2.7. Recommendation Formulation

Final agronomic recommendations were formulated by integrating the outcomes of yield simulation, economic profitability assessment, and multi-scenario risk analysis, following the decision framework of Paroda and Kumar [23]. For each inland valley zone, variety-nitrogen rate combinations were ranked against two complementary selection criteria: economic optimality, defined as the maximization of mean net benefit across simulated years, and risk-adjusted robustness, defined as the minimization of the coefficient of variation of net benefit under contrasting price and yield scenarios [24]. The combination simultaneously satisfying both criteria: highest mean net benefit with lowest relative variability, was designated the zone-specific optimal recommendation.

2.8. Statistical Analysis

All statistical analyses and data visualizations were carried out in R version 4.5.3 [25], using the dplyr [26], ggplot2 [27], and corrplot [28] packages. For each soil parameter, descriptive statistics, including mean, standard deviation, minimum, maximum, and coefficient of variation, were computed and stratified by longitudinal zone (upstream, downstream, middle) and transverse topographic position (hydromorphic, median, flat). Pearson correlation matrices were computed using pairwise complete observations to maximize sample size while accommodating missing texture data [29]. Soil fertility ratings for total nitrogen, available phosphorus, and soil reaction (pH) were assigned according to threshold values adapted to West African lowland rice soils following the classification frameworks [30] [31].

3. Results

3.1. Temporal Dynamics of Agronomic Feasibility

The agronomic feasibility index (FA) quantifies the suitability of prevailing climatic conditions for rice production. It is computed as a weighted composite of four normalized climatic variables: $FA = w_1 \times f(P) + w_2 \times f(T) + w_3 \times f(RH) + w_4 \times f(R)$, where f(P), f(T), f(RH), and f(R) are fuzzy membership functions (0 - 1) expressing the degree to which observed annual precipitation (P), mean temperature (T), relative humidity (RH), and solar radiation (R) fall within the optimal ranges for lowland rice [17] [18]; weights w_1-w_4 sum to 1 and reflect the relative importance of each variable (precipitation: 0.4; temperature: 0.2; humidity: 0.2; radiation: 0.2). The mean agronomic feasibility index showed a slight increase from 0.813 in 2020 to 0.820 in 2023, demonstrating the adaptive resilience of inland valley rice cultivation to moderate meteorological fluctuations (**Table 1**). The analysis reveals an optimum in April (index 0.930), a shift toward June (0.911 in 2021), and stabilization in May for 2022 and 2023 (0.947 and 0.928 respectively), reflecting a progressive modification of the rainfall regime. The slight upward trend in the mean FA index from 2020 to 2023 is attributable to the progressive increase in total annual precipitation over the study period (857 mm in 2020 to 1020 mm in 2023), which shifted observed rainfall closer to the optimal range for lowland rice (approximately 1000 - 1200 mm). The concomitant marginal decline in solar radiation (15.2 to 14.5 $MJ \cdot m^{-2} \cdot day^{-1}$) was insufficient to offset the positive precipitation effect, yielding a net improvement in the composite feasibility score. This trend underscores the sensitivity of the FA index to inter-annual precipitation dynamics and highlights the importance of adaptive sowing date management under a shifting rainfall regime.

Table 1. Annual summary of climatic parameters and agronomic feasibility index for rice in the inland valley (2020-2023).

Year	PT (mm)	Tmoy (˚C)	Rm ($MJ/m^2/day$)	HRm (%)	FAm	FAmax
2020	857	27.0	15.2	65.1	0.813	0.930
2021	889	27.2	14.9	65.5	0.808	0.911
2022	990	26.8	14.7	65.6	0.814	0.947
2023	1020	27.2	14.5	65.7	0.820	0.928

PT: total precipitation; Tmoy: mean temperature; Rm: mean solar radiation; HRm: mean relative humidity; FAm: mean agronomic feasibility; FAmax: maximum agronomic feasibility.

Monthly variation of maximum temperatures (˚C), cumulative precipitation (mm), and relative humidity (%) at the experimental sites between 2020 and 2023 revealed characteristic bimodal rainfall patterns with two rainy seasons per year (**Figure 2**). Peak precipitation occurred in May-June and September-October, with a pronounced dry season from November to February.

3.2. Physico-Chemical Soil Properties by Topographic Zone

Soil samples from upstream, downstream, and middle toposequence positions showed distinct characteristics influencing their agronomic potential (**Table 2**). Upstream soils showed a slightly lower mean pH (6.46 ± 0.38) compared to downstream soils (6.70 ± 0.28), but similar to middle soils (6.51 ± 0.46). Total nitrogen showed a decreasing gradient from upstream to middle: 0.36% ± 0.13%, 0.318% ± 0.12%, and 0.257% ± 0.10%, respectively. Similarly, organic carbon decreased slightly from upstream (3.44% ± 0.85%) to downstream (3.05% ± 0.79%) and middle (3.02% ± 0.93%). Downstream soils showed the highest clay content (58.4%) compared to upstream (53.0%) and middle (56.4%), while sand was more abundant upstream (14.6%). The C:N ratio increased from upstream (10.1) to middle (12.3), suggesting progressively less readily decomposable organic matter.

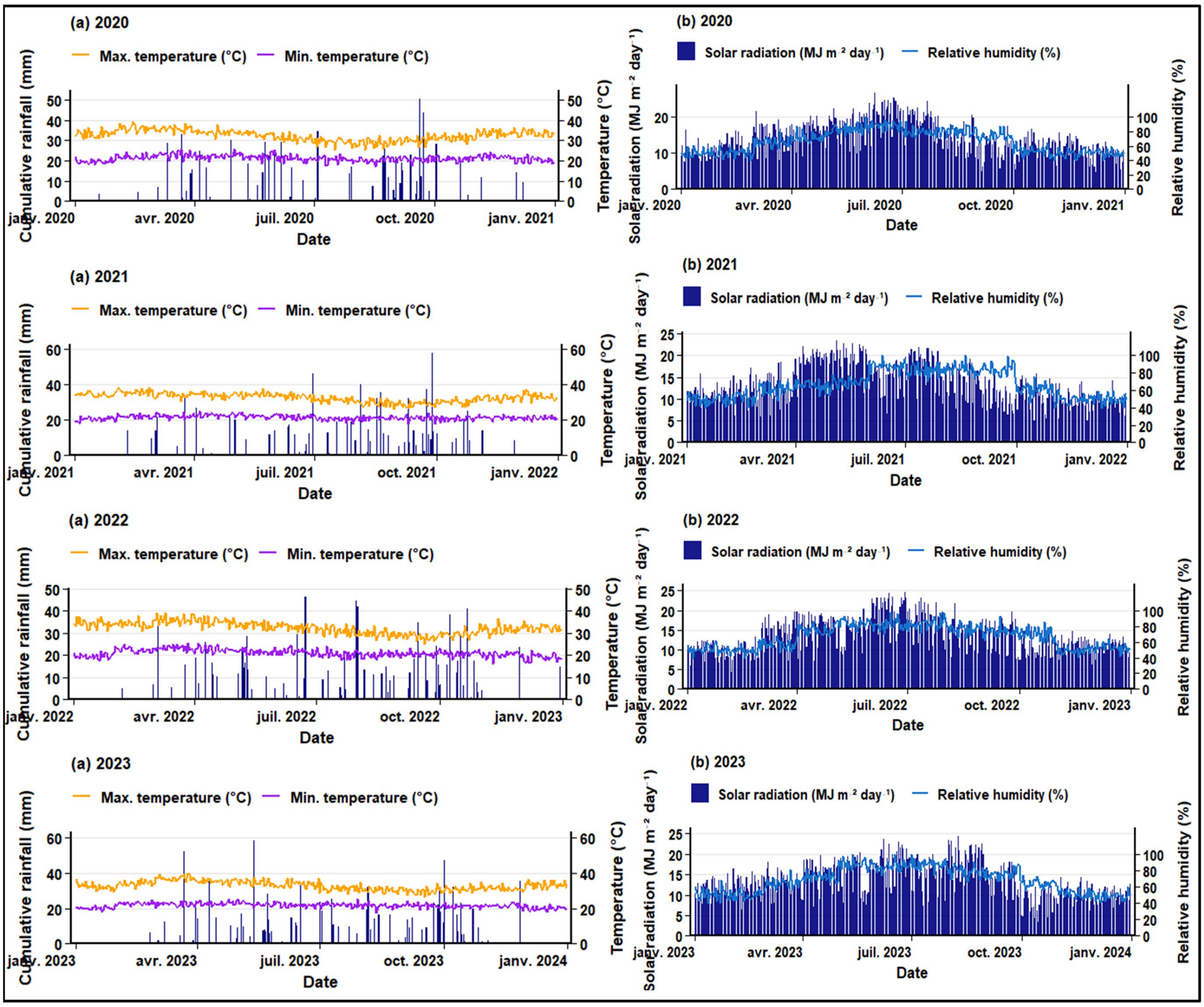

Figure 2. Monthly variation in maximum temperature (˚C), cumulative rainfall (mm), and relative humidity (%) across the experimental sites from 2020 to 2023.

Table 2. Physico-chemical properties of inland valley soils by longitudinal zone (mean ± SD).

Parameters	Upstream (n = 5)	Downstream (n = 10)	Middle (n = 10)
pH (water)	6.46 ± 0.38	6.70 ± 0.28	6.51 ± 0.46
Total nitrogen (%)	0.36 ± 0.13	0.318 ± 0.12	0.257 ± 0.10
Organic carbon (%)	3.44 ± 0.85	3.05 ± 0.79	3.02 ± 0.93
Available P (mg/kg)	7.80 ± 5.76	6.80 ± 2.10	6.40 ± 3.89
Clay (%)	53.0	58.4	56.4
Silt (%)	30.3	30.5	31.9
Sand (%)	14.6	9.18	9.87
C:N ratio	10.1	10.8	12.3
SEB (cmol(+)/kg)	28.6	33.8	30.2

SEB: sum of exchangeable bases. Values represent means of composite samples at 0 - 20 cm depth.

3.3. Influence of Hydrological Regime on Edaphic Properties

Analysis of soil properties by hydrological position revealed marked contrasts between hydromorphic, median, and flat positions (**Table 3**). Hydromorphic and median soils showed similar pH values (6.64 ± 0.39 and 6.67 ± 0.24, respectively), while flat soils were slightly more acidic (6.35 ± 0.43). Total nitrogen and organic carbon were significantly lower in flat positions (0.193% ± 0.10% and 2.52% ± 1.30%, respectively) compared to hydromorphic (0.338% ± 0.11%; 3.23% ± 0.62%) and median positions (0.333% ± 0.08%; 3.47% ± 0.36%). The C:N ratio was markedly higher in flat positions (13.6) than in hydromorphic (10.4) and median positions (10.9), suggesting slower organic matter mineralization. The SEB was maximal in median positions (41.6 cmol(+)/kg) and minimal in flat zones (21.0 cmol(+)/kg). Texture varied substantially: median positions exhibited very high clay (71.4%) and minimal sand (2.1%), while flat zones showed a more balanced profile with greater silt (42.2%) and sand (20.0%) (**Figure 3**).

Table 3. Physico-chemical properties of inland valley soils by hydrological position (mean ± SD).

Parameters	Hydromorphic (n = 13)	Median (n = 6)	Flat (n = 6)
pH (water)	6.64 ± 0.39	6.67 ± 0.24	6.35 ± 0.43
Total nitrogen (%)	0.338 ± 0.11	0.333 ± 0.08	0.193 ± 0.10
Organic carbon (%)	3.23 ± 0.62	3.47 ± 0.36	2.52 ± 1.30
Available P (mg/kg)	7.31 ± 3.99	4.50 ± 2.17	8.17 ± 3.31
Clay (%)	58.8	71.4	36.9
Silt (%)	29.1	23.9	42.2
Sand (%)	10.0	2.1	20.0
C:N ratio	10.4	10.9	13.6
SEB (cmol(+)/kg)	31.3	41.6	21.0

SEB: sum of exchangeable bases. Hydro: hydromorphic position.

3.4. Interactions between Topographic Position and Hydrological Regime

Cross-analysis of topographic and hydrological factors identified complex interactions influencing soil fertility (**Table 4**). Hydromorphic upstream positions showed the highest nitrogen contents (0.415% ± 0.085%), followed by hydromorphic downstream zones (0.376% ± 0.077%). Conversely, flat downstream positions displayed the lowest nitrogen values (0.15% ± 0.05%). The C:N ratio varied considerably across composite typologies, with minimum values in median upstream positions (8.87) and maximum values in flat downstream positions (15.5). Available phosphorus was particularly high in hydromorphic upstream (12.5 mg/kg) and flat middle positions (12 mg/kg), contrasting with low values in median upstream positions (2 mg/kg).

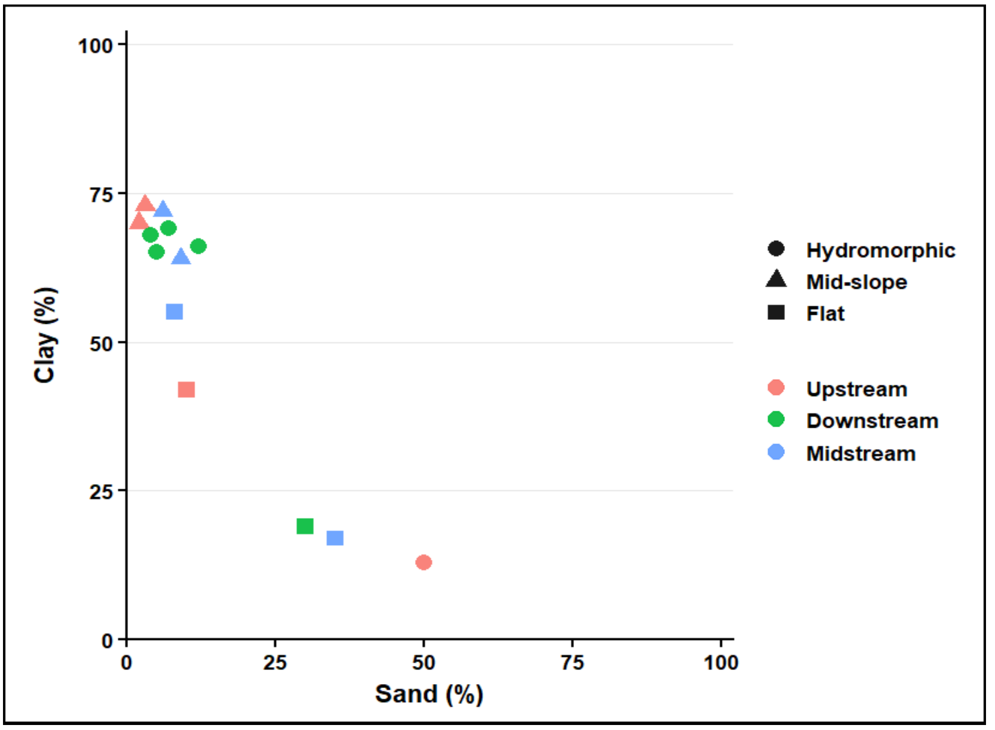

Figure 3. Soil texture of lowland soils in Pronou.

Table 4. Soil fertility summary by zone and topographic position (mean ± SD).

Zone	Position	Nitrogen (%)	C:N ratio	pH	Available P (mg/kg)	SEB (cmol(+)/kg)
Upstream	Hydromorphic	0.415 ± 0.085	9.82 ± 0.13	6.75 ± 0.00	12.5 ± 0.00	24.6
Upstream	Median	0.46 ± 0.00	8.87 ± 0.00	6.3 ± 0.00	2 ± 0.00	35.1
Upstream	Flat	0.255 ± 0.13	11.0 ± 0.00	6.25 ± 0.00	6 ± 0.00	29.3
Downstream	Hydromorphic	0.376 ± 0.077	8.98 ± 0.07	6.8 ± 0.00	8 ± 0.00	34.5
Downstream	Median	0.333 ± 0.122	10.7 ± 0.36	6.77 ± 0.08	5 ± 0.00	43.6
Downstream	Flat	0.15 ± 0.05	15.5 ± 0.00	6.35 ± 0.00	6.5 ± 0.00	17.3
Middle	Hydromorphic	0.28 ± 0.07	11.7 ± 0.43	6.47 ± 0.17	5 ± 0.00	30.9
Middle	Median	0.27 ± 0.00	12.1 ± 0.14	6.7 ± 0.00	5 ± 0.00	41.8
Middle	Flat	0.175 ± 0.00	14.4 ± 0.28	6.45 ± 0.00	12 ± 0.00	16.5

SEB: sum of exchangeable bases; Hydro: hydromorphic; n: number of composite samples per combination.

3.5. Physical and Hydraulic Properties of Inland Valley Soils

Three principal soil types with distinct hydrodynamic behaviors were identified (Table 5). Clay soils showed the highest field capacity (θfc = 0.38) but limited saturated hydraulic conductivity (Ksat = 15 mm/day), favoring water retention while limiting drainage. Clay-loam soils showed intermediate characteristics (θfc = 0.36; Ksat = 20 mm/day). Loam-clay soils, with lower field capacity (0.34) but higher conductivity (25 mm/day), offered better drainage but increased susceptibility to water stress during dry periods. Soil depth and organic matter followed a parallel gradient, from 80 cm and 2.5% in clay soils to 60 cm and 1.8% in loam-clay soils.

Table 5. Physical and hydraulic characteristics of the principal inland valley soil types.

Soil type	θfc	θpwp	θs	Ksat (mm/day)	Depth (cm)	OM (%)
Clay	0.38	0.20	0.48	15	80	2.5
Clay-loam	0.36	0.17	0.46	20	70	2.0
Loam-clay	0.34	0.14	0.44	25	60	1.8

θfc: field capacity; θpwp: permanent wilting point; θs: saturation; Ksat: saturated hydraulic conductivity; OM: organic matter content.

3.6. Agronomic Characteristics of Rice Varieties

The three varieties studied showed contrasting agronomic profiles (Table 6). NERICA-L19 is distinguished by its high yield potential (6.5 t/ha), optimal growth temperature (28˚C), low photoperiod sensitivity (0.01), and moderate water stress tolerance (Ks = 0.8). WAB 56-50 has a short cycle (105 days), reduced thermal requirements (1700 GDD), intermediate photoperiod sensitivity (0.02), and more limited water stress tolerance (Ks = 0.7). Despite its lower yield potential (5.2 t/ha), the local variety shows the best water stress tolerance (Ks = 0.9) and marked photoperiod sensitivity (0.05), enabling better synchronization with favorable seasons.

Table 6. Agronomic characteristics of the three rice varieties studied.

Variety	DC (d)	GDD	SPP	Tb (˚C)	Topt (˚C)	Tmax (˚C)	Ks	Yp (t/ha)
NERICA-L19	115	1800	0.01	10	28	38	0.8	6.5
WAB 56-50	105	1700	0.02	10	27	37	0.7	5.8
Local variety	125	1900	0.05	10	26	36	0.9	5.2

DC: cycle duration (days); GDD: growing degree days; SPP: photoperiod sensitivity; Tb: base temperature; Topt: optimal growth temperature; Tmax: maximum temperature; Ks: water stress tolerance coefficient; Yp: yield potential.

3.7. Predicted Crop Yields

Yield simulations were conducted for the three varieties as a function of topographic position and nitrogen dose applied (Figure 4). NERICA-L19 systematically showed the highest predicted yields, followed by WAB 56-50 and the local variety. For all varieties, an optimal nitrogen dose of 200 kg N/ha was identified, with predicted yields declining slightly from upstream to middle. For NERICA-L19, predicted yields were 6860, 6818, and 6757 kg/ha for upstream, downstream, and middle zones, respectively (Table 7). This trend was maintained for WAB 56-50 (6260, 6218, and 6157 kg/ha) and the local variety (5410, 5368, and 5307 kg/ha).

3.8. Cropping Calendar Optimization

Analysis of rice cultivation suitability indices (Figure 5) identifies a favorable period extending from March to October (indices 0.80 - 0.90), defining an optimal cultivation window of approximately eight months. The less favorable period (indices < 0.70) corresponds primarily to December, January, and February.

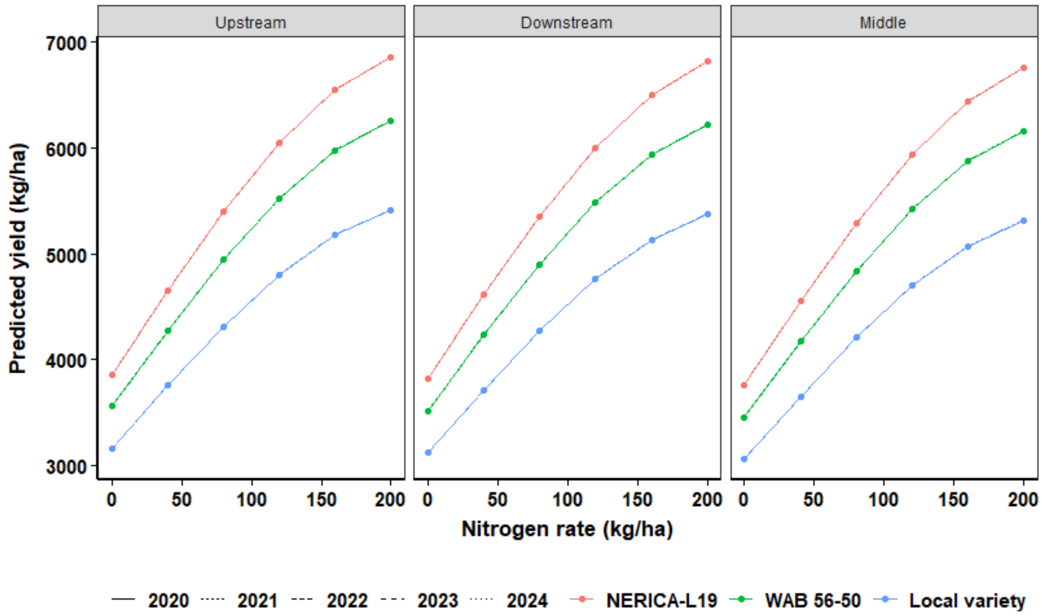

Figure 4. Predicted yields as a function of nitrogen rate, variety, and year.

Table 7. Predicted yield, baseline yield, yield gain, and nitrogen use efficiency by variety, zone, and nitrogen rate (selected scenarios).

N rate (kg/ha)	Variety	PPT (mm)	Scen.	Zone	N soil	Pred. yield (kg/ha)	Base yield (kg/ha)	Yield gain (kg/ha)	N use eff. (%)
40	NERICA-L19	947	10	Upstream	0.36	4652	3860	792	19.8
40	NERICA-L19	947	10	Middle	0.257	4549	3757	792	19.8
40	NERICA-L19	947	10	Downstream	0.318	4610	3818	792	19.8
120	NERICA-L19	947	20	Upstream	0.36	6044	3860	2184	18.2
120	NERICA-L19	947	20	Downstream	0.318	6002	3818	2184	18.2
200	NERICA-L19	947	30	Upstream	0.36	6860	3860	3000	15.0
200	NERICA-L19	947	30	Middle	0.257	6757	3757	3000	15.0
200	NERICA-L19	947	30	Downstream	0.318	6818	3818	3000	15.0
200	WAB 56-50	947	60	Upstream	0.36	6260	3560	2700	13.5
200	WAB 56-50	947	60	Middle	0.257	6157	3457	2700	13.5
200	WAB 56-50	947	60	Downstream	0.318	6218	3518	2700	13.5
200	Local	947	70	Upstream	0.36	5410	3160	2250	11.3
200	Local	947	70	Middle	0.257	5307	3057	2250	11.3
200	Local	947	70	Downstream	0.318	5368	3118	2250	11.3

PPT: annual precipitation (mm); Scen.: simulation scenario; N soil: soil nitrogen content (%); Pred. yield: predicted yield; NUE: nitrogen use efficiency. Only key scenarios are shown; all scenarios at N = 200 kg/ha yielded a negligible (virtually zero) probability of economic loss.

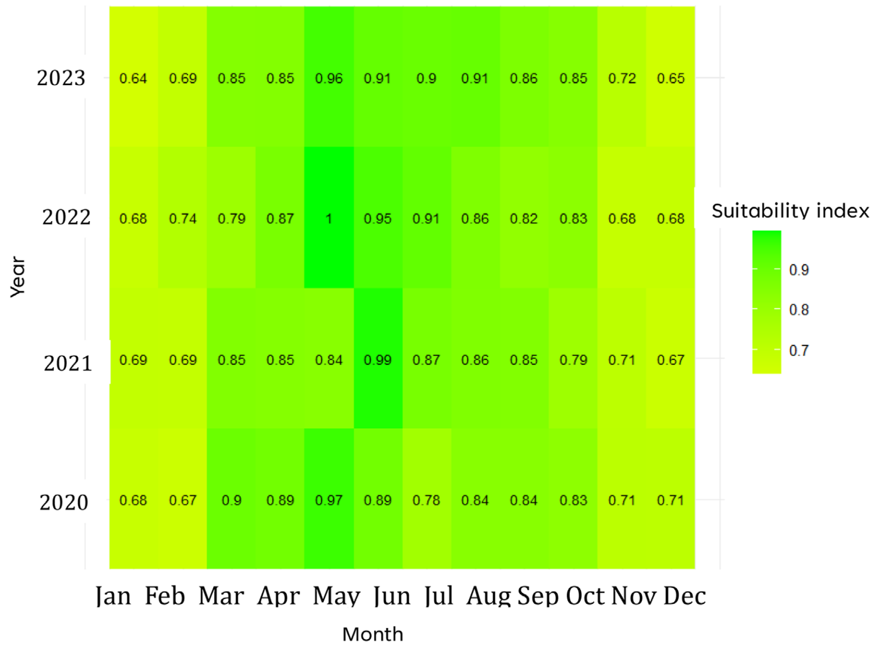

Figure 5. Monthly and annual agronomic feasibility index for rice cultivation in the Pronou inland valley (2020-2023).

Yield potential simulations by sowing date (**Figure 6**) confirmed this seasonality, with a bell-shaped dynamic and a productivity peak between April and October, culminating in May for most varieties and fertilization levels. Improved varieties, particularly NERICA-L19, showed marked superiority during this favorable period, with yields exceeding 5 t/ha under high fertilization, while WAB 56-50 reached approximately 4.5 t/ha and the local variety approximately 4 t/ha. Notably, WAB 56-50 showed a secondary yield peak in February under low fertilization, suggesting adaptation to exploiting residual soil moisture during the dry season.

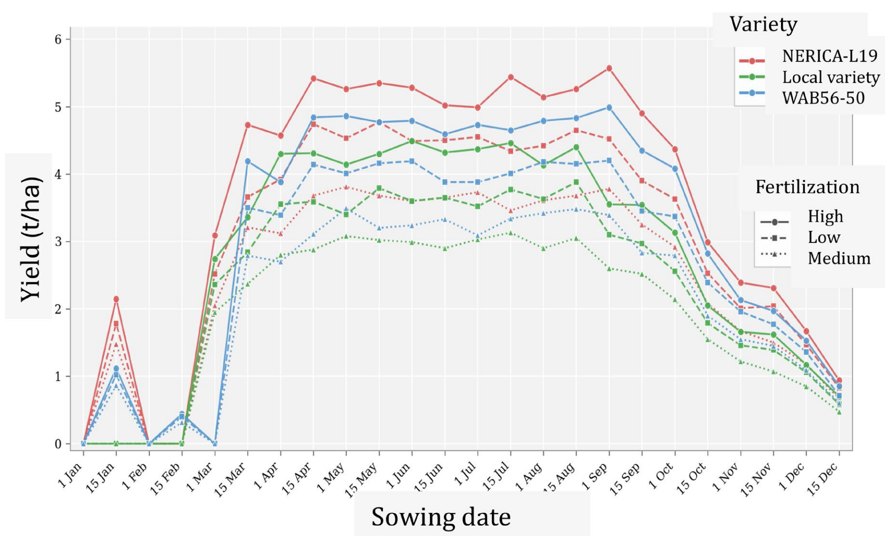

Figure 6. Simulation of potential yield by sowing date for three rice varieties using the APSIMX library using R.

The multiple regression model for factors influencing yield (**Figure 7**) confirmed these observations quantitatively, with strongly positive coefficients (3.5 - 4.0) for April-August sowing dates, moderately positive (2.0 - 3.0) for September–October, and weakly positive to negative (−0.5 to 1.5) for November-February. The model was statistically robust ($R^2 = 0.87$; $F = 62.4$; $p < 0.001$):

$$Yield\ (t/ha) = 2.1 + \beta_1 (sowing\ date) + \beta_2 (variety) + \beta_3 (fertilization)$$

where β_1 ranges from −0.5 to 4.0 by sowing month; β_2 = −0.4 for WAB 56-50 and −0.7 for the local variety (reference: NERICA-L19); β_3 = −0.6 for medium fertilization and −0.8 for low fertilization (reference: high fertilization).

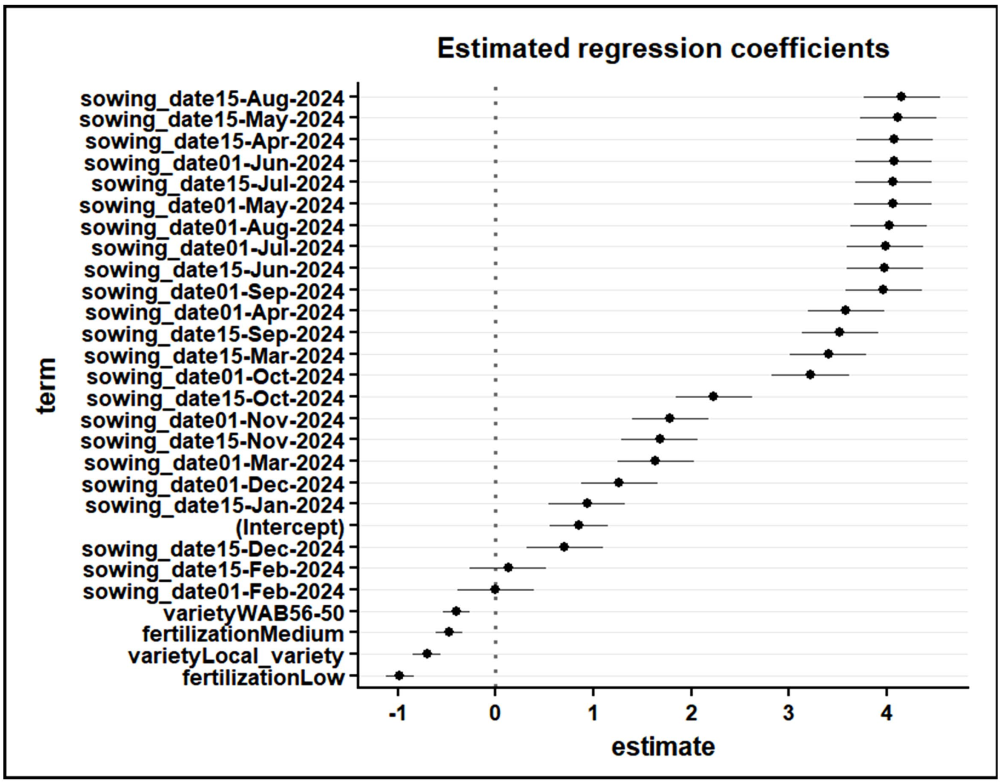

Figure 7. Estimated multiple regression coefficients and their confidence intervals for factors influencing rice yield in the Pronou inland valley.

3.9. Nitrogen Use Efficiency: Simulation Results

Detailed analysis of agronomic nitrogen use efficiency (**Figure 8**) revealed significant differences by variety and nitrogen dose. For NERICA-L19, efficiency declined progressively from 19.8% at 40 kg N/ha to 15.0% at 200 kg N/ha—consistent with the law of diminishing returns. Parallel trends were observed for WAB 56-50 (from 17.8% to 13.5%) and the local variety (from 14.8% to approximately 14.4%). Baseline yields (without nitrogen input) varied by variety and zone: 3860 kg/ha upstream for NERICA-L19, 3560 kg/ha for WAB 56-50, and 3160 kg/ha for the local variety. Maximum yield gains were 3000 kg/ha for NERICA-L19 at 200 kg N/ha, 2700 kg/ha for WAB 56-50, and 2250 kg/ha for the local variety.

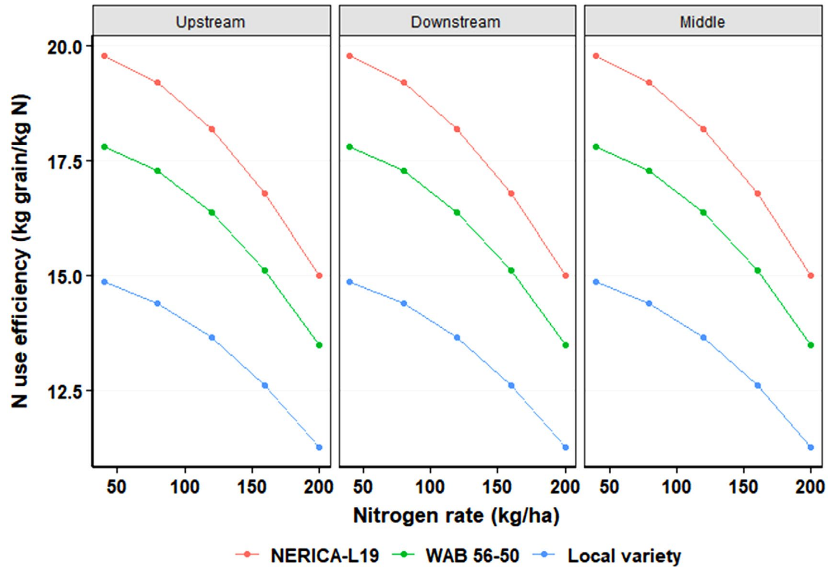

Figure 8. Nitrogen use efficiency by variety and inland valley zone across nitrogen application rates.

3.10. Economic Profitability Analysis

Economic analysis (Figures 9-11) demonstrated that profitability varied substantially by variety, nitrogen dose, and agroecological zone. The highest net benefits were systematically associated with NERICA-L19, followed by WAB 56-50 and the local variety. At the optimal dose of 200 kg N/ha, net benefits reached 2,174,000 FCFA/ha for NERICA-L19 upstream, 2,157,200 FCFA/ha downstream, and 2,132,800 FCFA/ha in the middle zone. For WAB 56-50, corresponding values were 1,934,000, 1,917,200, and 1,892,800 FCFA/ha. The local variety presented lower but substantial net benefits (1,594,000; 1,577,200; 1,552,800 FCFA/ha, respectively).

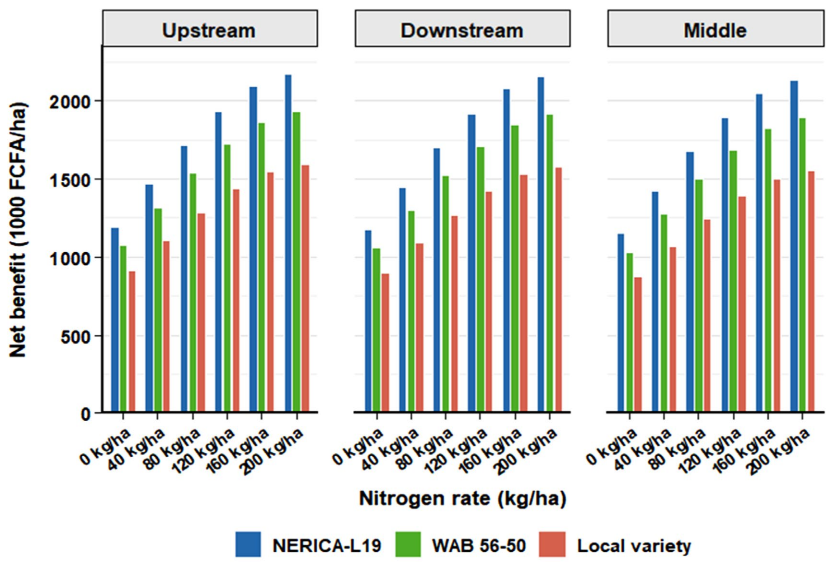

Figure 9. Net benefits by nitrogen dose and variety (thousands of FCFA/ha) across the three inland valley zones.

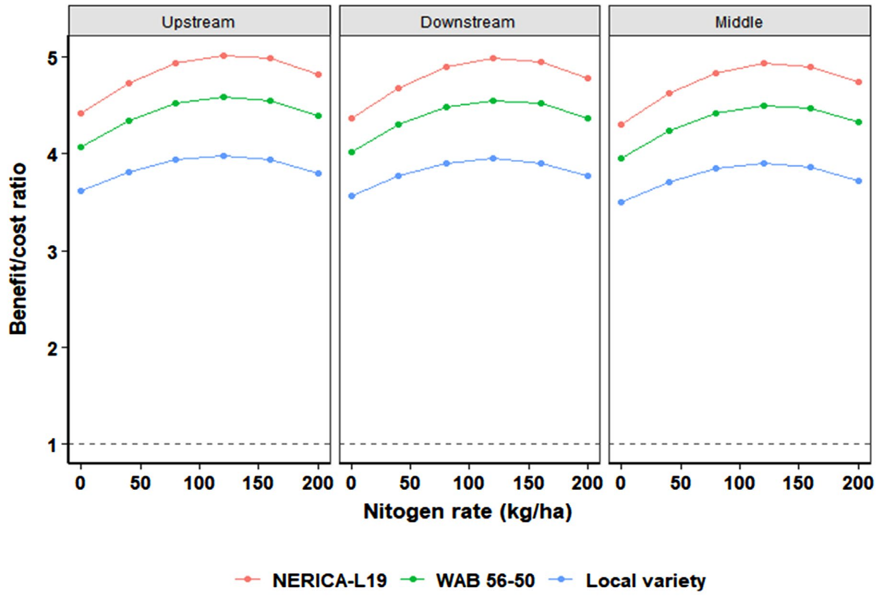

Figure 10. Benefit-cost ratio by nitrogen dose and variety across production scenarios.

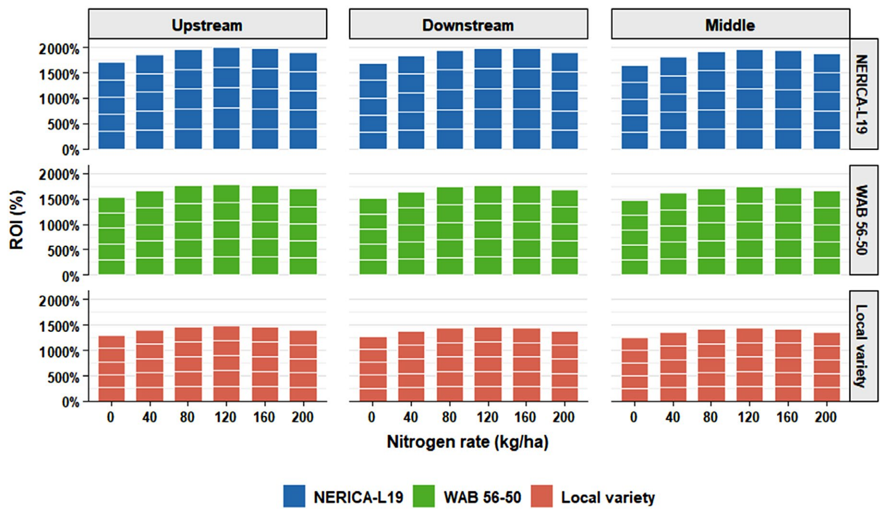

Figure 11. Return on investment (%) by scenario, variety, and inland valley zone.

3.11. Risk and Sensitivity Analysis

Risk analysis (Figure 12; Table 8) highlighted the robustness of the different scenarios against climatic and economic variability. At 200 kg N/ha, all scenarios showed a negligible (virtually zero) probability of economic loss across simulated price and yield conditions, indicating strong economic security. It should be noted, however, that these risk estimates are conditioned on the assumptions of the empirical model and on the price scenarios considered; actual on-farm risk may differ under more extreme conditions. Standard deviations of net benefits were proportional to mean yields: highest for NERICA-L19 (825,489-838,072 FCFA/ha by zone), intermediate for WAB 56-50 (752,188-764,771 FCFA/ha), and lowest for the local variety (648,345-660,928 FCFA/ha). Maximum mean net benefits were observed for NERICA-L19 upstream (2,082,533 FCFA/ha) and minimum values for the local variety in the middle zone (1,482,040 FCFA/ha).

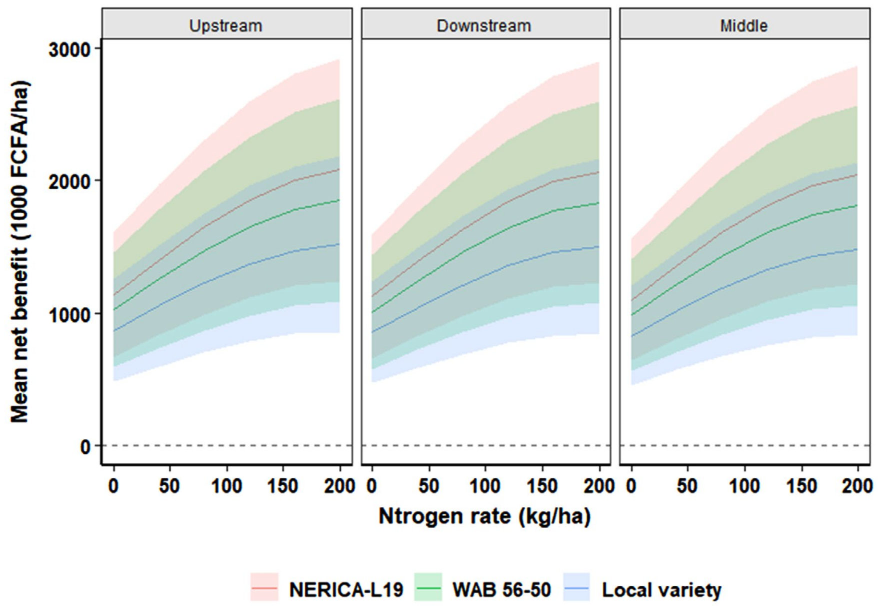

Figure 12. Risk analysis for different nitrogen doses and varieties (ribbon ± 1 SD across simulated years and scenarios).

Table 8. Identification of the most robust (lowest-risk) scenarios by variety and agroecological zone at 200 kg N/ha.

Variety	Zone	Mean net benefit (FCFA·ha⁻¹) (€·ha⁻¹)	SD (FCFA ha⁻¹) (€·ha⁻¹)	P (loss)
NERICA-L19	Upstream	2,082,533 (3175)	838 072 (1278)	0
NERICA-L19	Downstream	2,066,293 (3150)	832 941 (1270)	0
NERICA-L19	Middle	2,042,707 (3114)	825 489 (1258)	0
WAB 56-50	Upstream	1,850,533 (2821)	764 771 (1166)	0
WAB 56-50	Downstream	1,834,293 (2796)	759 640 (1158)	0
WAB 56-50	Middle	1,810,707 (2760)	752 188 (1147)	0
Local variety	Upstream	1,521,867 (2320)	660 928 (1008)	0
Local variety	Downstream	1,505,627 (2295)	655 797 (1000)	0
Local variety	Middle	1,482,040 (2259)	648 345 (988)	0

SD: standard deviation of net benefit across simulated scenarios; P(loss): probability of economic loss (net benefit < 0).

3.12. Final Recommendations

Based on yield, economic profitability, and risk analyses, specific agronomic recommendations were formulated (**Table 9**). For all agroecological zones, NERICA-L19 combined with 200 kg N/ha represents the most productive and profitable option, with excellent economic stability. WAB 56-50 constitutes a good compromise between yield and hardiness, while the local variety, though less productive, may be preferred under particularly challenging conditions due to its superior local adaptation. The synthesis of best recommendations by zone (**Figure 13**) and the simplified recommendation map for the Pronou inland valley (**Figure 14**) provide practical decision-support tools for farmers and extension services.

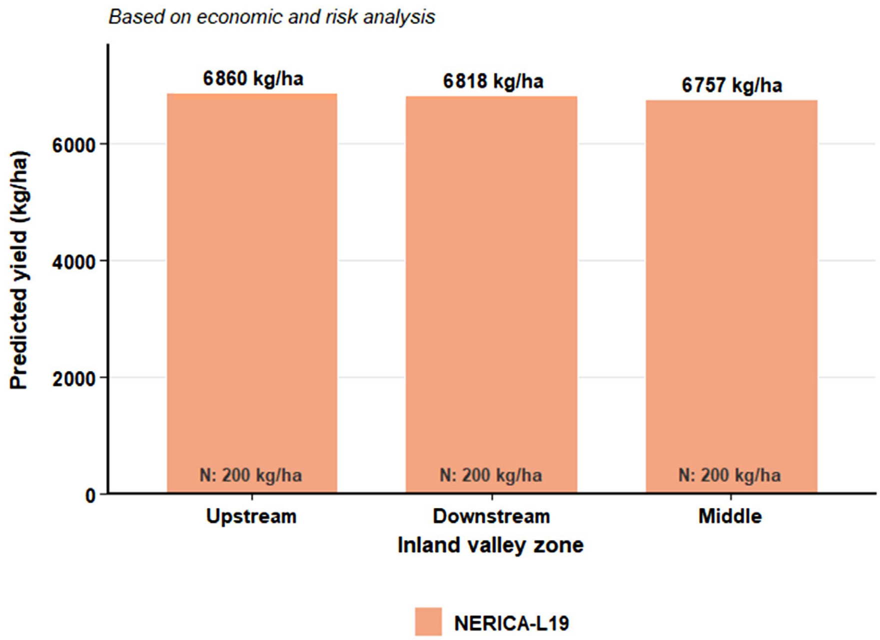

Figure 13. Synthesis of best recommendations by zone based on economic and risk analysis.

Table 9. Agronomic recommendations based on predicted yield, net benefit, and scenario robustness at 200 kg N/ha.

Variety	Zone	Pred. yield (kg/ha)	Net benefit (FCFA/ha)	Comment	Varietal advice
NERICA-L19	Upstream	6860	2174000	Excellent yield, high profitability	Improved variety, best adapted
NERICA-L19	Downstream	6818	2157200	Excellent yield, high profitability	Improved variety, best adapted
NERICA-L19	Middle	6757	2132800	Excellent yield, high profitability	Improved variety, best adapted
WAB 56-50	Upstream	6260	1934000	Very good yield, high profitability	Good balance yield/hardiness
WAB 56-50	Downstream	6218	1917200	Very good yield, high profitability	Good balance yield/hardiness
WAB 56-50	Middle	6157	1892800	Very good yield, high profitability	Good balance yield/hardiness
Local variety	Upstream	5410	1594000	Good yield, high profitability	Less productive, better adapted to difficult conditions
Local variety	Downstream	5368	1577200	Good yield, high profitability	Less productive, better adapted to difficult conditions
Local variety	Middle	5307	1552800	Good yield, high profitability	Less productive, better adapted to difficult conditions

Pred. yield: predicted yield at 200 kg N/ha; Net benefit computed using: rice price = 400 FCFA/kg; N price = 600 FCFA/kg; labor costs = 150,000 + 500 FCFA/kg N; fixed costs = 200,000 FCFA/ha.

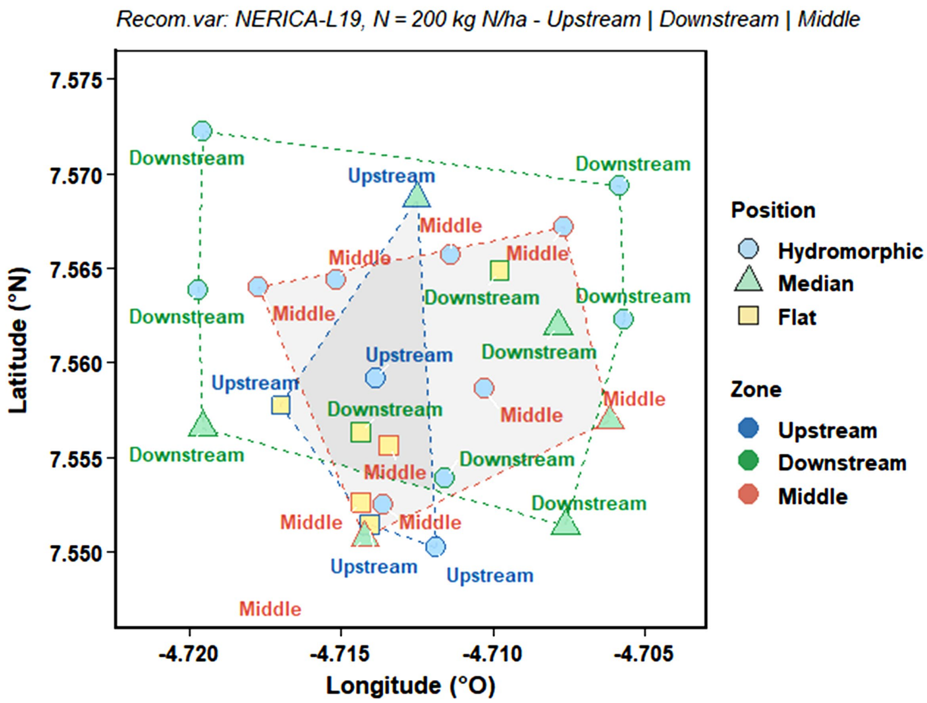

Figure 14. Simplified agronomic recommendation map for the Pronou inland valley (Gbêkê region, Côte d'Ivoire).

4. Discussion

4.1. Interaction between Topography and Soil Properties

The gradient of soil fertility generally decreasing from upstream to middle zones reflects well-documented processes of differential nutrient leaching and accumulation along slopes in West African inland valleys [32]. The near-neutral pH (6.35 - 6.70) observed across all positions is favorable for the availability of essential nutrients for rice, consistent with the optimal range of 5.5 - 6.5 identified by Sahrawat [30] for lowland rice cultivation. However, textural variations between positions, notably the high clay content in downstream zones (58.4%), constitute a critical factor for water and nutrient management that farmers must consider in their cultural practices.

4.2. Determinant Influence of Hydrological Regime

The marked superiority of hydromorphic zones in terms of nitrogen content (0.338%) and organic carbon (3.23%) compared to flat zones (0.193% and 2.52%, respectively) underscores the critical importance of hydrological regime as a fertility driver. These results converge with those of Abe *et al.* [33], who demonstrated that hydromorphic conditions promote organic matter accumulation and slow its mineralization. However, this relationship is not linear: clay soils, despite their high-water retention capacity (θfc = 0.38), show limited hydraulic conductivity (15 mm/day), which may generate waterlogging problems detrimental to water-sensitive varieties.

4.3. Differentiated Varietal Performance

The systematic superiority of NERICA-L19 in terms of yield potential (6.5 t/ha) over WAB 56-50 (5.8 t/ha) and the local variety (5.2 t/ha) reflects the advances of modern genetic improvement programs. Specifically, NERICA-L19's higher performance can be attributed to several complementary traits: i) a higher inherent yield potential (Y_0 = 3860 kg·ha^{-1} at zero N input, vs. 3560 for WAB 56-50 and 3160 for the local ecotype), reflecting superior harvest index and sink capacity; ii) a higher agronomic nitrogen use efficiency coefficient (NUE = 19.8 kg·grain·kg^{-1} N at 40 kg·N·ha^{-1}, vs. 17.8 for WAB 56-50 and 14.8 for the local variety), reflecting greater ability to convert applied nitrogen into grain biomass; iii) optimal growth temperature (28˚C) well-aligned with prevailing site conditions (mean T = 27.0˚C - 27.2˚C); and iv) low photoperiod sensitivity (0.01), enabling reliable and predictable performance across the broad sowing window identified for this site. These traits collectively translate into superior responsiveness to nitrogen fertilization, generating larger yield gains per unit of applied N across all topographic positions [34]. This hierarchy is observed across all pedological contexts and nitrogen doses tested. Nevertheless, this dominance must be qualified: the local variety shows better water stress tolerance (Ks = 0.9 vs. 0.8 for NERICA-L19) and more pronounced photosensitivity (0.05 vs. 0.01), which constitutes a valuable adaptive advantage under variable climatic conditions or in low-input farming systems. This observation is consistent with the work of Diagne *et al.* [35] on the complementarity between improved and traditional varieties.

4.4. Nitrogen Use Efficiency and Sustainability Implications

Agronomic nitrogen use efficiency declining with increasing doses for all varieties, from 19.8% at 40 kg N/ha to 15.0% at 200 kg N/ha for NERICA-L19, conforms to the law of diminishing returns—also documented by Peng *et al.* [36] and Zou *et al.* [37]. Beyond a saturation threshold estimated at approximately 120 kg·N·ha^{-1} in the present model (corresponding to the inflection point of the nitrogen saturation function g(N)), increased nitrogen inputs no longer translate proportionally into yield gains. Above this threshold, the marginal return per unit N applied declines sharply: NUE decreases from 18.2% at 120 kg·N·ha^{-1} to 15.0% at 200 kg·N·ha^{-1} for NERICA-L19, representing a 17.6% reduction in conversion efficiency. This pattern reflects the physiological constraints on nitrogen assimilation and the increasing risk of nitrate leaching and luxury uptake at high application rates. This reality questions the environmental sustainability of high-input systems, despite their immediate economic profitability. Intermediate nitrogen rates (120 - 160 kg·N·ha^{-1}) may represent a more sustainable compromise between yield maximization and input efficiency [37].

4.5. Calendar Optimization and Climatic Adaptability

The identification of an optimal cultivation window between March and October, with a peak in May, is consistent with the bimodal rainfall patterns of the Gbêkê region and aligns with similar findings for West African inland valley rice systems [38]. The secondary yield peak of WAB 56-50 in February under low fertilization opens interesting perspectives for double cropping or counter-season cultivation exploiting residual soil moisture. This calendar flexibility, little explored in traditional rice systems, offers prospects for sustainable intensification without necessarily increasing inputs—consistent with climate-smart agriculture approaches advocated by FAO [39].

4.6. Economic Analysis and Risk Management

The negligible probability of economic loss at 200 kg N/ha across all varieties and zones represents a strong economic argument for nitrogen intensification in the Pronou inland valleys, provided market stability and reliable input supply chains. These results should nonetheless be interpreted with appropriate caution, as the risk estimates derive from a scenario-based empirical simulation rather than from multi-year on-farm trials. The net benefits achieved by NERICA-L19 (up to 2,174,000 FCFA/ha) compare favorably with returns reported for intensified lowland rice systems in West Africa [40]. The positive relationship between yield variability and net benefit standard deviations indicates that risk-averse farmers may rationally prefer intermediate nitrogen rates or more robust (if lower-yielding) varieties to reduce income volatility—a behavioral pattern well documented in smallholder agricultural economics [41].

4.7. Synthesis and Perspectives

This study demonstrates the importance of an integrated approach simultaneously considering pedological, varietal, and economic factors for optimizing rice systems. The rigorous methodology combining field analyses and modeling constitutes a reproducible framework for other agroecological contexts. Several limitations should nonetheless be acknowledged. The predictive model is empirical and parameterized from published relationships rather than from locally measured crop growth data; its outputs should be regarded as scenario-based approximations pending validation against multi-season on-farm trial data. The 2024 projected climate year is an extrapolation rather than a calibrated forecast. Soil hydraulic and varietal trait parameters were largely drawn from literature values rather than directly measured at Pronou, and the economic analysis assumes stable input/output prices. Future research should address: i) validation of the predictive model with observed multi-season on-farm yield data; ii) long-term evolution of soil fertility under different management regimes; iii) integration of traditional ecological knowledge into adaptive management strategies; iv) quantification of climate change impacts on inland valley hydrology and crop-soil-water interactions; and v) socio-economic determinants of technology adoption by smallholder rice farmers in the region.

5. Conclusions

This integrated study of soil physico-chemical properties, varietal performance, and economic aspects in the Pronou inland valleys demonstrates that these ecosystems harbor substantial and largely underutilized rice production potential. The predictive modeling approach, deployed here for the first time in this system, proved capable of generating robust scenario analyses supporting evidence-based decision-making.

NERICA-L19 combined with 200 kg N/ha and a May sowing date represents the most productive and economically profitable scenario, delivering predicted yields up to 6860 kg/ha and net benefits exceeding 2,100,000 FCFA/ha with a negligible probability of economic loss under the simulated price and yield scenarios. The local variety, though less productive, offers complementary adaptive value under low-input or climatically stressed conditions, reinforcing the case for diversified variety portfolios in smallholder systems.

The spatial heterogeneity of soil properties across longitudinal zones and hydrological positions highlights the necessity of site-specific management. The integration of risk analysis with yield modeling provides farmers with the information needed to make variety-fertilization decisions aligned with their individual risk tolerance.

These results contribute to refining management strategies for lowland rice systems and promoting agricultural practices genuinely adapted to local specificities, thereby participating in global efforts to strengthen the resilience of food systems against the contemporary challenges of climate change and food security in West Africa.

Acknowledgments

The authors sincerely thank the farming communities of Pronou for their collaboration and access to their fields.

Author Contributions

Aikpa Mireille Christelle PITTA: Conception and design; methodology; fieldwork and data collection; data cleaning, coding, and entry into the software for analysis; data analysis, interpretation, and discussion; drafting the full paper. Brahima KONE: Supervision of the PhD study. Bolou Emile BOLOU-BI Zéphirin SEHI and Thierry Philippe GUETY: revising the paper critically for intellectual content. All authors consent to publish.

Conflicts of Interest

The authors report that there are no competing interests to declare.

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