Field Crops Research 321 (2025) 109679

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Tailoring fertilizer rates to catena positions improves nutrient use efficiency of rice in inland valleys of West Africa

Guy Marius Assogba [a,1], Gerrie W.J. van de Ven [a,*], Jonne Rodenburg [b,2], Krishna Prasad Devkota [c], Elliott Ronald Dossou-Yovo [d], Ken E. Giller [a]

[a] *Plant Production Systems, Department of Plant Sciences, Wageningen University & Research, Wageningen, the Netherlands*
[b] *Natural Resources Institute (NRI), University of Greenwich, Chatham Maritime, Kent ME4 4TB, United Kingdom*
[c] *International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat, Morocco*
[d] *Africa Rice Center (AfricaRice), Bouake, Cote d'Ivoire*

ARTICLE INFO

Keywords:
Fertilizer management
Inland valley
Nutrient use efficiency
Profitability
Upland-lowland continuum
Oryza sativa

ABSTRACT

Context: Rainfed rice production in inland valleys has the potential to improve food security in West Africa, yet the average grain yield ranges only between 1 and 3 t ha^{-1}. Increased nutrient use efficiency through site-specific fertilizer management can enhance the rice yield and make rice production economically attractive.
Objectives: This study aimed to assess the effects of catena position and nitrogen fertilizer rates on rice yield, nutrient use efficiency and economic profitability.
Methods: On-farm experiments were conducted in three inland valleys from 2019 to 2021, i.e. in Yawtabrikrom, Ghana and in Ouragahio and Pangbabo in Côte d'Ivoire. The experimental design was a split-plot design, with catena positions as the main factor (i.e., valley bottom, lower slope and middle slope), and fertilizer rates as the sub-factor. In the first (2019) and second (2020/2021) years of the experiment, four and eight fertilizer rates were used, respectively.
Results: Fertilizer applications consistently, and mostly linearly increased rice yields regardless of the catena positions. Yields at the valley bottom (2.1–7.4 t ha^{-1}) and lower slope (0.9–6.5 t ha^{-1}) were higher than those obtained at the middle slope (1.0–5.6 t ha^{-1}), where water deficits were more pronounced compared to the lower two catena positions. Overall, agronomic N use efficiency was higher in the valley bottom and lower slope (26 kg grain kg^{-1} N) than at the middle slope (19 kg grain kg^{-1} N). The higher returns on investment made on fertilizer were achieved at N application rates from 45 to 90 kg N ha^{-1}. At high N levels risks on lodging were observed.
Conclusions: Hydro-edaphic conditions, soil fertility distribution across the catena position, rice lodging risks, and economic indicators must be considered to guide site-specific fertilizer use in inland valley rice systems.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops in West Africa, consumed by more than 400 million people (Fofana et al., 2014). It is the most consumed cereal in Côte d'Ivoire and the second most consumed, after maize, in Ghana (Piao et al., 2020; Takahashi et al., 2019). Therefore, West-African governments are actively investing to promote domestic rice production and reduce dependence on imports (Bado et al., 2018). Yet while the area of rice harvested increased by 45 % over the last decade (FAOSTAT, 2022) and despite many investments, domestic rice production still lags far behind consumption. As such, Côte d'Ivoire and Ghana combined only met half their rice demand through domestic production, in part due to low yield levels.

Rice is cultivated in a wide range of agroecological zones and is a major crop in the inland valleys of West Africa (Andriesse et al., 1994; Windmeijer et al., 1994). Inland valleys (IVs) are rainfed lowlands that are located at the upper reaches of river systems, comprising the valley bottom and hydromorphic fringes, with untapped potential for agricultural production (Rodenburg et al., 2014). These inland valleys represent diverse ecosystems from the upland to the valley bottom

* Corresponding author.
E-mail address: gerrie.vandeven@wur.nl (G.W.J. van de Ven).
[1] The Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT), Dakar, Senegal (current affiliation).
[2] Centre for Crop Systems Analysis, Wageningen University & Research, Wageningen, the Netherlands (current affiliation).

https://doi.org/10.1016/j.fcr.2024.109679
Received 20 July 2023; Received in revised form 12 November 2024; Accepted 20 November 2024
Available online 3 December 2024

(Windmeijer and Andriesse, 1993). Rainfall and groundwater are the primary water sources in these valleys. Water and soil fertility resources determine the agricultural potential, varying spatially and temporally in inland valleys following catenary positions and rainfall seasonality (Andriesse et al., 1994). In the dry season, the water table is at its lowest level, and it rises to shallow depths at the lower slope and valley bottom during the wet season. Rice is cultivated across the inland valley catena (i.e. the upland-lowland continuum) benefiting from the shallow groundwater table in the valley bottoms and the availability of soil moisture across the catena during the rainy seasons (Boehme et al., 2016; Masiyandima et al., 2003). Soil properties and their fertility as well as the prevailing hydrological conditions vary with the position along the catena (Windmeijer and Andriesse, 1993). Moving from the upper slopes down to the valley bottom, soil texture varies from sandy to clayey as erosion and water flow moves minerals downslope and deposits them in the valley bottom. The largest N influx happens during the transition period from the dry to wet seasons (Bognonkpe and Becker, 2000; Yameogo et al., 2021). Although soil moisture availability and soil fertility decrease with elevation moving from the valley bottom to the upper slopes, rice is commonly grown across all catenary positions (Saito et al., 2010). This dynamic interplay of water and soil fertility across catenary positions influences the quantity of nutrients available for plant uptake from both the soil and applied fertilizers, thereby affecting rice yield (Haefele et al., 2008).

Rice yields in the inland valleys vary widely: the data collected by Africa Rice Center (AfricaRice) from 2012 to 2015, show that mean rice yields of rainfed lowlands across the West Africa region ranged from 1.1 t ha^{-1} to 3.0 t ha^{-1} (Dossou-Yovo et al., 2020; Tanaka et al., 2017). Average farmer's yield was 2.0 and 1.5 t ha^{-1} in rainfed lowland and rainfed upland, respectively, with maximum attainable yields of 6.5 and 4.0 t ha^{-1}. Different agroecological factors, including soil fertility, rainfall distribution, groundwater supply, varieties, and a wide diversity of agricultural practices, including amount, timing and mode of fertilizer application and weeding contribute to this variation in yields across locations and countries. The gap between actual average and best farmer yields in rainfed lowland rice across Africa is recently estimated at 3.1 t ha^{-1}, and part of this yield gap can be closed by better fertilizer management (Senthilkumar, 2022). The average rate of N fertilizer used for rainfed rice production in West Africa, is 57.9 ± 50.2 kg N ha^{-1} (Johnson et al., 2023) compared to the world average of 118 kg N ha^{-1} (IFA, 2022).

Becker et al. (2001) and Niang et al. (2018) highlighted shortages of water and N as the major biophysical yield-limiting factors, which partly explained the large yield gap (3 – 9 t ha^{-1}) in rainfed lowlands (Dossou-Yovo et al., 2020; Tsujimoto et al., 2019). Catena positions may affect water and nutrient availability in inland valleys. Yet we lack a detailed understanding of the interaction between water and N rates across the gradient of natural water availability from the valley bottom to the middle slopes in the inland valleys of West Africa. Therefore, the aim of this study was to understand the variation in rice yield and response to N fertilizer rates along the catena of inland valleys in two contrasting agroecological zones. The specific objectives were to: (i) assess the interactions of catena position and N fertilizer rates on rice yield, nutrient use efficiencies, and economic profitability and (ii) identify the optimum N fertilizer rates along catena positions in inland valleys of West Africa.

2. Materials and methods

2.1. Site description

In previous research, Alemayehu et al. (2022) selected four regions in two different agro-ecological zones to describe rice-based farming systems in inland valleys: i.e., Ahafo Ano North and South in Ghana and Gagnoa and Bouaké in Côte d'Ivoire. Building on this understanding of the farming systems, we conducted field experiments in one inland valley in three of the four regions, excluding Ahafo Ano South. Within each region, the inland valley was selected for the possibility to cultivate rice across the catena. The experiments were carried out from 2019 to 2021 in three locations: (1) Yawtabrikrom in Ahafo Ano North District (6°50'N 2°14'W), (2) Ouragahio in Gagnoa region (6°19'N 5°57'W) and (3) Pangbabo in Bouaké region (7°47'N 5°04'W) (Fig. 1). In Yawtabrikrom and Ouragahio, the experiments were implemented from March to July and in Pangbabo, from June to November. In the second year, the experiments in Yawtabrikrom and Pangbabo were carried out in 2021 rather than 2020, because of the COVID-19 pandemic.

The inland valleys differed in soil characteristics and topography. The difference between the lowest and highest contour lines was 15 m in Yawtabrikrom and 20 m in Ouragahio and Pangbabo (Fig. 1). The contour line of the lowest catena position was 205 m above sea level (m.a.s.l.) in Yawtabrikrom while it was 220 and 295 m.a.s.l. in Ouragahio and Pangbabo respectively. The proportion of the inland valley occupied by the valley bottom was large in Yawtabrikrom (46 %) compared to Ouragahio (11 %) and Pangbabo (7 %) (Table 1). The rainfall distribution in Ahafo Ano North and Gagnoa is bimodal with a major wet season from March to July and a minor wet season from September to November. The rainfall pattern in Bouaké is unimodal with the wet season from April to October (Table 1). For Yawtabrikom, rainfall data were obtained from the Ministry of Agriculture (Mofa) district service situated at 7.6 km distance from the experimental site. The rainfall data of Ouragahio was obtained from the Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Métérologique which is located 20.5 km from experimental site. In Pangbabo, rainfall data was collected from a weather station of AfricaRice at 10.8 km distance from the experimental site. The dominant soils are Eutric Nitosols in Yawtabrikrom, Ferralic Cambisols in Ouragahio and Plinthic Acrisols in Pangbabo. A detailed overview of soil properties is provided in Table 4.

2.2. Experimental treatments and management

Experiments were established along the catena of the inland valleys based on the slope between the upper and lower contour lines, i.e. at the valley bottom (VB), the lower slope (LS), and the middle slope (MS). A split-plot design with three replications per N fertilizer treatment and catena position was used and established for two years (2019, 2020/2021). In the first year of experimentation (2019), four N fertilizer rates were used at Yawtabrikrom and Ouragahio (0, 22, 45 and 68 kg N ha^{-1}), and five N fertilizer rates at Pangbabo (0, 45, 68, 90 and 125 kg N ha^{-1}). Since yield responses in 2019 were linear up to the maximum applied N fertilizer rate, N rates were increased stepwise to 315 kg N ha^{-1} in the second year of experimentation based on studies by Ye et al. (2007) and Zhu et al. (2017).

Apart from the no-fertilizer control plots, a basal dose of N:P:K fertilizer (15:15:15) was applied across treatments at different rates: 73 kg ha^{-1} for the 11 kg P and 11 kg K ha^{-1} treatment, 146 kg ha^{-1} for the 22 kg P and 22 kg K ha^{-1} treatment and 220 kg ha^{-1} for the 33 kg P and 33 kg K ha^{-1} treatment. The basal fertilizer was applied once after land preparation and following the transplanting the same day (Table 2). Additional N was applied as top-dressing urea (46 % N) in two splits, 50 % at 20–25 days after transplanting and 50 % before panicle initiation which was 45–50 days after transplanting. Table 3 provides the overview of experimental treatments and measured parameters across locations and years.

To avoid residual effects of fertilizer from the previous season, the repeated experimental plots were established about 5 m away from the first year plots. The main plots measured 10 × 20 m in 2019 and 10 × 40 m in 2020/2021. Each sub-plot was 10 m × 5 m and bunds of 0.30 m height were constructed around each sub-plot to reduce runoff and fertilizer loss. All plots were manually tilled and levelled. The residue was burnt before tillage operation.

The rice nurseries were established at the beginning of the wet season in March (Yawtabrikrom and Ouragahio) and in June (Pangbabo).

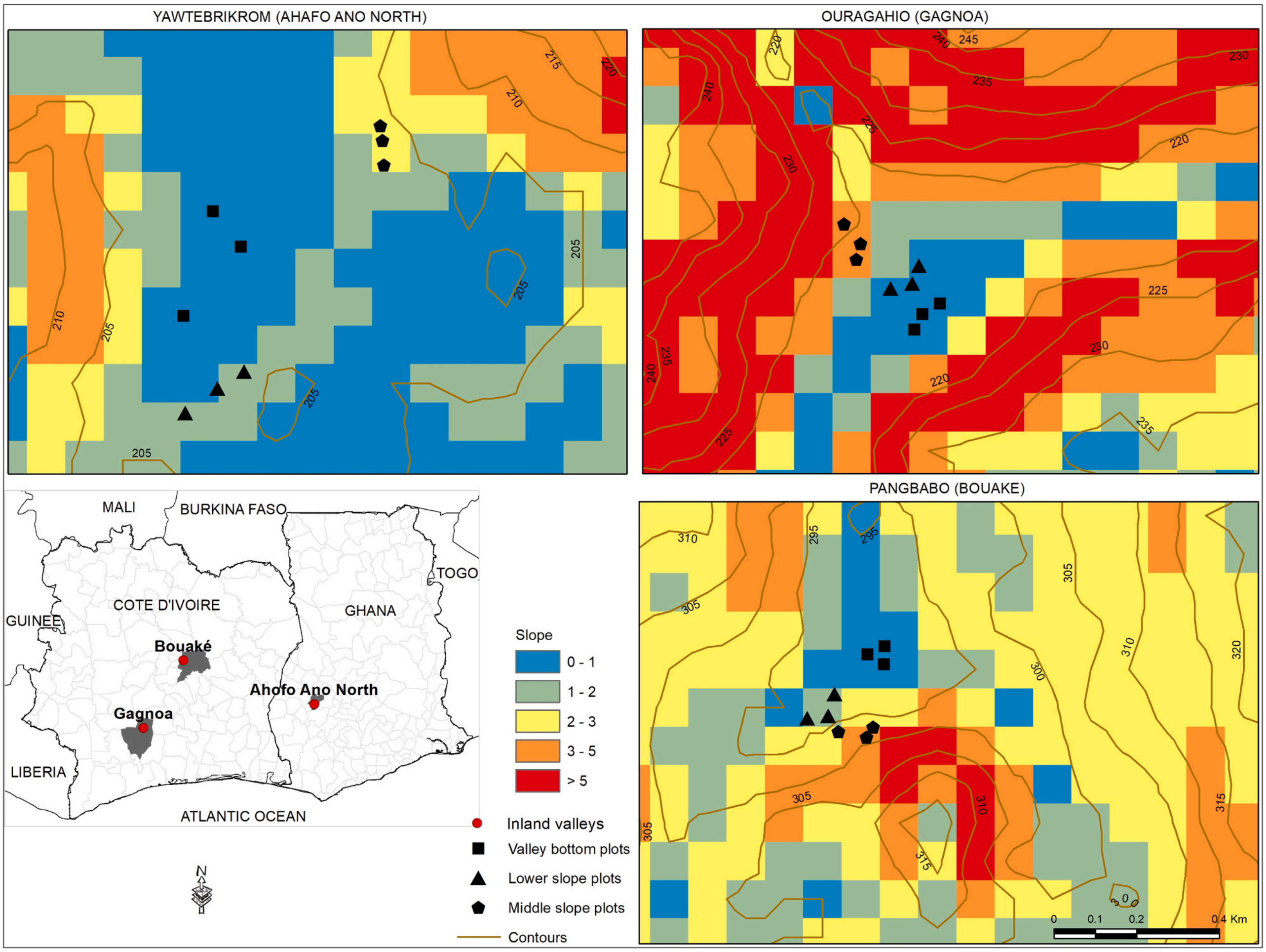

Fig. 1. Geographical location of the experimental sites in inland valleys of Yawtabrikrom, Ouragahio and Pangbabo. The red dots show the location of the inland valleys within the regions. The symbols ■, ▲ and ⬟ indicate the position of the experimental plots in IVs catena and represent valley bottom, lower slope and middle slope, respectively. The contour lines are expressed in m above sea level.

Two 20–25-day-old seedlings per hill were transplanted at 20 × 20 cm spacing at all locations. We used the rice variety WITA 9, which is a high yielding-rice cultivar developed by the International Institute of Tropical Agriculture (IITA). It is widely disseminated in Côte d'Ivoire and other countries (Saito et al., 2019). Weeds were controlled with Propanil (1.8 kg active ingredient ha^{-1}) and Triclopyr (0.36 kg active ingredient ha^{-1}) herbicides, sprayed 2 and 5 weeks after transplanting at 300 L ha^{-1}.

2.3. Sampling and measurements

Rice grain and straw yields were determined from a 4 m^2 net plot in the center of each experimental plot. The grain and straw were dried and the grain weights were adjusted to 14 % moisture content using a digital grain moisture meter (SATAKE Moistex Model SS-7). Plant samples for nutrient analysis were taken separately: ten hills of rice plants were sampled from the nearest row to the yield sampling plot at harvest time. The samples were sun-dried for 10–15 days and dried in an oven at 65°C for 48 h. The grain and the straw were separated prior to grinding. N, P and K contents in straw and grain were analysed in the Soil Laboratory of Council for Scientific and Industrial Research (CSIR) –Soil Research Institute (SRI) at Kumasi (Ghana). Nitrogen was analysed by the Kjeldahl method, total phosphorus by the vanadophosphomolybdate method and potassium by flame photometry.

Before land preparation in 2019, soil samples were collected at 0–15 cm and 15–30 cm depth, following a zig zag pattern at ten different spots, and bulked for each catena position. The soil samples were prepared (air-dried, crushed and packaged) at the AfricaRice Soil Laboratory in Côte d'Ivoire and sent to Yara Analytical Services in England for analysis. The soil particle size distribution (sand, clay and silt) was determined by laser diffraction. Soil pH (H_2O) was measured (1:2) in deionised water and organic matter content was assessed by the loss on ignition method at 400 °C. Available phosphorus was measured by Olsen extraction and estimation using a molybdenum blue method, and exchangeable cations (Na^+, Ca^{2+}, Mg^{2+}, K^+) were assessed by inductively coupled plasma (ICP) analysis in 1 M ammonium nitrate extracts.

Water availability was only measured during the growing season of the second year, as only then the required equipment was available. Piezometers were installed only in Pangbabo and tensiometers were used at all three locations. The water table was measured every five days during the growing season in each of the three catena positions in Pangbabo using a piezometer made of a 10 cm diameter, 120 cm long PVC pipe perforated with holes in the bottom 40 cm. Piezometers were installed near the experimental plots to a depth of 70 cm at the valley bottom and lower slope. At the middle slope, the PVC pipe was installed to a depth of 105 cm. Additionally, at all locations, the soil water potential was measured every five days until harvest using a tensiometer (Irrometer Company Inc., model SR which ranges from 0 to −100 kPa), installed at 15 cm depth in the sub-plots where 45 kg N ha^{-1} was applied in each catena position. In water-saturated soil, the water potential equals 0 kPa, at field capacity it varies from −33 kPa (heavy soil texture) to −10 kPa (light soil texture) and at the permanent wilting

Table 1
Biophysical characteristics of the inland valleys where the experiments were conducted.

Biophysical parameters	Inland valley		
	Yawtabrikrom (Ahafo Ano North)	Ouragahio (Gagnoa)	Pangbabo (Bouaké)
Agroecological zone[a]	Humid	Humid	Subhumid
Average rainfall[b] (mm)	1105	1400	1150
Rainfall pattern	Bimodal	Bimodal	Unimodal
Average temperature[c] (°C)	29	25.9	27
Dominant soil type (FAO)	Eutric Nitosols	Ferralic Cambisols	Plinthic Acrisols
Valley bottom (%)	46	11	7
Lower slope (%)	25	8	24
Middle slope (%)	28	41	66
Upslope (%)[e]	1	40	3
Cross sectional shape	wide	narrow	narrow
Water source	rainfall	rainfall	rainfall
Period of water availability	April to September	March to November	June to November

[a] (HarvestChoice, 2009),
[b] long-term annual mean rainfall from 1970 to 1991 data in Gagnoa (Cardinael et al., 2022; Ehounou et al., 2019), from 1994 to 2014 in Bouaké (Husson et al., 2022),
[c] long-term annual mean temperature from 1970 to 1991 in Gagnoa (Cardinael et al., 2022), from 1994 to 2014 in Bouaké (Husson et al., 2022),
[e] catena position which has a slope great than 5 % (Fig. 1)

Table 2
Nutrient rates (kg ha^{-1}) applied in the experiments in Ouragahio and Pangbabo in 2019 (first year) and in 2020 in Ouragahio and 2021 in Pangbabo (second year) in Côte d'Ivoire, and Yawtabrikom in Ghana in 2019 (first year) and 2021 (second year). All catena positions (valley bottom, lower slope and middle slope) received the same treatments.

Nutrient application rate (kg ha^{-1})					
First year			Second year		
N	P	K	N	P	K
0	0	0	0	0	0
22	11	11	45	22	22
45	22	22	90	33	33
68	33	33	135	33	33
90*	33*	33*	180	33	33
125*	33*	33*	225	33	33
-	-	-	270	33	33
-	-	-	315	33	33

* indicate treatments only applied in Pangbabo in first year.

point, it is −1500 kPa (Sui, 2017). In addition, rice phenological stage was recorded.

2.4. Data analysis

2.4.1. Soil properties and hydrological characteristics

Soil data were used to compute the average values of the soil chemical properties. Rainfall and soil water potential data were plotted to analyse the effect of spatial and temporal soil water variation on rice growth in each catena position.

2.4.2. Yield and nutrient uptake in responses to fertilizer

The response of rice yield to N fertilizer was linear in 2019 and 2020 and levelled off in 2021. Therefore, a linear regression (Eq. 1) was fitted to yields in 2019 and 2020, and a quadratic equation (Eq. 2) in 2021.

$$Y_{grain,N} = a + bN_{applied} \quad (1)$$

$$Y_{grain,N} = a + bN_{applied} + cN_{applied}{}^2 \quad (2)$$

Table 3
Overview of fertilizer treatments, measurements and agro-economic indicators analyzed across locations and years.

	Yawtabrikom		Ouragahio		Pangbabo	
	First year (2019)	Second year (2021)	First year (2019)	Second year (2020)	First year (2019)	Second year (2021)
Fertilizer rate (kg N ha^{-1})	0–68	0–315	0–68	0–315	0–125	0–315
Number of fertilizer treatments	4	8	4	8	6	8
Soil analysis	+		+		+	
Soil water potential		+		+		+
Soil water table						+
Agronomic N use efficiency	+	+	+	+	+	+
Internal efficiency for N, P and K		+		+		
Soil supply for N, P and K		+		+		
Recovery fraction for N, P and K		+		+		
Gross margin		+				+
Marginal rate of return to N		+				+
Value to cost ratio (VCR)	+	+	+	+	+	+

+ indicates the location and year in which soil and water data were collected, soil analysis was performed and indicators were computed.

where $Y_{grain,N}$ is the grain yield (14 % moisture; at $N_{applied}$ (kg ha^{-1}), $N_{applied}$ is the application rate (kg N ha^{-1}), a is the yield at 0 kg N applied, b is the increase in yield per unit increase in applied N and *c* is the quadratic coefficient (Harrell et al., 2011). The predicted maximum grain yield (Y_{max}) was obtained by equaling the first derivative of the response equation (Eq.2) to zero, solving for $N_{applied}$ and replacing the values of $N_{applied}$ in Eq.2 to get the Y_{max} (Hartinee et al., 2010).

N uptake (kg ha^{-1}) in the above-ground biomass (grain and straw) was computed using (Eq. 3). The P and K uptake were calculated similarly from P and K contents in the organs (straw and grain). The nutrient uptake was computed only for Yawtabrikom and Ouragahio in the second year. The reason was that the plant nutrient uptake data for the first year of the three locations and for the second year in Pangbabo are not available as the straw samples perished due to poor storage conditions.

$$N_{uptake} = \left(N_{grain\ content} \times Y_{grain,N}\right) + \left(N_{straw\ content} \times Y_{straw,N}\right) \quad (3)$$

with the N content in grain and straw expressed in kg N kg $^{-1}$ of the respective biomass and $Y_{straw,N}$ is the straw dry matter yield in kg ha^{-1} at $N_{applied}$.

2.4.3. Nutrient use efficiency

Nutrient use efficiency was assessed by three indicators: (1) agronomic nitrogen use efficiency (ANUE), (2) soil nutrient supply (SS) and (3) nutrient recovery fraction (RF). SS and RF were determined for all three macronutrients.

Agronomic nitrogen use efficiency (ANUE,) in the fertilized plots was calculated as grain yield increase compared to the yield at zero N applied, per kg of fertilizer N applied, (Eq. 4).

$$ANUE = \frac{Y_{grain,N} \quad - \quad Y_{grain,0}}{N_{applied}} \tag{4}$$

where $Y_{grain,0}$ is grain yield (kg ha^{-1}) without fertilizer application.

The relations between nutrient application, crop nutrient uptake and crop yield were visualized using a three-quadrant diagram (de Wit, 1953; Van Keulen, 1977; Van Duivenbooden et al., 1995). This diagram comprises three quadrants: (i) the relation between (fertilizer) nutrient input and crop yield, (ii) the relation between nutrient uptake by the crop and crop yield and (iii), the relation between (fertilizer) nutrient input and crop nutrient uptake. The value of the intercept in quadrant (iii) represents the amount of N fertilizer taken up in the absence of N fertilizer (Vos, 2009) and hence represents what the soil inherently supplies. On this basis, the soil supplies of N (SSN), P (SSP), and K (SSK) were estimated.

The nutrient recovery fraction (RF) is the quantity of a nutrient taken up per kg of that nutrient applied (Witt and Dobermann, 2002). The recovery fraction of N was derived from the fitted curve between N application and N uptake at the lower fertilizer rates, which indicates the highest recovery. As a blended fertilizer was used for P and K and part of the N, the effect of the single nutrients cannot be assessed. Hence, we calculated RFP as the difference between the phosphorus uptake at the highest fertilizer rate treatment (315 N – 33 P – 33 K) and at the control fertilizer rate treatment (0 N – 0 P – 0 K), divided by the difference between $P_{applied(2)}$ (33 kg P ha^{-1}) and $P_{applied(1)}$ (0 kg P ha^{-1}) of the two treatments, using Eq. 5. The RFK was calculated similarly.

$$RFP = \frac{P_{uptake_{(315N-33P-33K)}} \quad - \quad P_{uptake_{(0N-0P-0K)}}}{P_{applied(2)} \quad - \quad P_{applied(1)}} \tag{5}$$

2.4.4. Visual lodging rate

Lodging of rice plants to variable extents was observed during the maturation stage in Yawtabrikrom and Pangbabo during the second year of experimentation. We defined lodging rate before physiological maturity as a canopy height reduction due to bending of the shoot from the vertical position, expressed as the percentage of the plot area lodged (Eq. 6). Additionally, we estimated the yield loss due to lodging. Since most rice stems were broken at 25–50 % of the stem length, it resulted in a canopy height reduction of 50–75 %. Setter et al. (1997) reported a 1 % yield loss per 2 % canopy height reduction, translating into the estimation of yield losses due to lodging as follows: (Eq. 7). Yield loss is estimated for both 50 % and 75 % height loss of the crop.

$$Lodging\ rate = \frac{\text{lodged area in plot}}{\text{plot area}} \times 100\% \tag{6}$$

$$Yield\ loss\ due\ to\ lodging = Lodging\ rate \times \ Y_{grain,N} \ \times \ Height\ reduction \tag{7}$$

2.4.5. Economic analysis

An economic analysis was conducted based on three indicators, i.e. the gross margins, the marginal rates of return (MRR) and the value to cost ratio (VCR). The gross margin (Euro ha^{-1}) was computed by subtracting the total variable costs from the total revenue following (Eq. 8). The total variable costs (Euro ha^{-1}) represent the production costs including all labour for agricultural operations (tillage, weeding, fertilizer application, harvesting) and cost of inputs (seed, herbicide, fertilizer). The details of input and labour costs are summarized in Table S2 of the Supplementary material.

$$\text{Gross margin} = Y_{grain,N} \times P_y \ - \text{total variable cost}_N \tag{8}$$

where P_y is the rice purchase price (Euro kg^{-1}), total variable cost_N is the cost of all inputs, including the cost of N fertilizer, herbicide and seed (Euro kg^{-1}) plus the labour cost for all agricultural operations at the local market in Kumasi (Ghana) and in Gagnoa and Bouaké (Côte d'Ivoire). From our survey data, in Yawtabrikrom, on average the grain price was 0.25 Euro kg^{-1} and N fertilizer costed 0.96 Euro kg^{-1} in 2021. In Ouragahio and Pangbabo, the grain price was 0.30 Euro kg^{-1} and N fertilizer costed 1.45 Euro kg^{-1} in 2021.

The marginal rate of return to N (MRR) expresses the increase of the gross margin for one unit of extra N application. MRR was calculated by dividing the change in gross margin of two consecutive N application rates (i and i+1) by the change in costs of the applied N fertilizer, using (Eq. 9) (Bezabeh et al., 2021; CIMMYT, 1988).

$$\text{MRR} = \frac{\text{Gross margin}_{(i+1)} - \text{Gross margin}_{(i)}}{\text{Cost N applied}_{(i+1)} - \text{Cost N applied}_{(i)}} \tag{9}$$

From this equation, it can be derived that at MRR values above 1, the application of additional fertilizer is profitable whereas at MRR values below 1, the costs of additional fertilizers exceed the economic gains derived from the crop.

The value to cost ratio (VCR) comprises a more comprehensive indicator than the MRR. The VCR was computed by dividing the marginal revenues of the N fertilizer treatment over all the costs related to the N fertilizer treatment, which comprises the N fertilizer purchase costs, the labor costs to apply N fertilizer, and the additional costs to harvest a fertilized crop compared to an unfertilized crop (Fermont et al., 2010; Kayumba et al., 2023). VCR is calculated using (Eq. 10).

$$VCR = \frac{(Y_{grain,N} \quad - \quad Y_{grain,0}) \quad \times \quad P_y}{Cost_N + \ \text{Cost}_{app} \ + \ Cost_{\Delta h}} \tag{10}$$

Where Cost_N is the purchase cost of N fertilizer to achieve $Y_{grain,N}$, Cost_{app} is the application cost of that amount of N fertilizer and $\text{Cost}_{\Delta h}$ is the extra harvesting cost due to yield increase related to N applied.

The recommended N fertilizer rates are determined based on the minimum N fertilizer rate needed to achieve the target yield, ensuring a value to cost ratio greater than 2 (Burke et al., 2019; Van Noordwijk and Scholten, 1994). Hence a VCR of 2 could be interpreted as the threshold level under water unlimited production environments. Guo et al. (2009) and Okebalama et al. (2016) suggested to consider a VCR of > 4 under climate risk production environments such as rainfed conditions. As the experiments of the current study were conducted under rainfed conditions, we used a VCR > 4 as the benchmark.

2.4.6. Statistical analysis

Analysis of variance (ANOVA) was performed based on linear mixed model procedure using the Restricted Maximum Likelihood (REML) in R software 3.5.0 version. The fixed factors of the model were location, catena position and N fertilizer rate. Year was considered as random factor. The difference between treatment means was compared with Bonferroni test at $p < 0.05$. For the multiple mean comparisons, different letters indicate significant differences according to Tukey's HSD test ($p \leq 0.05$). Linear and quadratic regression models were fitted to describe the rice yield response to fertilizer N rates in both years of experimentation.

3. Results

3.1. Soil properties and hydrological characteristics across the inland valley catena

Soil characteristics varied between and within inland valleys. In Yawtabrikrom both the valley bottom and lower slope were of loamy texture, in Pangbabo soil texture ranged from clay-loam in the valley bottom to loam in the lower and middle slopes, while in Ouragahio all three positions were of sandy-loam (Table 4). The clay proportion was higher in the valley bottom (8–27 %) compared with the lower slope (7–20 %) and middle slope (6–15 %). The soils in Ouragahio and Pangbabo had soil pH values close to 5, whereas in Yawtabrikrom the pH was 6.8. In the topsoil (0–15 cm), the soil organic carbon (SOC) content was similar across the catena positions in Yawtabrikrom (average:

Table 4
Soil properties of the 0–15 cm and 15–30 cm layer at experimental fields in Yawtabrikrom, and Ouragahio and 0–15 cm layer in Pangbabo at different catena positions (VB=valley bottom, LS=lower slope and MS= middle slope).

Experimental locations	Yawtabrikrom (Ahafo Ano North)						Ouragahio (Gagnoa)						Pangbabo (Bouaké)		
Soil layer	0–15 cm			15–30 cm			0–15 cm			15–30 cm			0–15 cm		
Catena position	VB	LS	MS	VB	LS	MS	VB	LS	MS	VB	LS	MS	VB	LS	MS
Soil texture[a] (USDA)	loam	loam	sandy loam	loam	loam	sandy loam	sandy loam	sandy loam	sandy loam	loam	sandy loam	sandy loam	clay loam	loam	loam
Soil pH (1:2.5, H_2O)	7.6	6.3	6.5	8.0	6.4	6.5	4.8	4.9	5.1	4.5	5.0	5.3	5.0	5.0	5.6
Organic carbon (%)	2.6	2.5	2.8	1.4	1.1	1.1	4.8	4.1	2.6	1.2	1.6	0.9	2.3	1.5	1.7
P-Olsen (mg kg^{-1})	22.5	22.4	28.8	18.3	10.7	14.0	13.3	10.9	15.3	4.3	7.4	7.4	9.5	7.8	10.5
Ca^{2+} (cmol⁺ kg^{-1})	12.57	7.43	8.9	9.6	5.7	6.8	2.9	3.3	3.0	2.1	1.4	2.1	4.0	3.0	4.2
Mg^{2+}(cmol⁺ kg^{-1})	5.0	3.95	2.83	5.0	4.0	1.7	0.8	1.0	0.8	1.0	0.4	0.9	1.7	1.3	1.6
K^+ (cmol⁺ kg^{-1})	0.19	0.22	0.35	0.15	0.12	0.11	0.12	0.13	0.07	0.02	0.05	0.03	0.20	0.10	0.24
Na^+ (cmol⁺ kg^{-1})	1.57	0.59	0.19	2.17	1.57	0.50	0.26	0.31	0.29	0.27	0.12	0.70	0.26	0.22	0.14
CEC (cmol⁺ kg^{-1})	21.0	13.7	14.2	18.2	12.3	10.2	7.7	8.0	5.8	5.9	3.3	3.8	10.9	8.2	8.9
Base saturation (%)	92.0	89.0	86.4	93.0	92.6	89.3	53.0	59.3	71.7	57.5	59.5	98.2	56.5	56.3	69.4

[a] soil textural class defined according to USDA system. Critical soil nutrients level for rice are: P(Olsen) < 5 mg kg^{-1} and K < 0.15 $cmol^+$ kg^{-1} (Dobermann and Fairhurst, 2000a; Kalala et al., 2017; Senthilkumar et al., 2018).

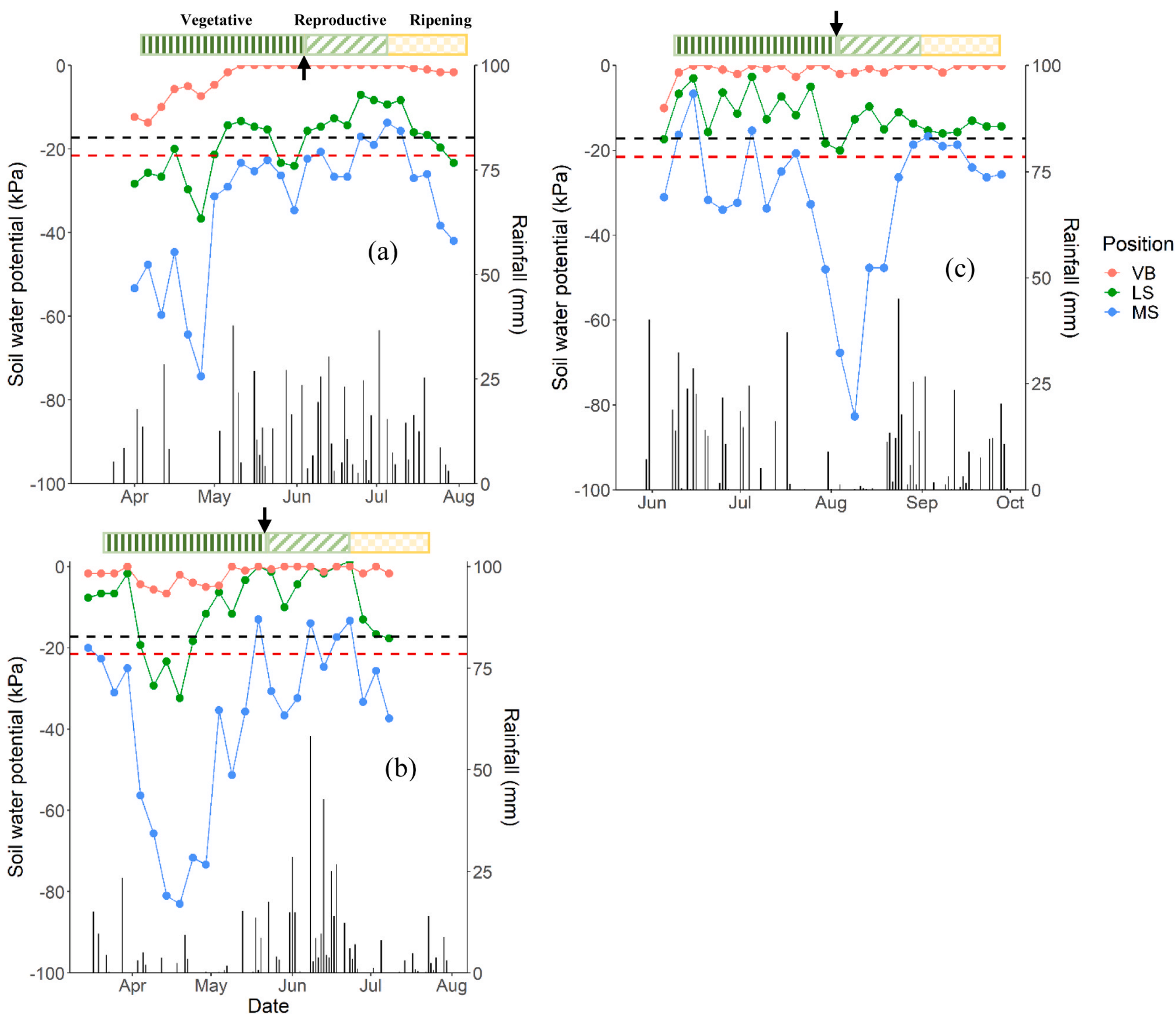

Fig. 2. Temporal variation of rainfall and soil water potential in (a) Yawtabrikrom 2021, (b) Ouragahio 2020, (c) Pangbabo 2021 at three catena positions during the rice growing season. The red, green, and blue circles indicate soil water potential at different catena positions (VB=valley bottom, LS=lower slope and MS= middle slope). The dashed black line represents the typical field capacity of sandy loam soil (-17,2 kPa, lower and middle slope) and the dashed red line indicates the field capacity of sandy clay loam soil (-21.5 kPa, valley bottom) based on the finding of Phogat et al. (2022). The black arrow indicates rice panicle initiation. The main rice growing periods are from March to July in Yawtabrikrom and Ouragahio, and from June to October in Pangbabo.

2.6 %). In Ouragahio, SOC was higher in the valley bottom (4.8 %), than the lower and middle slopes (4.1 and 2.6 % respectively). Also, in Pangbabo the SOC was higher in the valley bottom (2.3 %) than in the lower and middle slopes (average 1.6). Additionally, the mean P content in the soil varied among the inland valleys, with 22 mg kg^{-1} in Yawtabrikrom and ≤ 15 mg kg^{-1} in Ouragahio and Pangbabo across catena positions. Soil K content in the topsoil was low ranging between 0.1 and 0.35 cmol+ kg^{-1} across all locations. The soil at the three locations was relatively limited in K. The cation exchange capacity (CEC) was higher in the valley bottom than in the lower and middle slopes in all locations. The base saturation was higher than 85 % in all catena positions in Yawtabrikrom and 60 % across catena positions in Ouragahio and Pangbabo.

Soil water potential (SWP) varied between - 14 and 0 kPa in the valley bottom, −35 and 0 kPa in the lower slope, and - 83 to −5 kPa in the middle slope over all locations (Fig. 2a-c). During the growing period, water deficit (SWP<-40 kPa) was severe at the middle slope across locations. The soil water potential at the middle slope varied between −78 and −12 kPa in Yawtabrikrom, - 82 and - 15 kPa in Ouragahio and −83 to −5 kPa in Pangbabo. Considering the field capacity threshold, the water deficit occurred only in the middle slope with an average <-30 kPa (Fig. 2 and Supplementary Table S1). The groundwater table in the valley bottom and lower slope of Pangbabo increased during the wet season due to water accumulation in the two catena positions (Fig. S6). The average water table value was −7.0 ± - 9.3 cm at the valley bottom, −17.6 ± - 11.0 cm at the lower slope, and −67.0 ± - 9.2 cm at the middle slope (Supplementary Table S1). Waterlogging was observed in the valley bottom, and the water level reached 11 cm between September and October 2021. In contrast to the middle slope, water level was < −50 cm and it fluctuated from −85 to −52 cm (Fig. S6).

3.2. Grain yield and lodging

3.2.1. Grain yield

Rice grain yield differed significantly with N rate and catena position. There was no significant difference in rice yield between the locations and there were no significant N rate × catena position, N rate × location or catena position × location interaction effects on rice yields (Table 5). Fig. 3 shows the relationship between N application and the grain yield for each inland valley, catena position and year. Rice yields varied across catena positions. In Yawtabrikom, yields ranged from 2.1 to 7.4 t ha^{-1} (valley bottom), from 0.9 to 6.5 t ha^{-1} (lower slope) and from 1.0 to 5.6 t ha^{-1} (middle slope). In Ouragahio, it varied from 3.0 to 6.5 t ha^{-1} (valley bottom), from 1.5 to 5.9 t ha^{-1} (lower slope) and from 0.9 to 2.9 t ha^{-1} (middle slope). In Pangbabo, rice yields varied from 3.6 to 7.8 t ha^{-1} (valley bottom), from 3.0 to 6.5 t ha^{-1} (lower slope) and from 2.4 to 5.5 t ha^{-1} (middle slope). Rice yields were highest in the valley bottoms (from 2.1 to 7.8 t ha^{-1}) and lowest in the middle slopes (from 0.9 to 5.6 t ha^{-1}) across locations and years. Rice yields showed a clear linear response to increasing N at lower rates (0–120 kg N ha^{-1}) with decreasing increments at higher rates (from 135 to 315 kg N ha^{-1}), except for Ouragahio in 2020 where the response was still linear. Across the valley bottom, lower slope and middle slope positions, average control rice yields varied between 3.2, 2.3, 1.9 t ha^{-1} in Yawtabrikrom, between 3.4, 2.0, 1.0 t ha^{-1} in Ouragahio, and between 3.7, 3.0, 2.5 t ha^{-1} in Pangbabo respectively. The yields in control plots in the second year were greater than those in the first year at all catena positions in Yawtabrikom. In Pangbabo this was the case also for the valley bottom, but the yields in control plots in the lower slope and middle slope were not significantly different in the second year. In Ouragahio, in the second year (2020), all the rice planted (in all plots) in the middle slope died due to water shortage as the dry spell lasts for six weeks after planting. The valley bottom in Ouragahio yielded less in the second year (2020) with 3.0 t ha^{-1} compared to the first year (2019) with 4.3 t ha^{-1}, but the lower slope had a larger yield (2.5 t ha^{-1}) without N application in the second year (2020) than in first year (2019) with 1.5 t ha^{-1}.

Table 5
Analysis of variance of the effect of position, N rate and locations on rice yield.

Source of variation	df	F value	Pr >F
Nitrogen rate (N)	10	69.34	0.014*
Catena position (P)	2	30.84	0.031*
Locations (L)	2	2.77	0.264ns
N × P	20	3.99	0.219ns
N × L	17	2.16	0.362ns
P × L	4	1.20	0.499ns

df: degrees of freedom;
* significant at $p<0.05$. ns: not significant - $p>0.05$

3.2.2. Lodging and yield loss

No lodging was observed in the first year of experimentation. Lodging of rice plants occurred in the valley bottom and lower slope when N was applied at a rate above 90 kg N ha^{-1} in Yawtabrikrom and Pangbabo during the second year of the experiment (Fig. 4), but it was not observed in the middle slope of the inland valleys. In Ouragahio, lodging was not observed. The lodging rate increased with N rate and was most severe in the valley bottoms. Lodging rate ranged from 5 % to 25 % of the crop at the lower slope and from 10 % to 80 % at the valley bottom. On average, lodging was more prevalent at Yawtabrikrom than Pangbabo. Estimated yield losses due to lodging ranged between 2 % and 10 % at lower slope while it varied from 5 % to 25 % at the valley bottom (Supplementary Fig. S4). The yield losses were higher in the valley bottom than in the lower slope at both locations. Considering 50 % of the canopy height reduction, estimated yield losses ranged between 0.2 ± 0.1 t ha^{-1} at the lower slope and 0.7 ± 0.2 t ha^{-1} at the valley bottom in Yawtabrikrom. It varied from 0.3 ± 0.2 t ha^{-1} at the lower slope to 0.4 ± 0.2 t ha^{-1} at the valley bottom in Pangbabo. However, with 75 % of the canopy height reduction, estimated yield losses ranged between 0.3 ± 0.2 t ha^{-1} and 0.4 ± 0.2 t ha^{-1} at the lower slope, and between 0.7 ± 0.2 t ha^{-1} and 1.0 ± 0.6 t ha^{-1} at the valley bottom in Pangbabo and Yawtabrikrom, respectively.

3.3. Nutrient use efficiency

3.3.1. Agronomic N use efficiency

The agronomic N use efficiency (ANUE) was derived from the slope of the yield response curves in Fig. 3. and Fig S1. (Supplementary material). ANUE varied across catena positions, locations and years (Table 6) and was always highest in the valley bottom and lowest in the middle slope. The only exception was in the first year in Ouragahio, where the lower slope had the highest agronomic N use efficiency. Higher agronomic N use efficiencies were achieved at lower N rates. They were constant up to 125 kg N ha^{-1} and ranged from 32 to 48 kg grain kg^{-1} N in the valley bottom, 31–45 kg grain kg^{-1} N in the lower slope and 17–30 kg grain kg^{-1} N in the middle slope across locations in first year. In the second year, at higher N rates (>125 kg N ha^{-1}) the ANUE varied between 9 and 21 kg grain kg^{-1} N in the valley bottom, 7–22 kg grain kg^{-1} N in the lower slope and 11–14 kg grain kg^{-1} N in the middle slope across locations. For the second year, the ANUE values were low compared to the first year in all locations and the ANUE was exceptionally low (< 10 kg kg^{-1}) in Ouragahio.

3.3.2. Soil nutrient supply

The soil nutrient supply was the nutrient uptake in control plots (0N-0P-0K) and was derived from the three-quadrant diagram (Fig. 5 and Supplementary Fig. S2 and S3). The soil nitrogen and potassium supply at all catena positions in Yawtabrikrom were higher than the ones in Ouragahio. The soil nutrient supply was higher at the valley bottom compared to lower slope in both locations. Average soil nitrogen supply was 54, 76 and 80 kg N ha^{-1} in Yawtabrikrom at middle slope, lower slope and valley bottom, respectively, and 48 and 62 kg N ha^{-1} in

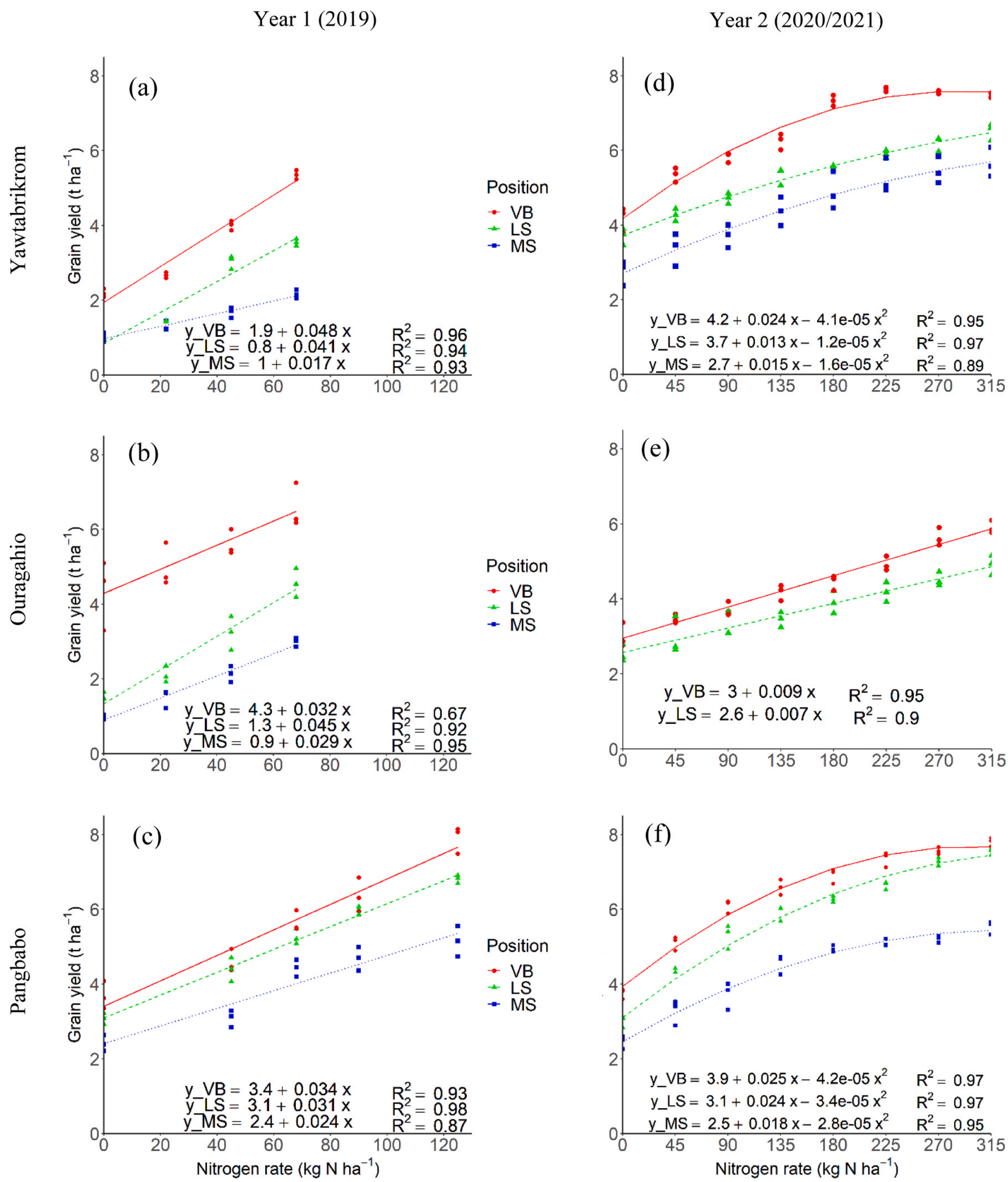

Fig. 3. Rice yield responses to nitrogen application at three positions in an inland valley catena. (VB=valley bottom, LS=lower slope and MS= middle slope), in (a) Yawtabrikrom 2019, (b) Ouragahio 2019, (c) Pangbabo 2019, (d)Yawtabrikrom 2021, (e)* Ouragahio 2020, and (f) Pangbabo 2021. * In Ouragahio in 2020 all rice plants in the middle slope treatments died due to water shortage.

Ouragahio at lower slope and valley bottom, respectively. Estimated soil phosphorus supply was 5, 5 and 8 kg P ha^{-1} in Yawtabrikrom at middle slope, lower slope, and valley bottom, respectively, and 6 and 9 kg P ha^{-1} in Ouragahio at lower slope and valley bottom, respectively (Supplementary Fig. S2 and S3). The mean soil potassium supplies were 13, 24 and 29 kg K ha^{-1} in Yawtabrikrom at middle slope, lower slope and valley bottom, respectively, and 11 and 14 kg K ha^{-1} in Ouragahio at lower slope, and valley bottom, respectively.

3.3.3. Nutrient recovery fraction

The recovery fraction of N was larger in Yawtabrikrom than in Ouragahio (Table 7). The recovery fraction of N was higher at the middle slope with 0.39 kg kg^{-1} followed by the valley bottom with 0.31 kg kg^{-1} and the lower slope with 0.25 kg kg^{-1}. However, the recovery fraction of P was highest at the middle slope of Yawtabrikrom (0.78 kg kg^{-1}). The recovery fraction of k in the valley bottom of Ouragahio (0.56 kg kg^{-1}) were greater than those in Yawtabrikrom (0.43 kg kg^{-1}) (Table 7).

3.4. Economic analysis

3.4.1. Value to cost ratio

The value to cost ratio (VCR) of N fertilizer varied across catena positions in each location for both years (Table 8). The VCR ranged from

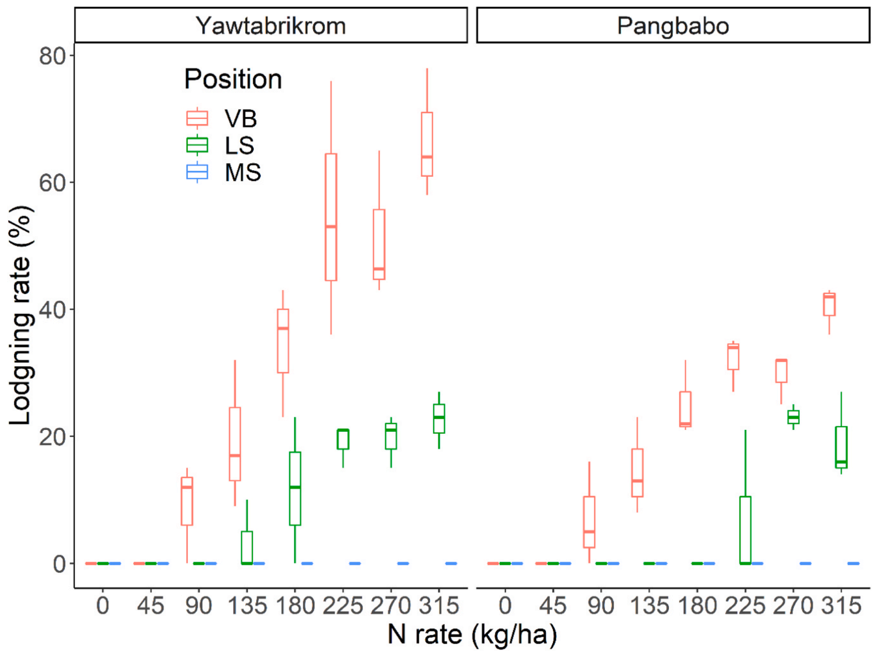

Fig. 4. The lodging rate (%) related N application at the three catena positions (VB=valley bottom, LS=lower slope and MS= middle slope) in Yawtabrikrom and Pangbabo in second year (2021).

Table 6
Effect of the inland valley catena position (VB=valley bottom, LS=lower slope and MS= middle slope), N rates and locations on the agronomic nitrogen use efficiency (ANUE in kg kg^{-1}).

Location	Catena position	First year (2019)		Second year (2020/2021)	
		N rate (kg N ha^{-1})[a]	ANUE (kg kg^{-1}).	N rate (kg N ha^{-1})[b]	ANUE (kg kg^{-1})
Yawtabrikom	VB	0–68	48	0–200	16
	LS	0–68	41	0–260	10
	MS	0–68	17	0–244	11
Ouragahio	VB	0–68	32	0–315	9
	LS	0–68	45	0–315	7
	MS	0–68	30	-	-
Pangbabo	VB	0–125	34	0–163	21
	LS	0–125	31	0–174	22
	MS	0–125	24	0–197	14

[a] the highest N rate applied,
[b] N rate at the break point of the linear plateau yield response curve (Fig. 3 and Supplementary Fig. S1)

2.2 to 6.0 (valley bottom), from 1.9 to 5.4 (lower slope) and from 1.9 to 4.3 (middle slope) in Yawtabrikrom. In Ouragahio the VCR varied from 1.5 to 4.5 (valley bottom), from 1.3 to 5.6 (lower slope) and from 3.6 to 4.3 (middle slope). In Pangbabo, it ranged between 2.2 and 4.7 (valley bottom), between 2.4 and 4.5 (lower slope) and between 1.7 and 4.3 (middle slope). Overall and across all catenary positions the highest VCR were observed at an N rate of 68 kg N ha^{-1} in Yawtabrikrom (VCR 3.2–6.0) and Ouragahio (VCR 4.3–5.6). In Pangbabo, highest VCR values were observed at an N rate of 90 kg N ha^{-1} with 4.7 in the valley bottom, and at a rate of 45 kg N ha^{-1} with 4.5 and 4.3 in the lower and middle slope, respectively.

3.4.2. Gross margin and marginal rate of return

The gross margin and marginal rate of return were computed in Yawtabrikrom and in Pangbabo in the second year, but not in Ouragahio because the yield response did not fit to a quadratic regression. The greatest gross margin was found in the valley bottom at all N rates and the smallest at the middle slope in both locations (Supplementary Fig. S5). The gross margin at each catena position in Yawtabrikrom was higher than those in Pangbabo. The gross margin ranged from 385 to 1560 Euro ha^{-1} in Yawtabrikrom, and from 370 to 1320 Euro ha^{-1} in Pangbabo. The gross margin was largest at an N application rate of 240 kg N ha^{-1} in the valley bottom of both locations. The marginal rate of return (MRR) was greater at the lower N rates and decreased to 1 or less starting from 225 kg N ha^{-1} for all catena positions and locations (Supplementary Table S3). Apart from the middle slope at Pangbabo where it was already below 1 at 180 kg N ha^{-1}, suggesting that from 180 k N ha^{-1} onwards, fertilizers application was not economically profitable.

4. Discussion

The aim of this study was to understand the influence of catena position on rice yield and on the crop response to applied nitrogen. The study convincingly demonstrated similar, mostly linear N-fertilizer yield responses across locations, years and positions along the catena. Consistent higher rice yields were recorded with either increasing N rates or decreasing catena positions, and no interaction effects between fertilizer and catena position were observed. Below we first describe the differences between the study locations and the influence of catena position on water availability. We then discuss the response of rice yield to N, P and K fertilizer and the efficiency of nitrogen applied across locations and catenary positions before concluding with a discussion of the economic benefits of the nitrogen fertilizer application rates.

4.1. Water availability across catenary positions of inland valleys

Water availability in inland valleys depends on several factors (e.g. soil texture, slope) which relate to catenary position. We can assume that rainfall is similar for different catenary positions within each location, but that water is redistributed through run-on, run-off and percolation along the catena. The soil texture also differs among catenary positions, with more clay accumulation and better water storage at lower inland valley positions. Inland valleys vary in terms of topography, climate, and soil texture, but they present similar hydraulic patterns, with soil water

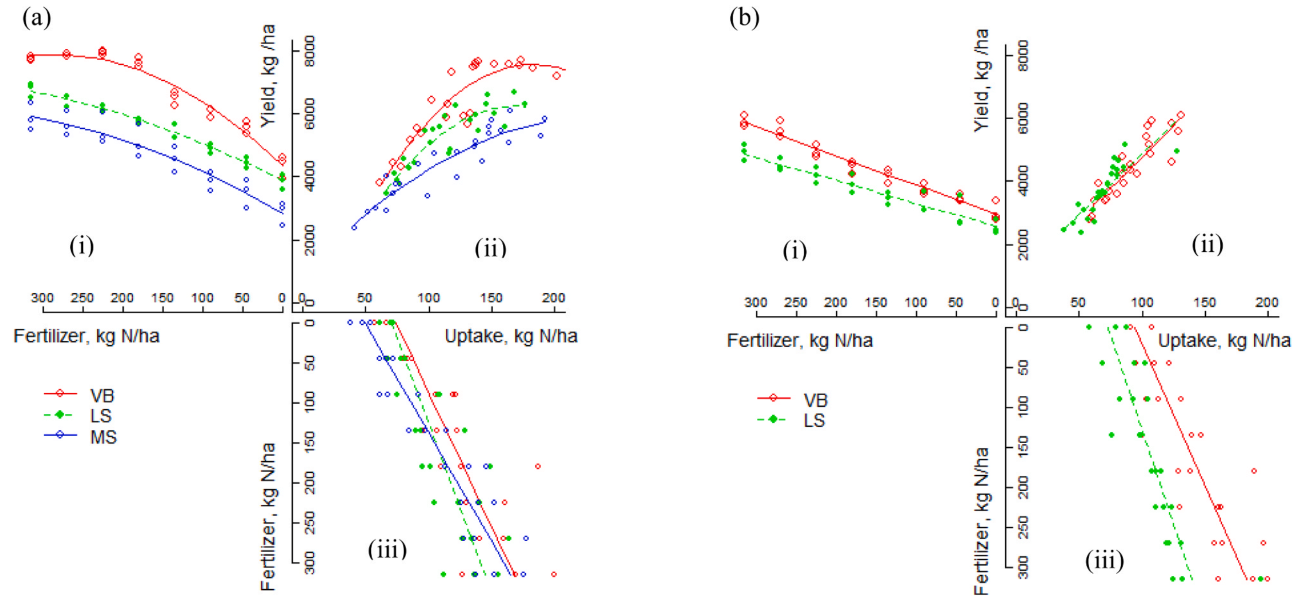

Fig. 5. Three-quadrant diagram showing the relation between (i) N application rate and rice yield, (ii) N uptake and yield, and (iii) N application rate and N uptake in (a) Yawtabrikrom 2021 and (b) Ouragahio 2020, at VB=valley bottom (red), LS=lower slope (green) and MS=middle slope (blue) in the second year.

Table 7
Soil supply (SS in kg nutrients ha^{-1}) and recovery fraction (RF in kg kg^{-1}) of N, P and K in Yawtabrikrom and Ouragahio in the second experimental year at three positions in an inland valley catena (VB=valley bottom, LS=lower slope and MS= middle slope).

Indicators	Yawtabrikrom			Ouragahio	
	VB	LS	MS	VB	LS
Derived from 3-quadrant figures					
SSN	80	76	54	62	48
SSP	8.5	5.3	5.1	9	6
SSK	29	24	13	14	11
RFN	0.31	0.25	0.39	0.18	0.14
Calculated rice grain and straw nutrient data					
RFP	0.42	0.49	0.70	0.48	0.48
RFK	0.43	0.57	0.78	0.56	0.43

Table 8
Average Value to cost ratio of N fertilizer for rainfed rice at three catena positions (VB=valley bottom, LS=lower slope and MS= middle slope) in the inland valleys in Côte d'Ivoire and Ghana over two years.

N rate (kg N ha^{-1})	Value to cost ratio (VCR)								
	Yawtabrikrom			Ouragahio			Pangbabo		
	VB	LS	MS	VB	LS	MS	VB	LS	MS
0	-	-	-	-	-	-	-	-	-
22	3.8	3.8	2.6	3.7	3.9	3.6	3.8	3.9	2.7
45	4.9	4.3	2.8	2.9	3.4	3.9	4.2	4.5	4.3
68	6.0	5.4	3.2	4.5	5.6	4.3	4.1	4.2	3.1
90	3.4	2.3	2.2	1.5	1.5	-	4.7	4.3	3.4
135	2.9	2.4	2.4	1.6	1.3	-	3.3	3.4	2.6
180	3.3	2.1	2.4	1.5	1.4	-	2.9	2.9	2.4
225	2.9	2.0	2.3	1.5	1.3	-	2.7	2.7	2.0
270	2.5	2.0	2.1	1.7	1.3	-	2.4	2.6	1.8
315	2.2	1.9	1.9	1.7	1.4	-	2.2	2.4	1.7

availability decreasing across the catena from the valley bottom to the middle slope. Gabiri et al. (2018) indicated that soil properties, topography and rainfall are the main factors which control the dynamics of soil water in inland valleys. Across all three study locations, the soil had a higher silt and clay content and higher soil organic carbon in the valley bottom compared with other catena positions, which confirms earlier findings (Andriesse et al., 1994; Ogban and Babalola, 2003). Clay soil has higher water holding capacity, and higher soil organic carbon which is associated with high rice yields (Dossou-Yovo et al., 2020). Our measurements showed the expected pattern where water availability was higher in the valley bottom and decreased progressively in the lower slope and middle slope across locations. A soil water potential below −45 kPa in a sandy loam soil, indicates a severe water deficit which reduces rice yields (Yang et al., 2007). The water deficit expresses the level at which the water content in soil is less than the plant water requirement, and it is commonly known as drought (Cabuslay et al., 2002; Suleiman et al., 2022). Phogat et al. (2022) found that at a field capacity, soil water potential value were −17.2 kPa in sandy loam soil and −21.5 kPa sandy clay loam soil. Kumar et al. (2017) and Panigrahi and Das (2018) reported that the optimal soil water potential value for rice ranges from −45 to −30 kPa in sandy loam and silt loam soils. The average of our measurements of soil water potential indicated −1.8 kPa in the valley bottom and −13.4 kPa at lower slope. There was no water deficit in valley bottom and lower slope. However, water deficit was observed in the middle slope during the period from April to May in Yawtabrikrom and Ouragahio, and from mid-July to end August in Pangbabo (SWP $<$ - 45 kPa). The water deficit occurred more often in the middle slope at different rice development stages during the growing season, because of the higher slope position and lower clay content (6–15 %) in the surface horizon. For instance, in Yawtabrikrom, the water deficit was observed during the vegetative stage for two weeks. It lasted for six weeks at the vegetative stage in Ouragahio where all the rice plants died due to lack of water. In Pangbabo, the water deficit happened around panicle initiation which is a critical moment for rice yield formation.

4.2. Variation of rice yields across catenary positions

The yield variation among catena positions that we observed followed the same pattern as water availability. Across locations and years, rice yields were highest in the valley bottoms (from 2.1 to 7.8 t ha^{-1}), followed by the lower slopes (from 1.0 to 7.5 t ha^{-1}) and the middle slopes (from 0.9 to 5.6 t ha^{-1}). This result is consistent with previous studies in rainfed rice production systems in inland valleys across West Africa (Niang et al., 2018; Touré et al., 2009; Worou et al., 2013). For example, Touré et al. (2009), observed yields of 3.3 and 1.3 t ha^{-1} at the valley bottom and the valley fringe, respectively. However, Worou et al. (2013) reported that the yield at upslope positions was higher than in downslope for three consecutive growing seasons in the north of Benin. In that study there was a plausible explanation for this observation as iron content of the soil downslope was likely too high. Simulated yields in the study by Grotelüschen et al. (2022) indicated similarly higher yield potentials in the mid valley and the valley bottom and this was explained by more favourable hydro-edaphic conditions.

Without fertilizer, average rice yields of 2.5 and 3.5 t ha^{-1} were observed, respectively at the lower slope and the valley bottom for the three locations in both years. Under irrigated lowland conditions in Côte d'Ivoire, Saito et al. (2019) obtained similar yield which ranged between 2.5 and 3.4 t ha^{-1} with the same rice cultivar (WITA 9) without fertilizer application. Ofori et al. (2005) also achieved yields of 2.8 and 4.4 t ha^{-1} with WITA 9 without applying fertilizer, respectively under rainfed and irrigated lowland conditions in Ghana. This difference between experiments and farmers' practice was explained by the improved agronomic practices applied in the experimental plots. In Ouragahio the rains ceased six weeks after planting in 2020 leading to drought so severe in the middle slope that the rice crop failed completely irrespective of the nitrogen fertilizer application rates. This drought occurred between the vegetative and reproduction stages. Water deficit is a main abiotic factor which limits yield or causes total yield loss depending on the duration of the drought and the plant development stage on which it occurs. Severe water deficit during the reproductive stage can cause more than 50 % of rice yield loss (Lafitte et al., 2004; Venuprasad et al., 2007).

4.3. Rice yield response to nitrogen

Nitrogen is the most yield limiting nutrient for rice production (Dobermann et al., 2000; Dobermann, 2005; Fageria and Baligar, 2003), followed by phosphorus and potassium (Johnson et al., 2019, 2023). Although rice yield can also be limited by micronutrients (Awio et al., 2021; Senthilkumar et al., 2018), they were not considered in our study. We focused only on macronutrients, particularly on nitrogen. In our study, N rates varied from 68 to 315 kg ha^{-1} and P and K rates varied between 11 and 33 kg ha^{-1} across sites and years. The large differences in rice yield observed were attributed to the large variation in N rates supplied. Rice responded strongly and mostly linearly to nitrogen application in all locations and years, demonstrating that nitrogen was one of the overarching yield limiting factors. Stronger N-fertilizer responses were observed in the valley bottoms compared with the lower and middle slopes. In the first season, yields increased linearly up to the maximum rate of N applied which was 68 kg N ha^{-1} at Yawtabrikrom and Ouragahio and 125 kg N ha^{-1} at Pangbabo. For this reason, in the second season we increased the rate of fertilizer applied to a maximum of 315 kg N ha^{-1}. This resulted in rice yields plateauing between 180 and 225 kg N ha^{-1}, with a start in diminishing returns beyond 135 kg N ha^{-1}, in Yawtabrikrom and Pangbabo, but surprisingly yields increased linearly at Ouragahio. The second season yields in the valley bottoms, which were close to 8 t ha^{-1} in Yawtabrikrom and Pangbabo, could reflect the potential yield of rice under these environments given that plots were carefully weeded and water supply was not limiting. The N-fertilizer – yield response curves could here simply reflect the plant growth response to resource supply whereby the plant physiology itself becomes the limiting factor for continued linear increase. Previous studies (Dong et al., 2015; Zhang et al., 2018), have however shown that rice yield responses to N level off well above 200 kg N ha^{-1}. The fact that in the current study, the response curves, at least at two locations, start levelling off at much lower N-rates (above 135 kg N ha^{-1}), could point at other nutrient deficiencies. The most likely deficiencies causing this leveling off would be potassium (K) and perhaps even phosphorus (P). The soils were mostly near or below critical concentrations of K, and to a lesser extent P, and the K and P fertilizer rates in these experiments did not increase proportionally to the N-fertilizer rate increases. It is therefore likely that K and P have become increasingly yield-limiting nutrients with increasing N-fertilizer levels.

Yield limitations by P and K deficiencies are not uncommon for rainfed rice production. Under rainfed conditions in Java, Boling et al. (2004) found yield reductions of 0.1 and 1.6 t ha^{-1} due to P and K fertilizer omissions, respectively. Yield losses of 1.2–2.2 t ha^{-1} were recorded for K omissions on degraded soils in Thailand (Mussgnug et al., 2006). Yield reductions of 0.6 t ha^{-1} and 0.4 t ha^{-1} in sub-Saharan Africa were reported by Saito et al. (2019) due to the omission of P and K, respectively.

When N rates exceeded 90 kg N ha^{-1} in the second season, lodging occurred at the valley bottom and the lower slope. We estimated the yield loss was more than 5 % at rates of 180 kg N ha^{-1} and above and was more severe (0.2–1.9 t ha^{-1}) in the valley bottom than in the lower slope (0.1–0.7 t ha^{-1}). Although a high N rate enables rice plants to produce more biomass and panicles, the increased stem length renders the plant susceptible to lodging. When subjected to an external force such as wind pressure or heavy rain, the rice stem can break or bend at the basal internodes (Shrestha et al., 2020; Zhu et al., 2016). Rice lodging reduces both rice yield and grain quality (Berry et al., 2004; Setter et al., 1997). Dong et al. (2015) reported rice yield losses under rainfed conditions of 0.4 and 0.7 t ha^{-1} due to lodging with 270 and 315 kg N ha^{-1}, respectively.

4.4. Efficiency of nutrient use

Our results confirm that the agronomic N use efficiency (ANUE) differed between catena positions and was generally higher in the valley bottom. There was a large variation in ANUE among locations and across catena positions (7–48 kg grain kg^{-1} N). A range of 20–25 kg grain kg^{-1} N was indicated as the agronomic N use efficiency threshold for a good rice crop and water management practices (Dobermann and Fairhurst, 2000b). The most striking differences were seen in Yawtabrikrom in the first year where ANUE was 48, 41 and 17 kg grain kg^{-1} N in the valley bottom, lower slope and middle slope, respectively. In general, the ANUE was similar in the valley bottom and lower slope, and poorer in the middle slope. Touré et al. (2009) found a similar pattern with average ANUE of 23 kg grain kg^{-1} in the valley bottom compared with 11 and 8 kg grain kg^{-1} N in the middle valley and valley fringe, respectively. The ANUE values observed in the current study were much higher (17–48 kg grain kg^{-1} N) in the first year than the second year (7–22 kg grain kg^{-1} N), although the pattern across the catena with the smallest values in the middle slope remained the same. The lowest ANUE (7 and 9), recorded in Ouragahio (second year), may be explained by the six weeks of water shortage from which the rice plants suffered during their vegetative stage. It thus appears that soil moisture availability is the over-riding factor determining to improve the ANUE. Previous studies in rainfed lowlands of West Africa reported a wide variation in ANUE: in Côte d'Ivoire a range of 6–16 kg grain kg^{-1} N (Becker and Johnson, 2001) and 7–31 kg grain kg^{-1} N in northern Ghana (Tsujimoto et al., 2017). In a recent study in an inland valley in a humid tropical zone in Uganda (East Africa), however, ANUEs had a smaller range (18–34; mean: 27) due to favourable hydro-edaphic condition and N applied at rates of 0–120 kg ha^{-1} (Grotelüschen et al., 2022). Their study reported that the ANUEs in the middle valley were higher than those in the valley bottom. This shows that other factors, such as rainfall distribution and inherent soil conditions, also play important roles.

The soil nutrient supply (SSN, SSP or SSK) varied across catenary position and soil nutrient supply in the valley bottom was higher than those of the lower and middle slopes. The results are consistent with those of Boling (2007), who reported that the soil supply of N and K was higher at valley bottom and lower middle slope than upper middle and upland under rainfed rice production in Indonesia. The soil supplies of N we found (48–80 kg ha^{-1}) were higher than those observed by Boling et al. (2004), in Java, Indonesia, and Naklang et al. (2006), in Thailand, who indicated, respectively 52 and 38 kg N ha^{-1} under rainfed conditions. Our SSN was also higher than those reported by Haefele et al. (2003), from irrigated lowland soils of four Sahelian countries, which ranged between 32 and 62 kg N ha^{-1}. SSN can be considered as an indicator of soil fertility. Although the current study did not determine total soil N, previous research conducted at the same locations provides the total soil N value. In Gagnoa, the total soil N ranged from 0.15 % to 0.21 %, while in Bouake, it varied between 0.01 % and 0.23 % (Bongoua-Devisme et al., 2024; Kpan et al., 2023). Similarly, Issaka et al. (2012) reported total soil N levels of 0.01–0.16 % in Ahafo Ano. These values are higher than those reported by Boling et al. (2004), who found 0.04 %, and Naklang et al. (2006), whose values varied from 0.06 % to 0.08 %. This may explain a high level of SSN in our study compared to the one found by Boling et al. (2004) and Naklang et al. (2006). However, the soil supplies for P (5–9 kg ha^{-1}) and K (11–29 kg ha^{-1}) in the current study were lower than the soil supplies for P (10–14 kg ha^{-1}) and K (67–169 kg ha^{-1}) observed in the Sahel by Haefele et al. (2003), and those observed in Java (i.e. 26 kg P ha^{-1} and 41 kg K ha^{-1}) by Boling et al. (2004). This implies that the soil of the three inland valleys was richer in nitrogen supply but poorer in phosphorus and potassium supply compared with those in Haefele et al. (2003) and Boling et al. (2004). The strong, mostly linear response to N fertilizers shows however that soil nitrogen was still an important yield limiting factor in this study. The lower soil supplies for P and K are supported by the low P and K concentrations observed in the soil. Whereas the soil P concentrations were still primarily above the critical levels for rice production (as determined by: Dobermann and Fairhurst, 2000a; Kalala et al., 2017; Senthilkumar et al., 2018), the soil K contents were often below that level. Given the relative low P and K levels, the application of P and K fertilizers in this study may have contributed to increased rice yield and ANUE until a certain level.

The recovery fraction (RF) indicates the proportion of nutrients applied with fertilizer that is taken up by the rice crop. The recovery fraction of N varied from 0.25 to 0.39 and 0.14–0.18 kg N kg^{-1} applied N in Yawtabrikom and Ouragahio, respectively. Thus, the rice crop did not use 61–86 % of the applied N. During the topdressing application, the water level in rice plots in Yawtabrikom was higher than the 5 cm recommended for fertilizer application in the valley bottom and lower slope which could explain the lower N recovery fraction (0.25 and 0.31 kg N kg^{-1} applied N, respectively) than in the middle slope (0.39 kg N kg^{-1} applied N). Fertilizer N applied in standing water is easily lost by volatilization or leaching. In irrigated lowlands in West Africa, the average N recovery fraction ranges from 0.19 to 0.50 kg N kg^{-1} applied N (Haefele et al., 2003). Previous studies reported a range of recovery fraction of N at 0.20–0.33 kg N kg^{-1} applied N in rainfed lowland rice in Thailand (Naklang et al., 2006). The RFs values of this study were higher than those of (Naklang et al., 2006) and fell in the range reported by (Haefele et al., 2003). However, the N recovery fraction in Ouragahio was much smaller (0.14–0.18 kg N kg^{-1} applied N) which may be due to the water shortage that rice plants experienced at the beginning of the growing season. Haefele et al. (2003) reported RFN of 0.44 kg N kg^{-1} applied N in the wet season which fell to 0.19 kg N kg^{-1} applied N in the hot dry season.

4.5. *Economic profitability of N rates*

The value to cost ratio were on average higher than 4 when applied N fertilizer rate ranged between 45 kg N ha^{-1} and 90 kg N ha^{-1}. According to Burke et al. (2019), smallholder farmers favor the adoption of technologies which provide high return on their investment. Economic analysis revealed that the gross margin of rice production increased with N rate application regardless of the catena positions. The highest gross margin was achieved between 240 and 315 kg N ha^{-1} application. However, the highest return of investment from N application was obtained at N rates $\leq$ 180 kg N ha^{-1}, because the marginal rate to return (MRR) fell below 1 at higher N rates. At an MRR below 1, application of additional fertilizer is not profitable (CIMMYT, 1988). In a recent study in Uganda, the highest MRR from N fertilizer was obtained at much lower rates (i.e., 60 kg N ha^{-1}) at all inland valley positions, but the decrease in MRR beyond that optimum fertilizer rate was much steeper at the valley fringes compared to the bottom and lower slope (Grotelüschen et al., 2022). Within the range of N rates below these optimum MRR values, the profitability of rainfed rice will be increased and nutrient loss and lodging will be minimized.

4.6. *Experimental set-up and measurements*

The experimental setup underwent changes across locations from the first to second year in terms of fertilizer rates and one year of fallow at two locations. In the first year, the fertilizer rate was fixed based on recommendations in Ghana and Côte d'Ivoire (Bado et al., 2018) and rates applied in previous studies in inland valleys in West Africa (Touré et al., 2009; Worou et al., 2013). The rice yield response to N fertilizer was linear in the three locations which did not allow site-specific fertilizer recommendations to be derived. With the objective of obtaining a yield response curve which reached a plateau, we increased the N rate to 315 kg N ha^{-1} in the three locations for the repeated experiments in the second year. We referred to previous studies where the response of rice to nitrogen levelled off between 225 and 300 kg N ha^{-1} (Ye et al., 2007; Zhu et al., 2017). An assessment of soil nitrogen prior to the experiments could potentially have given us a better indication of the necessary range of N-fertilizer levels. However, the soil concentrations of plant available nitrogen are strongly dependent on soil moisture content and associated soil microbial activity at the time of sampling making it an unreliable parameter for guiding fertilizer application. An omission in the research data collection protocol, was the lack of water potential measurements in year 1. This could have contributed to more detailed rice yield data interpretations and would have provided a stronger evidence base to the distinctness of the different catena positions and therefore an additional confirmation that the delimitations of these positions were well chosen. However, the year 1 rice yield data were consistent, and the distribution therein was relatively small, which did not necessitate availability of soil water potential data for better interpretations or explanations. The year 2 water potential data did show distinct differences between catenary positions providing solid evidence that these positions were well delimited.

Overall, our findings were in line with previous studies in inland valleys (Grotelüschen et al., 2021; Touré et al., 2009; Worou et al., 2013).

5. Conclusions

We assessed the effect of nitrogen application rates and catena positions on rainfed rice yield and nutrients use efficiency in three inland valleys. Water availability along catena positions varied and was influenced by hydro-edaphic conditions such as soil texture and slope. The catena positions and applied nitrogen rates have a strong effect on grain yields and nutrient use efficiency. Application of nitrogen increased grain yield regardless of the catena positions. Catena specific maximum economic N rates were 68 kg N ha^{-1} in Yawtabrikrom (VCR 3.2–6.0) and Ouragahio (VCR 4.3–5.6). In Pangbabo, the N rates were 90 kg N ha^{-1} in the valley bottom (VCR 4.7), and 45 kg N ha^{-1} in the lower (VCR 4.5) and middle slopes (VCR 4.3). The application of large N rates under rainfed conditions can also lead to high N losses with subsequent environmental consequences. High nitrogen application rate, above 90 kg N ha^{-1} caused rice lodging in the valley bottom. For rice production in inland valleys to be economically profitable, fertilizer management should be tailored to the catena positions. The recommended fertilizer rate will be specific to each inland valley and should consider the target yield, economic indicators, nutrient use efficient indicators and hydro-edaphic condition of the catena positions. Further experimental investigations are necessary to determine the optimal rates of P and K at different inland valley catena positions.

CRediT authorship contribution statement

Elliott Ronald Dossou-Yovo: Writing – review & editing, Supervision, Project administration. **Krishna Prasad Devkota:** Writing – review & editing, Conceptualization. **Ken E. Giller:** Writing – review & editing, Supervision, Conceptualization. **Guy Marius Assogba:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Jonne Rodenburg:** Writing – review & editing, Conceptualization. **Gerrie W.J. van de Ven:** Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

We declare that we have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgements

This research was conducted as part of the project Capitalizing on the Inland Valley Potential for Food and Nutrition Security for Smallholder Farmers in West Africa (CIPA). The CIPA project was led by AfricaRice in collaboration with Wageningen University and Research (WUR) and other partners, with financial support from the International Fund for Agricultural Development (IFAD) (Grant Agreement number: 2000001206). We thank IFAD, AfricaRice and WUR for financial and technical support. The Centre National de Recherche Agronomique (CNRA, Côte d'Ivoire) and the Council for Scientific and Industrial Research – Soil Research Institute (CSIR-SRI, Ghana) provided facilities and logistical support and are kindly acknowledged. We thank Prof Mohammed Moro Buri and Dr. Ernest Depieu, for their support while conducting the trials, Dr. Djagba Justin for the study area map and Salifou Goube Mairoua and Tcheho Blaise for technical assistance. We thank the smallholder farmers for their collaboration.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2024.109679.

Data availability

Data will be made available on request.

References

Alemayehu, T., Assogba, G.M., Gabbert, S., Giller, K.E., Hammond, J., Arouna, A., Dossou-Yovo, E.R., Van De Ven, G.W., 2022. Farming systems, food security and farmers' awareness of ecosystem services in inland valleys: a study from Côte d'Ivoire and Ghana. Front. Sustain. Food Syst. 244.
Andriesse, W., Fresco, L., Van Duivenbooden, N., Windmeijer, P., 1994. Multi-scale characterization of inland valley agro-ecosystems in West Africa. Neth. J. Agric. Sci. 42, 159–179.
Awio, T., Senthilkumar, K., Dimkpa, C.O., Otim-Nape, G.W., Kempen, B., Struik, P.C., Stomph, T.J., 2021. Micro-nutrients in East African lowlands: are they needed to intensify rice production? Field Crops Res. 270.
Bado, V.B., Djaman, K., Mel, V.C., 2018. Developing fertilizer recommendations for rice in Sub-Saharan Africa, achievements and opportunities. Paddy Water Environ. 16, 571–586.
Becker, M., Johnson, D., 2001. Improved water control and crop management effects on lowland rice productivity in West Africa. Nutr. Cycl. Agroecosyst. 59, 119–127.
Becker, M., Wopereis, M., Johnson, D., 2001. The role of N nutrition on lowland rice yields along an agroecological gradient in West Africa. Plant Nutr.: Food Secur. Sustain. agro-Ecosyst. Basic Appl. Res. 970–971.
Berry, P., Sterling, M., Spink, J., Baker, C., Sylvester-Bradley, R., Mooney, S., Tams, A., Ennos, A., 2004. Understanding and reducing lodging in cereals. Adv. Agron. 84, 217–271.
Bezabeh, M.W., Haile, M., Sogn, T., Eich-Greatorex, S., 2021. Yield, nutrient uptake, and economic return of faba bean (Vicia faba L.) in calcareous soil as affected by compost types. J. Agric. Food Res. 6, 100237.
Boehme, B., Becker, M., Diekkrueger, B., Foerch, G., 2016. How is water availability related to the land use and morphology of an inland valley wetland in Kenya? Phys. Chem. Earth Parts A/B/C. 93, 84–95.
Bognonkpe, J.P.I., Becker, M., 2000. Native soil N dynamics and use efficiency by lowland rice as a function of slope management. Deutscher Tropentag. Müllerbader Press. University of Hohenheim.
Boling, A., Tuong, T.P., Jatmiko, S.Y., Burac, M.A., 2004. Yield constraints of rainfed lowland rice in Central Java, Indonesia. Field Crops Res. 90, 351–360.
Boling, A.A., 2007. Yield constraint analysis of rainfed lowland rice in Southeast Asia. PhD thesis. Wageningen University and Research. 1–140.
Bongoua-Devisme, A.J., Kpan, W.H., Adou, P.K., Michaë, F., Kouadio, K.K.H., Koko, A.K. L., 2024. Residual Effects of Phosphate Amendments on Rainfed Rice (Oryza sativa L.) Nutrition and Soil Properties in Three Agroecological Zones of Côte d'Ivoire. Open Journal of Soil Science 14 (10), 606–634.
Burke, W.J., Frossard, E., Kabwe, S., Jayne, T.S., 2019. Understanding fertilizer adoption and effectiveness on maize in Zambia. Food Policy 86, 101721.
Cabuslay, G.S., Ito, O., Alejar, A.A., 2002. Physiological evaluation of responses of rice (Oryza sativa L.) to water deficit. Plant Sci. 163, 815–827.
Cardinael, R., Guibert, H., Brédoumy, S.T.K., Gigou, J., N'Goran, K.E., Corbeels, M., 2022. Sustaining maize yields and soil carbon following land clearing in the forest–savannah transition zone of West Africa: Results from a 20-year experiment. Field Crops Res. 275, 108335.
CIMMYT, 1988. From Agronomic Data to Farmer Recommendations: An Economics Training Manual. Completely revised. CIMMYT, Mexico,D.F.
Dobermann, A., Fairhurst, T., 2000b. Rice: Nutrient disorders & nutrient management. Int. Rice Res. Inst.
Dobermann, A., Fairhurst, T., 2000a. Nutrient disorders and nutrient management. In: Potash and Phosphate Institute, 191. Potash and Phosphate Institute of Canada and International Rice Research Institute, *Singapore*.
Dobermann, A., Dawe, D., Roetter, R.P., Cassman, K.G., 2000. Reversal of rice yield decline in a long-term continuous cropping experiment. Agron. J. 92, 633–643.
Dobermann, A.R., 2005. Nitrogen use efficiency-state of the art. Agronomy–Faculty Publications, p. 316.
Dong, Z., Wu, L., Chai, J., Zhu, Y., Chen, Y., Zhu, Y., 2015. Effects of nitrogen application rates on rice grain yield, nitrogen-use efficiency, and water quality in paddy field. Commun. Soil Sci. Plant Anal. 46, 1579–1594.
Dossou-Yovo, E.R., Vandamme, E., Dieng, I., Johnson, J.-M., Saito, K., 2020. Decomposing rice yield gaps into efficiency, resource and technology yield gaps in sub-Saharan Africa. Field Crops Res. 258, 107963.
Ehounou, J.-N., Kouamé, B., Tahi, M.G., Kassin, E.K., Dékoula, C.S., Yao, G.F., Kouadio, H.K., N'guessan, A.E., Soro, N., 2019. Impact of local global warming on rainfall and annual cocoa water requirements in the regions of lôh-djiboua and gôh in west-central côte d'ivoire. Int. J. Environ. Clim. Change 9, 503–517.
Fageria, N.K., Baligar, V.C., 2003. Methodology for evaluation of lowland rice genotypes for nitrogen use efficiency. J. Plant Nutr. 26, 1315–1333.
FAOSTAT (2022). Food and Agriculture Data.
Fermont, A.M., Tittonell, P.A., Baguma, Y., Ntawuruhunga, P., Giller, K.E., 2010. Towards understanding factors that govern fertilizer response in cassava: lessons from East Africa. Nutr. Cycl. Agroecosyst. 86, 133–151.
Fofana, I., Goundan, A., Domgho, L.V.M., 2014. Impact Simulation of ECOWAS Rice Self-Sufficiency Policy. FPRI Discussion Paper 01405.
Gabiri, G., Diekkrüger, B., Leemhuis, C., Burghof, S., Näschen, K., Asiimwe, I., Bamutaze, Y., 2018. Determining hydrological regimes in an agriculturally used tropical inland valley wetland in Central Uganda using soil moisture, groundwater, and digital elevation data. Hydrol. Process. 32, 349–362.
Grotelüschen, K., Gaydon, D.S., Langensiepen, M., Ziegler, S., Kwesiga, J., Senthilkumar, K., Whitbread, A.M., Becker, M., 2021. Assessing the effects of management and hydro-edaphic conditions on rice in contrasting East African wetlands using experimental and modelling approaches. Agric. Water Manag. 258, 107146.
Grotelüschen, K., Gaydon, D.S., Senthilkumar, K., Langensiepen, M., Becker, M., 2022. Model-based evaluation of rainfed lowland rice responses to N fertiliser in variable hydro-edaphic wetlands of East Africa. Field Crops Res. 285, 108602.
Guo, Z., Koo, J., and Wood, S. (2009). Fertilizer profitability in East Africa: a spatially explicit policy analysis.
Haefele, S., Wopereis, M., Ndiaye, M., Barro, S., Isselmou, M.O., 2003. Internal nutrient efficiencies, fertilizer recovery rates and indigenous nutrient supply of irrigated lowland rice in Sahelian West Africa. Field Crops Res. 80, 19–32.
Haefele, S., Jabbar, S., Siopongco, J., Tirol-Padre, A., Amarante, S., Cruz, P.S., Cosico, W., 2008. Nitrogen use efficiency in selected rice (Oryza sativa L.) genotypes under different water regimes and nitrogen levels. Field Crops Res. 107, 137–146.
Harrell, D.L., Walker, T.W., Salassi, M.E., Bond, J.A., Gerard, P.D., 2011. Modeling rice grain yield response to nitrogen fertilization for delayed-flood production. J. Plant Nutr. 34, 2158–2171.
Hartinee, A., Hanafi, M., Shukor, J., Mahmud, T., 2010. Model comparisons for assessment of NPK requirement of upland rice for maximum yield. Malays. J. Soil Sci. 14, 15–25.
HarvestChoice, 2009. AEZ Tropical (5 class). International Food Policy Research Institute, Washington, DC. ⟨http://http.harvestchoice.org/node/4996⟩ (and University of Minnesota, St. Paul, MN).
Husson, O., Tano, B.F., Saito, K., 2022. Designing low-input upland rice-based cropping systems with conservation agriculture for climate change adaptation: a six-year experiment in M'bé, Bouaké, Côte d'Ivoire. Field Crops Res. 277, 108418.
IFA, 2022. Fertilizer use by crop and country for the 2017-2018 period. International Fertilizer Association (IFA).

Issaka, R.N., Buri, M.M., Tobita, S., Nakamura, S., Owusu-Adjei, E., 2012. In: Whalen, KJ (Ed.). pp. 119–134.
Johnson, J.M., Ibrahim, A., Dossou-Yovo, E.R., Senthilkumar, K., Tsujimoto, Y., Asai, H., Saito, K., 2023. Inorganic fertilizer use and its association with rice yield gaps in sub-Saharan Africa. Glob. Food Sec 38, 100708.
Johnson, J.-M., Vandamme, E., Senthilkumar, K., Sila, A., Shepherd, K.D., Saito, K., 2019. Near-infrared, mid-infrared or combined diffuse reflectance spectroscopy for assessing soil fertility in rice fields in sub-Saharan Africa. Geoderma 354, 113840.
Kalala, A.M., Amuri, N.A., Semoka, J.M., 2017. Optimum levels of phosphorus and potassium for rice in Lowland areas of kilombero district, Tanzania. Agric. For. Fish. J. 6, 26–33.
Kayumba, J., Wendt, J., Cyamweshi, A.R., Ndayisaba, P.C., Kuyah, S., Ngunjiri, M., Rutebuka, J., Nabahungu, L.N., 2023. Urea briquettes combined with a fertilizer blend reduces fertilizer costs and improves yields of irrigated rice in Rwanda. Agron. J. 115, 1202–1213.
Kpan, W.H., Bongoua-Devisme, A.J., Kouadio, K.K.H., Kone, B., Bahan, F.M.L., 2023. Response of lowland rice to phosphate amendments in three acidics agroecological zones of Côte d'Ivoire. Man-Gagnoa-Bouaké. International Journal of Environment, Agriculture and Biotechnology 8 (5), 135–144.
Kumar, A., Nayak, A., Pani, D., Das, B., 2017. Physiological and morphological responses of four different rice cultivars to soil water potential based deficit irrigation management strategies. Field Crops Res. 205, 78–94.
Lafitte, H., Price, A.H., Courtois, B., 2004. Yield response to water deficit in an upland rice mapping population: associations among traits and genetic markers. Theor. Appl. Genet. 109, 1237–1246.
Masiyandima, M.C., van de Giesen, N., Diatta, S., Windmeijer, P.N., Steenhuis, T.S., 2003. The hydrology of inland valleys in the sub-humid zone of West Africa: rainfall-runoff processes in the M′bé experimental watershed. Hydrol. Process. 17, 1213–1225.
Mussgnug, F., Becker, M., Son, T., Buresh, R., Vlek, P., 2006. Yield gaps and nutrient balances in intensive, rice-based cropping systems on degraded soils in the Red River Delta of Vietnam. Field Crops Res. 98, 127–140.
Naklang, K., Harnpichitvitaya, D., Amarante, S., Wade, L., Haefele, S., 2006. Internal efficiency, nutrient uptake, and the relation to field water resources in rainfed lowland rice of northeast Thailand. Plant Soil 286, 193–208.
Niang, A., Becker, M., Ewert, F., Tanaka, A., Dieng, I., Saito, K., 2018. Yield variation of rainfed rice as affected by field water availability and N fertilizer use in central Benin. Nutr. Cycl. Agroecosyst. 110, 293–305.
Ofori, J., Hisatomi, Y., Kamidouzono, A., Masunaga, T., Wakatsuki, T., 2005. Performance of rice cultivars in various sawah ecosystems developed in inland valleys, Ashanti Region, Ghana. Soil Sci. Plant Nutr. 51, 469–476.
Ogban, P.I., Babalola, O., 2003. Soil characteristics and constraints to crop production in inland valley bottoms in southwestern Nigeria. Agric. Water Manag. 61, 13–28.
Okebalama, C.B., Safo, E.Y., Yeboah, E., Abaidoo, R.C., Logah, V., 2016. Fertilizer microdosing in the humid forest zone of Ghana: an efficient strategy for increasing maize yield and income in smallholder farming. Soil Sci. Soc. Am. J. 80, 1254–1261.
Panigrahi, N., Das, B., 2018. Canopy spectral reflectance as a predictor of soil water potential in rice. Water Resour. Res. 54, 2544–2560.
Phogat, V., Petrie, P.R., Collins, C., Bonada, M., 2022. Plant available water capacity of soils at regional scale: analysis of fixed and dynamic field capacity. Pedosphere.
Piao, S.Y., Li, Z.R., Sun, Y.C., Lee, J.I., Amanor, Y.E., 2020. Analysis of the factors influencing consumers' preferences for rice: locally produced versus the imported in the Ga East municipality of the greater Accra region of Ghana. J. Agric. Life Environ. Sci. 32, 177–192.
Rodenburg, J., Zwart, S.J., Kiepe, P., Narteh, L.T., Dogbe, W., Wopereis, M.C.S., 2014. Sustainable rice production in African inland valleys: seizing regional potentials through local approaches. Agric. Syst. 123, 1–11.
Saito, K., Azoma, K., Sokei, Y., 2010. Genotypic adaptation of rice to lowland hydrology in West Africa. Field Crops Res. 119, 290–298.
Saito, K., Touré, A., Arouna, A., Fiamohe, R., Silué, D., Manful, J., Bèye, A., Efisue, A.A., 2019. Multidisciplinary assessment of agricultural innovation and its impact: a case study of lowland rice variety WITA 9 in Côte d'Ivoire. Plant Prod. Sci. 22, 428–442.
Senthilkumar, K., 2022. Closing rice yield gaps in Africa requires integration of good agricultural practices. Field Crops Res. 285, 108591.
Senthilkumar, K., Tesha, B.J., Mghase, J., Rodenburg, J., 2018. Increasing paddy yields and improving farm management: results from participatory experiments with good agricultural practices (GAP) in Tanzania. Paddy Water Environ. 16, 749–766.
Setter, T., Laureles, E., Mazaredo, A., 1997. Lodging reduces yield of rice by self-shading and reductions in canopy photosynthesis. Field Crops Res. 49, 95–106.
Shrestha, S., Laza, M.R.C., Mendez, K.V., Bhosale, S., Dingkuhn, M., 2020. The blaster: a methodology to induce rice lodging at plot scale to study lodging resistance. Field Crops Res. 245, 107663.
Sui, R., 2017. Irrigation scheduling using soil moisture sensors. J. Agric. Sci. 10 (1).
Suleiman, S.O., Habila, D.G., Mamadou, F., Abolanle, B.M., Olatunbosun, A.N., 2022. Grain yield and leaf gas exchange in upland NERICA rice under repeated cycles of water deficit at reproductive growth stage. Agric. Water Manag. 264, 107507.
Takahashi, K., Mano, Y., Otsuka, K., 2019. Learning from experts and peer farmers about rice production: experimental evidence from Cote d'Ivoire. World Dev. 122, 157–169.
Tanaka, A., Johnson, J.-M., Senthilkumar, K., Akakpo, C., Segda, Z., Yameogo, L.P., Bassoro, I., Lamare, D.M., Allarangaye, M.D., Gbakatchetche, H., 2017. On-farm rice yield and its association with biophysical factors in sub-Saharan Africa. Eur. J. Agron. 85, 1–11.
Touré, A., Becker, M., Johnson, D.E., Koné, B., Kossou, D.K., Kiepe, P., 2009. Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. Field Crops Res. 114, 304–310.
Tsujimoto, Y., Inusah, B., Katsura, K., Fuseini, A., Dogbe, W., Zakaria, A.I., Fujihara, Y., Oda, M., Sakagami, J.-I., 2017. The effect of sulfur fertilization on rice yields and nitrogen use efficiency in a floodplain ecosystem of northern Ghana. Field Crops Res. 211, 155–164.
Tsujimoto, Y., Rakotoson, T., Tanaka, A., Saito, K., 2019. Challenges and opportunities for improving N use efficiency for rice production in sub-Saharan Africa. Plant Prod. Sci. 22, 413–427.
Van Duivenbooden, N., De Wit, C.T., Van Keulen, H., 1995. Nitrogen, phosphorus and potassium relations in five major cereals reviewed in respect to fertilizer recommendations using simulation modelling. Fertil. Res. 44, 37–49.
Van Keulen, H., 1977. Nitrogen requirements of rice with special reference to Java. Res. Inst. Agric. Bogor. 30, 67.
Van Noordwijk, M., Scholten, J., 1994. Effects of fertilizer price on feasibility of efficiency improvement: case study for an urea injector for lowland rice. Fertil. Res. 39, 1–9.
Venuprasad, R., Lafitte, H.R., Atlin, G.N., 2007. Response to direct selection for grain yield under drought stress in rice. Crop Sci. 47, 285–293.
Vos, J., 2009. Nitrogen responses and nitrogen management in potato. Potato research 52, 305–317.
Windmeijer, P.N., Andriesse, W., 1993. *Inland valleys in West Africa: an agro-ecological characterization of rice-growing environments* (No. 52). International Institute for Land Reclamation and Improvement (ILRI), Wageningen.
Windmeijer, P., Van Duivenbooden, N., Andriesse, W., 1994. Characterization of rice-growing agro-ecosystems in West Africa: Semi-detailed characterization of inland valleys in Côte d'Ivoire. Technical Report, 3. SC-DLO vol. 2 basic data.
Wit, de C.T., 1953. A physical theory on placement of fertilizer. PhD thesis. Landbouw Hogeschool Wageningen 59 (4), 1–71.
Witt, C., Dobermann, A., 2002. A site-specific nutrient management approach for irrigated, lowland rice in Asia. Better Crops Int 16, 20–24.
Worou, O.N., Gaiser, T., Saito, K., Goldbach, H., Ewert, F., 2013. Spatial and temporal variation in yield of rainfed lowland rice in inland valley as affected by fertilizer application and bunding in North-West Benin. Agric. Water Manag. 126, 119–124.
Yameogo, P.L., Becker, M., Segda, Z., 2021. Seasonal soil nitrogen dynamics affect yields of lowland rice in the savanna zone of West Africa. J. Plant Nutr. Soil Sci. 184, 98–111.
Yang, J., Liu, K., Wang, Z., Du, Y., Zhang, J., 2007. Water-saving and high-yielding irrigation for lowland rice by controlling limiting values of soil water potential. J. Integr. Plant Biol. 49, 1445–1454.
Ye, Q., Zhang, H., Wei, H., Zhang, Y., Wang, B., Xia, K., Huo, Z., Dai, Q., Xu, K., 2007. Effects of nitrogen fertilizer on nitrogen use efficiency and yield of rice under different soil conditions. Front. Agric. China 1, 30–36.
Zhang, D., Wang, H., Pan, J., Luo, J., Liu, J., Gu, B., Liu, S., Zhai, L., Lindsey, S., Zhang, Y., Lei, Q., Wu, S., Smith, P., Liu, H., 2018. Nitrogen application rates need to be reduced for half of the rice paddy fields in China. Agric. Ecosyst. Environ. 265, 8–14.
Zhu, D.-w, Zhang, H.-c, Guo, B.-w, Ke, X., Dai, Q.-g, Wei, H.-y, Hui, G., Hu, Y.-j, Cui, P.-y, Huo, Z.-y, 2017. Effects of nitrogen level on yield and quality of japonica soft super rice. J. Integr. Agric. 16, 1018–1027.
Zhu, G., Li, G., Wang, D., Yuan, S., Wang, F., 2016. Changes in the lodging-related traits along with rice genetic improvement in China. PloS One 11, e0160104.