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Differences in seasons and rice varieties provide opportunities for improving nitrogen use efficiency and management in irrigated rice in Kenya

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E-mail: gweyi.joseph@ku.ac.ke**Keywords:** grain filling, temperature, nitrogen use efficiency, nitrogen agronomic efficiency, N-mining, N uptake and remobilization, policySupplementary material for this article is available [online](#)

Abstract

Apart from nitrogen (N) rates, N use efficiency (NUE) (yield N/total input N) is affected by seasons, crop developmental stages, and varieties. Knowledge of how these factors affect NUE in rice production in Kenya is limited. Therefore, field experiments were conducted with 'low rates' of N (simulating farmers' practices) of 0, 26, 52 and 78 kg N ha⁻¹ with five varieties (MWUR1, MWUR4, IRAT109, NERICA4 and NERICA10) and higher rates of N (125, 175, and 225 kg N ha⁻¹) simulating researchers' doses with two lowland varieties (Basmati 370 and BW 196) and IR 72. Another experiment on NUE responses to sites, N rates and dose (split or full dose) was undertaken with the IR97 variety. With the 'low rate', yields increased with incremental N rates up to 52 Kg N ha⁻¹ and declined (during cold periods, for some varieties). In this scenario, the N agronomic efficiencies (AE_N) declined with increasing N but depended on sites and seasons. However, most AE_N values were above 100, implying nutrient mining. In most cases (except at the Mwea site), the N utilization efficiency (NUE) ranged from 16 to 22 kg kg⁻¹ and were not significantly affected by sources and methods of N application. In all cases, an increase in N elicited declining trends in NUE. Moreover, N uptake efficiency ranged between 22 and 90 kg kg⁻¹ without significant variation among varieties. For the 'high N rates', high biomass yield resulted in higher grain yields in BW 196 and IR 72 but yield declined beyond 75 kg ha⁻¹ N rates due to poor grain filling, particularly when a cold period coincided with booting and grain filling. We conclude that N rates, doses and rice varieties are key determinants of AE_N and NUE in contrasting rice growing seasons in Kenya. Cropping seasons and rice varieties are therefore potential key determinants of sustainable rice productivity and improved NUE in rice-based systems in the studied regions of Kenya.

1. Introduction

In sub-Saharan Africa (SSA), rice is the most rapidly expanding food crop for both consumption and commercial purposes (Tsujimoto *et al* 2019). According to the USDA report (2018), the milled grain yield of

rice has tripled from 9.2 to 31.5 Mt between 1990 and 2018, largely due to increased use of synthetic nitrogen (N) fertilizer. It is anticipated that with the current growth in population and rapid urbanization, there will be a need for increased rice production to meet the consumption demands (Njinju *et al* 2018,

Fróna *et al* 2019). However, rice yields have stagnated in SSA for a considerable period of time (USDA 2018). In addition, the general production is low. For instance, the productivity of upland rice varieties in Kenya is at 1 t ha^{-1} which is way below the regional potential that is estimated at 7 t ha^{-1} (Magoti *et al* 2019). Rice production in Kenya only meets 16% of the total country's demand. The Government of Kenya's Ministry of Agriculture report (2008–2018) indicated that consumption was increasing at a rate of 12% per annum as compared to the increase in consumption of other cereals. Furthermore, there is a rapid shift in the trend of the modern eating habits among youths, a fact that will further increase the demand of rice. There is therefore a need to reverse the trend and enhance the yield performance of rice by first identifying the bottlenecks and taking informed corrective measures. The major factors contributing towards a lower rice yield in Kenya, and in Africa in general, include, but are not limited to: a lower yield potential (according to Emitiyagoda *et al* (2010)) (where yield potential is 'the maximum yield that a variety can reach under the best environment') of rice genotypes, a lack of fertilizer inputs, drought and poor water control, low-nutrient soils, poor soil fertility management, a shortage of labour and a high incidence of pests, weeds and diseases (Saito *et al* 2013, Kajisa 2016).

In developed and transition economies like China, East Asia and many European countries, crop, particularly rice, yields have increased by leaps and bounds due to increased reactive N application. Unfortunately, this has environmental costs in terms of pollution through gaseous emissions and leaching into water bodies. The flipside of the coin is too little N application in developing countries because of poor economies that can barely support N fertilizer imports. Therefore, a need to strike a balance in N application for better N use efficiency (NUE) is crucial. In the present study, the NUE is defined as grain yield per unit of the applied N fertilizer, which is a product of Nitrogen Use physiological Efficiency (NUpE) and N utilization efficiency (NUtE) (Rakotoson *et al* 2017). To improve NUE, it is necessary to enhance N uptake, N utilization efficiency, and the N harvest index, with many complex and interactive environment-crop, as well as physiological, mechanisms and agronomic traits (van Bueren and Struik 2017). In SSA, NUE is estimated to be above 100%, indicating nutrient mining and low productivity (Edmonds *et al* 2009). However, a large percentage of N losses are unaccounted for, especially in lowland rice which is partly contributed to by surface runoff, volatilization, denitrification and leaching (Fageria and Baligar 2003), hence the need for the adoption of fertilizer-responsive varieties and responsible fertilizer use strategies (Estudillo and Otsuka 2013). Crop characteristics, environmental and management factors interactively influence the NUE of a

crop, i.e. crops and crop varieties differ in their ability to acquire N from the soil and respond to incremental reactive N. Furthermore, environmental factors such as temperature, rainfall and irradiance, soil and crop management practices such as nutrient management, crop rotation, cover crop, tillage, weed and pest management and irrigation are also important factors that influence the NUE of a crop (Balasubramanian *et al* 2004) and equally affect crop yield potential. Many farmers in SSA have no access to adequate N fertilizers and mostly apply less than recommended by both the Abuja and Malabo declarations by African heads of state. It is therefore important to test the NUE with the N rates accessible to these farmers. Indeed, Jian-Feng *et al* (2011) established that NUE under no, or low levels of, N were very effective, but those of N absorption efficiency and N harvest index (NHI) in rice were noneffective because their genotypic differences must be given full expression under higher N levels. Hence the further need to compare with higher rates.

Most experiments reported in SSA and part of Kenya have relied on data extractions from different databases such as FAOSTAT, IFASTAT, GFM (Lassaletta *et al* 2014, Zhou *et al* 2014, Elrys *et al* 2019) to estimate the NUE with less focus on specific crops and factors other than N that have a direct bearing on NUE. Therefore, in this study, we looked at NUE at a plot scale level under controlled research conditions and compared two sites as well as different varieties, in two seasons, under varying fertilizer regimes. To our knowledge, there is no other kind of study that has previously been undertaken in Kenya and the general Lake Basin region. According to Dobermann (2007), the NUE achieved in research trials may serve as a reasonable indicator of what can be targeted with good management, but this may only apply to short term experiments such as at the Ahero site, which closely simulates a farmer's field. However, for the Mwea site (a research station) where long term experiments are continuously conducted, caution in the interpretation of results is necessary to avoid overestimation of the values of control plots. We hypothesized that yields of rice are not controlled by N rates alone, instead additional factors like varieties and seasons are paramount. Therefore, this study aimed to evaluate the effects of N rates on selected local and improved varieties in two contrasting seasons and sites, and understand their N use efficiencies to form a reference for policy formulation on N management. Indeed, rice varieties, particularly landraces adapted to the local environments and selected by the farmers for their better yield, under low or zero inputs, form an interesting genetic material for the identification of donors and genomic regions for better NUE. Landraces, given their past evolutionary history and adaptation to stress environments, often out-yield modern cultivars under low-input production systems, as demonstrated by Flint-Garcia *et al* (2003).

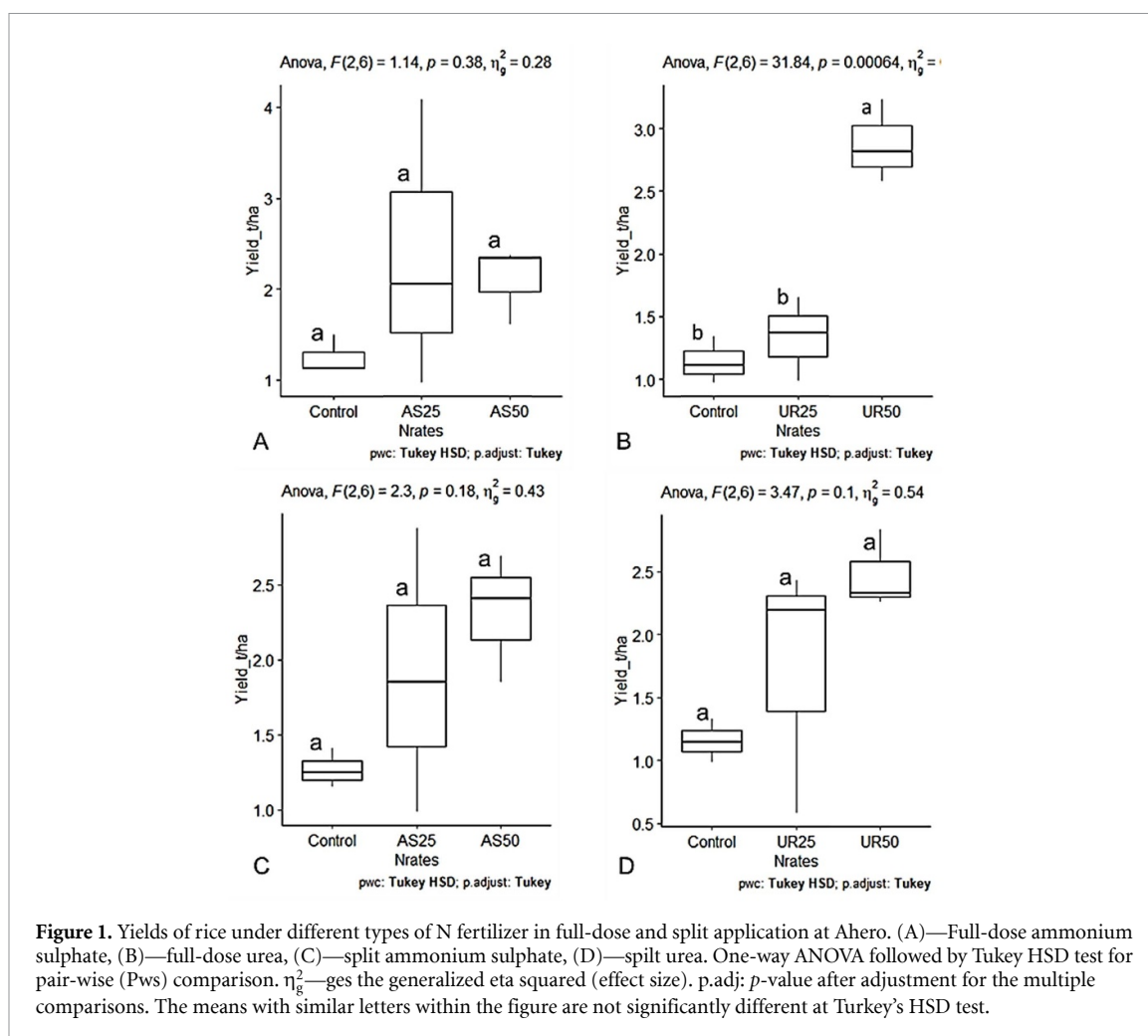


Figure 1. Yields of rice under different types of N fertilizer in full-dose and split application at Ahero. (A)—Full-dose ammonium sulphate, (B)—full-dose urea, (C)—split ammonium sulphate, (D)—split urea. One-way ANOVA followed by Tukey HSD test for pair-wise (Pws) comparison. η_g^2 —ges the generalized eta squared (effect size). p.adj: *p*-value after adjustment for the multiple comparisons. The means with similar letters within the figure are not significantly different at Turkey's HSD test.

We further hypothesized that discriminative traits related to NUE better express themselves under low input than under high input. However, testing under both low and high input can yield cultivars that are adapted to low-input conditions but also respond to high-input conditions (van Bueren and Struik 2017).

2. Materials and methods

2.1. Study site and experimental design

The experiments were conducted in two sites; Kirogo farm in Mwea in Central Kenya and the Ahero irrigation scheme in Western Kenya (supplementary figure 1 (available online at stacks.iop.org/ERL/16/075003/mmedia)). Kirogo farm is located at the Kenya Agricultural and Livestock Research Organization (KALRO-Mwea), at $0^{\circ} 37' S, 37^{\circ} 20' E$, about 1159 m above sea level. Rainfall ranges from 500 to 850 mm per annum in a bimodal pattern with long rains (March–June) and short rains (October–December). The temperatures for this area range between $15.4^{\circ} C$ and $29.5^{\circ} C$. The soils are nitosols, deep, well-drained dusky-red to dark reddish-brown, friable clay with low fertility (Njinju *et al* 2018). The Ahero irrigation scheme is located in the middle of

the Kano Plain, 25 km Southeast of Kisumu town at $0^{\circ} 08' S, 34^{\circ} 58' E$, about 1168 m above sea level. Rainfall ranges from 1200 to 1735 mm in a bimodal pattern, long rains (March–May) and short rains (October–December). In this region, the average daily temperatures range from $15^{\circ} C$ to $25^{\circ} C$.

2.1.1. Experiment 1—effect of fertilizer application method on rice yields and NUEs

The experiments were conducted at the Mwea and Ahero sites. The experiments were laid out in a randomized complete block design (RCBD) in factorial arrangements. Factor one comprised two forms of N fertilizer, sulphate of ammonia (SA) and urea at various levels (0, 25, and 50 kg ha^{-1}). Factor two comprised two methods of applications: full dose and two splits. The treatments were replicated three times. In this experiment, the plot sizes were $3 \times 4 \text{ m}$. The rice variety used was IR97 (obtained from the National Irrigation Board (NIB) of Kenya). Three-week-old seedlings were transplanted at a spacing of $25 \times 15 \text{ cm}$ in 36 plots, each plot had a total of 320 plants (table 1). IR97 is nonaromatic and is the only one that can grow in Ahero due to attacks from birds.

Table 1. Experimental treatments.

N fertilizer type	Fertilizer levels (N kg ha ⁻¹)	Description	
Ammonium sulphate (full dose)	0, 25 and 50	Type—highland and lowland	Experiment 1
Ammonium sulphate (split dose)	0, 25 and 50	Sites—Ahero and Mwea	
Urea (full dose)	0, 25 and 50	Period—2017 to 2018	
Urea (split dose)	0, 25 and 50	Planting—seedlings transplanting	
Rice varieties	Fertilizer levels (N kg ha ⁻¹)	Description	Experiment 2
IRAT109	0, 26, 52 and 78	Type—lowland	
MWUR1	0, 26, 52 and 78	Site—Mwea	
MWUR4	0, 26, 52 and 78	Period—2015 to 2016	
NERICA4	0, 26, 52 and 78	Planting—direct sowing	
NERICA10	0, 26, 52 and 78		
Rice varieties	Fertilizer levels (N kg ha ⁻¹)	Description	
Basmati 370	75125, 175 and 225	Type—highland	Experiment 3
BW 196	75125, 175 and 225	Site—Mwea	
IR 72	75125, 175 and 225	Period—2014 to 2015 Planting—seedlings transplanting	

2.1.2. Experiment 2—effect of higher rates of N fertilizer application on rice yields and NUEs

The experiment was undertaken at the Mwea site with the ‘high N rate’, an RCBD with a factorial arrangement was adopted. Factor one was the N rates comprising 75 (the standard farmers’ rate), 125, 175 and 225 Kg N ha⁻¹, rice varieties (Basmati 370, BW 196 and IR 72) constituted the second factor. The N fertilizer application rates were calculated by subtracting the basal application from the top-dressing rates. Treatments were replicated three times. Trials were conducted between February–August 2014 and January–June 2015.

2.1.3. Experiment 3—effect of lower rates of N fertilizer application on rice yields and NUEs

The ‘low N’ experiment was laid out in RCBD with a factorial arrangement at the Mwea site. Factor one was rice varieties (IRAT109, MWUR1, MWUR4, NERICA4 and NERICA10) in five levels while factor two treatment was N rates (0, 26, 52 and 78 kg N ha⁻¹) (four levels). In this experiment, seeds were directly sown at a spacing of 20 × 15 cm by dibbling. Each plot had five rows. Calcium ammonium nitrate fertilizer was randomized in each block and a blanket application of zinc sulphate was applied at a rate of 25 kg ha⁻¹. The fertilizer treatments were carried out in two equal splits with the first split being applied at the tillering stage (21 d after sowing), and the second split applied after 45 d (at the panicle initiation stage). Treatments were replicated three times. This was carried out for two seasons, May–October 2015 and October 2015–April 2016.

The water was supplied by irrigation throughout most of the growing periods at the Mwea site. Being a research site, water was not limited, unlike in Ahero where there was regulation of water through the constant opening and closing of canals followed

by redirecting to the necessary farms. In both sites the water was supplied by NIB.

2.2. Data collection and analysis

2.2.1. Plant harvesting

Harvesting was done at about 40–50 d after heading when 80% of the grain had reached the hard dough stage. A net plot of 1.00 m² was harvested at the middle of each plot comprising of about 25 hills, leaving out the border rows.

2.2.2. Biomass collection, weighing and analysis

The straw from the harvested plants was oven-dried for 24 h at 72 °C (until constant weight). The above-ground biomass was determined by weighing the oven-dried straw of the samples.

2.2.3. Yield and yield components

The harvested panicles were dried, threshed and the weight of the total grain weight obtained after drying to 13% moisture content. Filled grains and unfilled grains were also weighed separately. Total grain yield in tonnes per hectare was estimated using the following formula:

$$\text{Total grain yield (t ha}^{-1}\text{)} = \frac{(\text{filled grain weight gm}^{-2}) \times 10000\text{m}^2 \times 1\text{ t}}{1\text{ m}^2 \times 1\text{ m}^2 \times 1000000\text{ g} \times 1\text{ ha}}$$

2.2.4. Plant tissue analysis

Plants for data collection were selected and marked randomly. Within the five rows in a plot, the outer rows were not considered while sampling. Leaves and stems from the sampled plants were oven-dried at 70 °C for 24 h, then ground to powder using a Heiko vibrating mill. The N content (%) was separately analysed from the straw and seeds in each treatment for

Table 2. NUE indicators.

No.	Nitrogen use efficiency indicator	Formula
1	N utilization efficiency (NUE)	$\text{NUE} = \frac{\text{Yield (kg ha}^{-1}\text{)}}{\text{Plant N (kg ha}^{-1}\text{)}}$
2	Apparent N recovery rate (ANR): The net increased total N uptake by the plant N fertilizer application against the total amount of N fertilizer applied	$\text{ANR} = \frac{\text{N uptake (kg ha}^{-1}\text{) at N application} - \text{N uptake (kg ha}^{-1}\text{) at 0 N application}}{\text{N fertilizer application (kg ha}^{-1}\text{)}}$
3	Agronomic N efficiency (NpUE): Net increased yield against the net increased N uptake with N fertilizer application	$\text{AE}_N = \frac{\text{Yield (kg ha}^{-1}\text{) at N application} - \text{Yield (kg ha}^{-1}\text{) at 0 N application}}{\text{N fertilizer application (kg ha}^{-1}\text{)}}$
4	N physiological use efficiency (NpUE)	$\text{NpUE} = \frac{\text{Yield (kg ha}^{-1}\text{) at N application} - \text{Yield (kg ha}^{-1}\text{) at 0 N application}}{\text{N uptake (kg ha}^{-1}\text{) at N application} - \text{N uptake (kg ha}^{-1}\text{) at 0 N application}}$
5	N harvest index (NHI)	$\text{NHI} = \frac{\text{Grain nitrogen uptake (kg ha}^{-1}\text{)}}{\text{Total plant nitrogen uptake (kg ha}^{-1}\text{)}}$

all genotypes after harvest. The N content from plant tissue was obtained using the Kjeldahl method using standard procedure (Horwitz 2010).

2.2.5. Soil analysis

Soils were randomly sampled at 0–20 cm depth using an auger, mixed thoroughly and subsampled. The subsamples were air-dried, ground, and sieved using a 2.0 mm sieve. The samples were thereafter kept in a well-labelled plastic container for further analysis. The soil pH_(water) was determined using a pH meter (ASTM 1995). Organic matter was determined by a wet oxidation/chromic acid digestion method (Walkey and Black 1934). The total N in the soil was determined using the Kjeldahl method (Bremner 1960) (supplementary table 1).

2.2.6. Meteorological data

Data on temperatures, rainfall and solar radiation were obtained from a weather data station at Kirogo farm in Mwea, and where gaps existed, they were filled by data accessed and extracted using the ‘Data Download’ web tool (Hegewisch and Abatzoglou 2020) (supplementary figures 2 and 3).

2.2.7. Nitrogen use efficiency

Biomass and grain yield results were used to estimate the NUE characteristics using the following modified formulas described by Good *et al* (2004), Xu *et al* (2012) and table 2.

2.2.8. Data analysis

Data on the yield characteristics and NUE indicators were organized in excel spreadsheets and subjected to various statistical procedures (analysis of variance, Welch two-sample *t*-test, and Pearson correlations) using R software version 3.4.4.

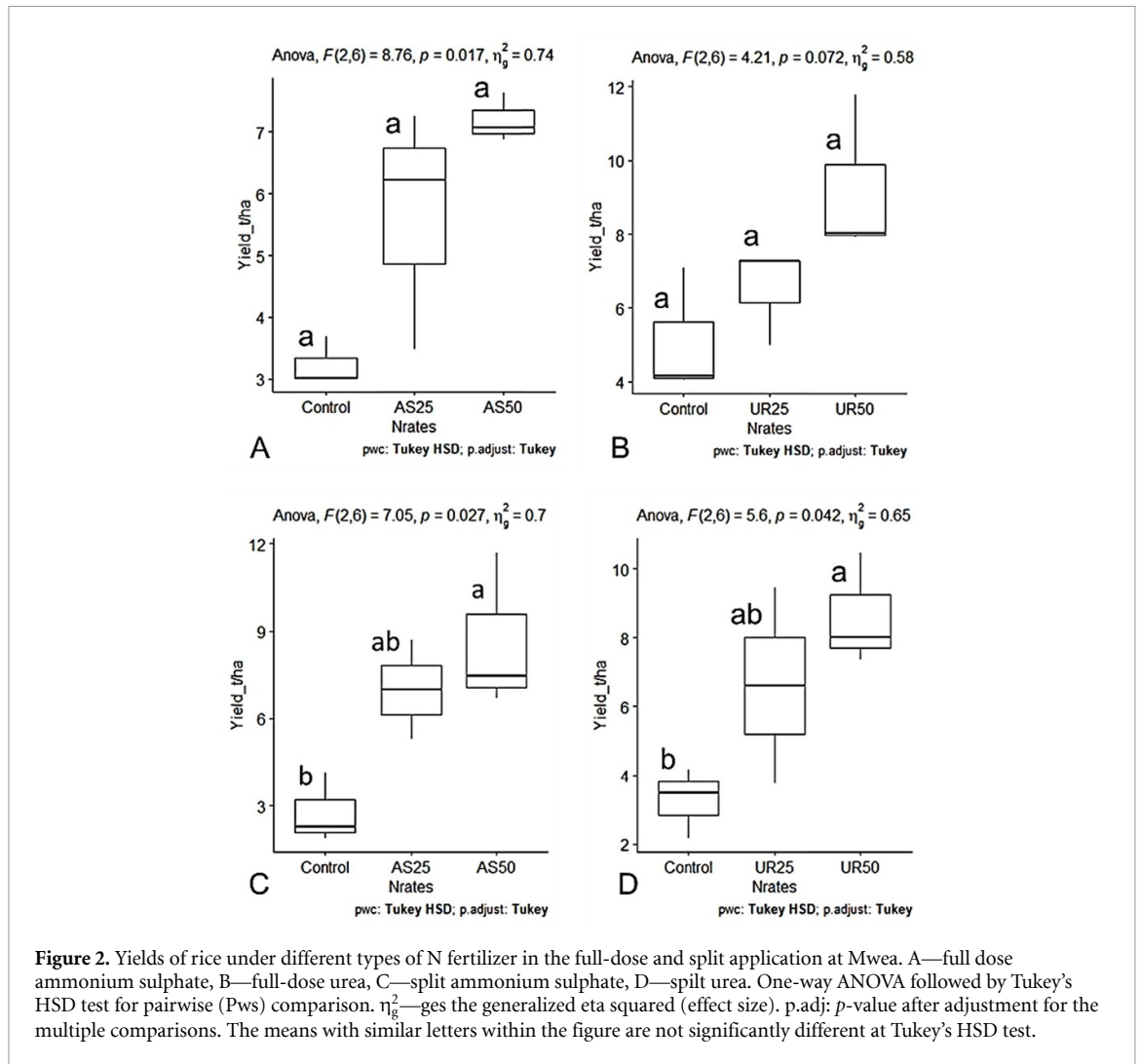
3. Results

3.1. Varietal responses to N forms and doses on rice grain yield and yield components in two sites

There were no significant statistical differences amongst different N application methods ($p > 0.05$) for sulphate of ammonium (whether split or full dose) at different rates (figure 1). A similar trend was observed with (UR) under the split application. The application of UR at 50 kg ha⁻¹ under full dosage elicited the highest grain yields compared to the control. In addition, the application of 25 kg ha⁻¹ in two split doses at the Mwea site resulted in higher grain yield ($p \leq 0.05$) compared to the control and this was evident irrespective of the N sources (figures 2(C) and (D)). However, significant differences ($p \leq 0.05$) were only observed between the highest rate (50 kg ha⁻¹ N) and the control for urea at full dose (figure 2(B)).

3.2. Nitrogen utilization, physiological use efficiencies, apparent recovery and agronomic efficiency

NUE was not influenced by the method of N application (whether split or full dose) but showed a decrease with increase in levels of N fertilizers (table 3). These differences were not significant ($p > 0.05$). Unfertilized plots had the highest NUE of 23.47 followed by ammonium sulphate at 25 Kg N ha⁻¹ (20.29) when applied in split applications and the lowest NUE was observed in urea (50 Kg N ha⁻¹) in split applications with a value of 17.31 at the Ahero site (supplementary table 2). In Mwea, a similar trend was observed with NUE where higher N levels elicited the lowest values, while the control (unfertilized)-to-low N application had higher NUE when applied in split methods. N physiological efficiency (NpUE) exceeded 100% in



some treatments under urea (25 Kg N ha^{-1}) in Ahero when applied in full dose (220.76) while in Mwea the same rate applied in splits resulted in 111.03 NpUE.

In Ahero, there were no significant differences among AE_N values ($p > 0.05$), with values ranging from 7.90 to 45.02 (table 3), without clear trends in N rates and methods of application (full dose or split). At the Mwea site, the values were three-fold to five-fold higher than at the Ahero site. As compared to full dose, all the split applications had values of more than 100, with the highest values registered with $25 \text{ kg ha}^{-1} \text{ N}$ (irrespective of N source). The ANR showed variations with N application methods and rates at both the Ahero and Mwea sites. The ANR values ranged from 0.42 to 2.2 at the Ahero site, while the values at Mwea were from 3.41 to 8.17. At the Ahero site, the interactive effects of N rates and dosage (split/full) had no significant effects on the NUE components. However, at Mwea, the N rates had a significant effect on NUtE, ANR, AE_N and NHI (Nr^{***}) but no effect on NpUE (Nr^{ns}). Furthermore, dosage (split/full) did not affect all these NUE components (Do^{ns}) (table 3).

3.3. Nitrogen use efficiency components in two seasons with different varieties and N rates

The treatments with lower rates ($0\text{--}78 \text{ kg N ha}^{-1}$) showed varietal differences in NUtE ($p \leq 0.05$) with the control (unfertilized plots) having the highest NUtE in both seasons. There was a decreasing trend of NUtE with increase in N rates. The varieties MWUR1 and MWUR4 showed the lowest NUtE values in both seasons under highest N supply (supplementary table 3). The NpUE values had wide variations with some varieties exhibiting negative NUE values at different N rates of application during season 1. At 78 kg N ha^{-1} , MUR1 (season 1) had the extreme value of NpUE of -289.04 which could indicate high loss of applied N to the environment or a high extent of soil mining that degrades the soil quality, or these values were just outliers. NERICA 4 in unfertilized plots exhibited values close to the optimal NpUE of 61.05. In season 2 there was a clear declining trend in NpUE with the increase in N rates and this was evident in all varieties. Compared to varieties, the effects of N rates on NpUE values were more pronounced in both seasons. Moreover,

Table 3. NUE parameters under split and full dose application (IR 97 variety) at Ahero and Mwea sites.

N rates (N kg ha ⁻¹)	Dose	NUtE	ANR	AE _N	NpUE	NHI
Ahero						
0	—	23.47 ± 1.66 a	—	—	—	0.39 ± 0.02 a
UR 25	Full	19.82 ± 1.99 a	0.42 ± 0.23 a	7.90 ± 3.71 a	32.07 ± 24.98 a	0.39 ± 0.04 a
	Split	18.66 ± 1.94 a	1.32 ± 0.81 a	23.10 ± 19.65 a	31.95 ± 11.83 a	0.37 ± 0.04 a
AS 25	Full	18.41 ± 3.03 a	2.11 ± 1.10 a	45.02 ± 37.75 a	9.13 ± 12.42 a	0.43 ± 0.07 a
	Split	20.29 ± 3.77 a	1.68 ± 0.05 a	25.58 ± 20.03 a	14.89 ± 12.09 a	0.41 ± 0.08 a
UR 50	Full	18.53 ± 2.03 a	2.02 ± 0.30 a	34.76 ± 1.73 a	18.01 ± 2.77 a	0.45 ± 0.05 a
	Split	17.31 ± 2.25 a	1.89 ± 0.48 a	26.38 ± 4.01 a	14.90 ± 2.66 a	0.40 ± 0.06 a
AS 50	Full	18.41 ± 1.51 a	1.24 ± 0.19 a	17.21 ± 4.19 a	13.54 ± 1.77 a	0.44 ± 0.03 a
	Split	15.87 ± 1.32 a	1.97 ± 0.20 a	21.02 ± 5.43 a	10.35 ± 1.73 a	0.39 ± 0.03 a
Influence and interactions		Nr ^{ns}	Nr ^{ns}	Nr ^{ns}	Nr ^{ns}	Nr ^{ns}
		Do*	Do**	Do ^{ns}	Do*	Do ^{ns}
		NrXDo ^{ns}	NrXDo ^{ns}	NrXDo ^{ns}	NrXDo ^{ns}	NrXDo ^{ns}
Mwea						
0	—	21.50 ± 1.17 a	—	—	—	0.53 ± 0.02 a
UR 25	Full	22.68 ± 0.56 a	3.41 ± 2.00 a	56.58 ± 69.79 a	62.29 ± 38.93 a	0.66 ± 0.02 a
	Split	21.29 ± 1.68 a	5.71 ± 2.93 a	133.28 ± 88.31 a	7.78 ± 16.58 b	0.63 ± 0.07 a
AS 25	Full	20.22 ± 1.18 a	4.54 ± 1.09 a	96.81 ± 43.63 a	19.06 ± 7.12 b	0.62 ± 0.03 a
	Split	20.94 ± 0.49 a	7.95 ± 1.19 a	168.48 ± 24.77 a	21.36 ± 2.02 b	0.63 ± 0.01 a
UR 50	Full	17.79 ± 0.50 a	6.41 ± 1.70 a	82.98 ± 39.84 a	11.66 ± 3.90 b	0.65 ± 0.02 a
	Split	18.54 ± 0.62 a	6.09 ± 1.17 a	106.87 ± 30.51 a	16.95 ± 1.66 b	0.64 ± 0.03 a
AS 50	Full	16.91 ± 0.89 a	5.32 ± 0.55 a	79.21 ± 7.14 a	15.45 ± 2.86 b	0.61 ± 0.04 a
	Split	16.16 ± 0.68 a	8.17 ± 2.68 a	116.93 ± 36.88 a	14.45 ± 1.27 b	0.58 ± 0.03 a
Influence and interactions		Nr**	Nr***	Nr**	Nr ^{ns}	Nr**
		Do ^{ns}	Do ^{ns}	Do ^{ns}	Do ^{ns}	Do ^{ns}
		NrXDo ^{ns}	NrXDo ^{ns}	NrXDo ^{ns}	NrXDo ^{ns}	NrXDo ^{ns}

Means followed with same letters within a column are not significantly different under Student–Newman–Keuls test mean separation at a 95% level of confidence. UR—urea, AS—ammonium sulphate. Nr—N fertilizer rates, Do—fertilizer application dosages, NrXDo—interaction between the N fertilizer rates and the application dosages. * (p -value ≤ 0.05), ** (p -value ≤ 0.01), *** (p -value ≤ 0.001), ns (nonsignificant).

the results revealed a decreasing trend in AE_N with increasing N rate for most varieties in season 1. During season 2, the AE_N values ranged from 88 to 151. Just like in season 1, there was an increasing trend in AE_N as N rates declined. In addition, there were significant variations ($p \leq 0.05$) in NHI among N application rates and varieties in both seasons, with values ranging from 0.54 to 0.84 as shown in table 4.

The variations in yields in the two seasons were not consistent among the varieties and N rates, probably due to several outliers and poor mean distributions (figure 3 and table 4). On the contrary, trials with higher fertilizer rates (75–225 kg ha⁻¹) showed yield differences between seasons under different fertilization regimes and were also affected by varieties (figure 4 and supplementary table 4). The varieties BW 196 and IR 172 had significantly lower yields ($p \leq 0.05$) in season 2 compared to season 1 under different fertilizer rates (figures 4(B(iii)) and (B(iv))). The booting and initiation of flowering coincided with the warmer part of the growing period during season 2 for the Basmati 370 variety, while for BW 196 and IR 72 varieties, these critical developmental stages coincided with warmer parts of season 1, which partially explains the patterns of

grain yield reported in figure 5 (see supplementary figures 2 and 3).

3.4. Regression analysis of yield and nitrogen rates in different seasons

In season 1 (supplementary figures 4(a(i))–(e(i))) there were poor relationships between fertilizer rates and yields (grain and total biomass) and this was irrespective of varieties (R^2 values ranged from 0.11 to 0.42). Under high N fertilization, the relationship between yields and N rates showed exceptionally low R^2 values in season 1 (ranging between 0.1 and 0.5) depending on variety (supplementary figures 5(a)–(c)). In season 1, the biomass yield showed an increasing trend with an increase in N levels, while the grain yield dropped with an increase in N (starting after 75 kg ha⁻¹). The relationship between yield and N rates for BW 196 was $R^2 = 0.50$ and $R^2 = 0.15$ for total biomass and grain yields in season one and two, respectively. In season two, the BW 196 variety showed an increase in both grain and biomass yield but showed a plateau at 150 kg ha⁻¹ N. In both seasons, there was a decrease in filled grain as the N rate increased, but this was pronounced in the second season (supplementary figure 6). This has implications on N utilization and general NUE.

Table 4. NUE characteristics of rice varieties under low N fertilizer levels.

Variety	N rates (kg ha ⁻¹)	NUtE	ANR	AE _N	NpUE	NHI
Season 1						
MWUR1	0	41.11 ± 1.21 cd	—	—	43.96 ± 6.05 a	0.68 ± 0.02 bcd
	26	38.49 ± 0.94 d	2.51 ± 1.22 ab	104.15 ± 54.43 a	-5.73 ± 47.85 a	0.69 ± 0.02 bcd
	52	36.37 ± 1.20 d	3.49 ± 0.40 a	125.30 ± 16.23 a	35.64 ± 2.43 a	0.69 ± 0.02 bcd
	78	26.44 ± 1.29 f	1.79 ± 0.45 ab	36.95 ± 13.23 a	289.04 ± 301.36a	0.62 ± 0.03 d
MWUR4	0	49.93 ± 1.83 a	—	—	51.14 ± 5.38 a	0.65 ± 0.02 cd
	26	40.65 ± 0.86 cd	0.78 ± 0.82 ab	57.81 ± 35.21 a	-44.30 ± 86.17 a	0.81 ± 0.02 a
	52	37.99 ± 0.33 d	2.76 ± 0.62 ab	113.75 ± 24.87 a	48.14 ± 6.57 a	0.80 ± 0.01 a
	78	24.70 ± 1.89 f	0.15 ± 0.78 b	-15.71 ± 24.80 a	39.23 ± 11.75 a	0.54 ± 0.04 e
NERICA4	0	49.48 ± 0.87 a	—	—	61.05 ± 7.69 a	0.74 ± 0.01 abc
	26	46.46 ± 1.12 ab	3.22 ± 1.31 ab	155.54 ± 66.51 a	36.01 ± 9.25 a	0.73 ± 0.02 abc
	52	45.97 ± 0.60 ab	2.09 ± 0.62 ab	97.14 ± 28.24 a	46.06 ± 1.68 a	0.75 ± 0.01 abc
	78	38.19 ± 0.79 d	2.18 ± 0.50 ab	77.46 ± 19.11 a	47.27 ± 10.71 a	0.69 ± 0.01 abc
NERICA10	0	43.53 ± 1.11 bc	—	—	48.81 ± 6.81 a	0.72 ± 0.02 abc
	26	38.49 ± 2.77 d	2.94 ± 1.05 ab	121.21 ± 52.41 a	53.86 ± 16.67 a	0.65 ± 0.05 bcd
	52	36.80 ± 1.22 d	2.64 ± 0.79 ab	98.60 ± 30.73 a	36.67 ± 3.92 a	0.74 ± 0.02 abc
	78	30.45 ± 0.74 e	2.87 ± 0.53 ab	86.16 ± 17.04 a	29.73 ± 1.22 a	0.76 ± 0.02 ab
IRAT109	0	47.87 ± 0.85 ab	—	—	22.68 ± 21.12 a	0.72 ± 0.01abcd
	26	45.57 ± 1.03 ab	2.56 ± 0.49 ab	121.87 ± 24.07 a	46.09 ± 3.22 a	0.72 ± 0.02 bcd
	52	36.43 ± 1.02 d	2.24 ± 0.40 ab	80.17 ± 14.81 a	35.16 ± 1.72 a	0.69 ± 0.02 bcd
	78	32.15 ± 0.81 e	1.98 ± 0.40 ab	63.26 ± 12.95 a	30.37 ± 2.76 a	0.74 ± 0.02 abc
Influence and interaction		Var**	Var ^{ns}	Var ^{ns}	Var ^{ns}	Var**
		Nr***	Nr***	Nr***	Nr ^{ns}	Nr***
		VarXNr***	VarXNr ^{ns}	VarXNr ^{ns}	VarXNr ^{ns}	VarXNr***
Season 2						
MWUR1	0	43.89 ± 0.74 c	—	—	45.69 ± 6.53 a	0.79 ± 0.01 abcd
	26	45.81 ± 0.51 bc	3.56 ± 0.37 ab	163.73 ± 18.99 a	44.91 ± 1.46 a	0.76 ± 0.01 cde
	52	39.20 ± 0.67 de	2.45 ± 0.29 b	94.80 ± 13.39 a	37.34 ± 1.60 a	0.74 ± 0.01 def
	78	28.82 ± 0.92 h	3.24 ± 0.34 ab	88.63 ± 12.45 a	26.74 ± 1.33 a	0.68 ± 0.02 g
MWUR4	0	53.46 ± 0.37 a	—	—	62.51 ± 13.25 a	0.69 ± 0.03 fg
	26	39.55 ± 0.51 de	3.07 ± 0.39 ab	124.83 ± 17.18 a	40.06 ± 0.94 a	0.79 ± 0.01 abcd
	52	38.61 ± 0.64 de	2.95 ± 0.55 ab	117.66 ± 23.10 a	39.03 ± 1.09 a	0.81 ± 0.01 abcd
	78	32.04 ± 0.23 g	4.33 ± 0.36 a	135.89 ± 12.14 a	31.26 ± 0.30 a	0.70 ± 0.01 efg
NERICA4	0	51.69 ± 0.80 a	—	—	61.36 ± 47.93 a	0.78 ± 0.01 bcd
	26	47.72 ± 1.28 b	2.38 ± 0.23 b	115.35 ± 14.71 a	46.44 ± 3.14 a	0.75 ± 0.02 de
	52	47.40 ± 0.80 b	2.18 ± 0.27 b	105.09 ± 15.13 a	47.51 ± 1.16 a	0.77 ± 0.01 bcd
	78	39.27 ± 0.74 de	2.43 ± 0.35 b	94.23 ± 15.22 a	37.81 ± 1.23 a	0.71 ± 0.01 efg
NERICA10	0	49.07 ± 0.34 b	—	—	45.53 ± 2.28 a	0.81 ± 0.01 abcd
	26	46.07 ± 0.86 bc	2.61 ± 0.81 b	123.82 ± 39.80 a	39.99 ± 9.08 a	0.78 ± 0.01 abcd
	52	41.18 ± 0.85 d	2.23 ± 0.47 b	93.95 ± 21.21 a	41.97 ± 1.64 a	0.82 ± 0.02 abc
	78	33.80 ± 0.38 fg	3.59 ± 0.14 ab	121.88 ± 6.05 a	33.81 ± 0.49 a	0.84 ± 0.01 a
IRAT109	0	52.64 ± 1.04 a	—	—	90.56 ± 28.08 a	0.79 ± 0.02 abcd
	26	48.63 ± 1.24 b	3.04 ± 0.44 ab	151.69 ± 24.43 a	48.60 ± 1.53 a	0.79 ± 0.01 abcd
	52	38.34 ± 1.34 de	2.67 ± 0.29 b	100.50 ± 13.15 a	35.79 ± 2.80 a	0.76 ± 0.02 cde
	78	36.25 ± 0.49 ef	3.33 ± 0.27 ab	121.13 ± 11.60 a	36.08 ± 0.63 a	0.83 ± 0.01 ab
Influence and interaction		Var***	Var*	Var ^{ns}	Var ^{ns}	Var***
		Nr***	Nr***	Nr***	Nr**	Nr*
		VarXNr***	VarXNr ^{ns}	VarXNr ^{ns}	VarXNr ^{ns}	VarXNr***

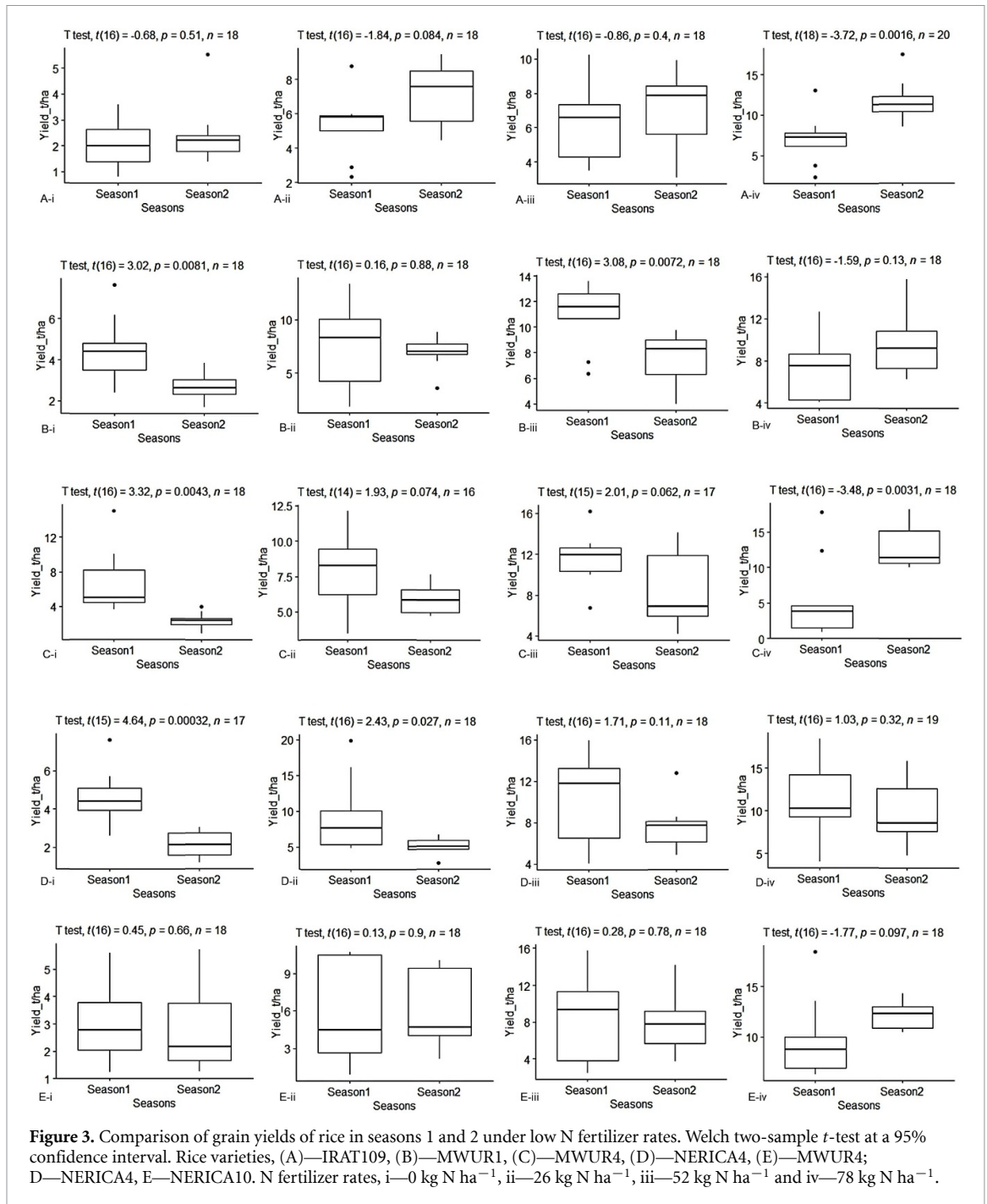
Means with same letters within a column are not significantly different under Student–Newman–Keuls test mean separation at a 95% level of confidence. Var—rice varieties, Nr—N fertilizer rates, VarXNr— interaction between rice varieties and N fertilizer rates.

* (p -value ≤ 0.05), ** (p -value ≤ 0.01), *** (p -value ≤ 0.001), ns (nonsignificant).

3.5. Correlation of yield parameters and nitrogen use efficiency characteristic for different rice varieties at low and high nitrogen levels

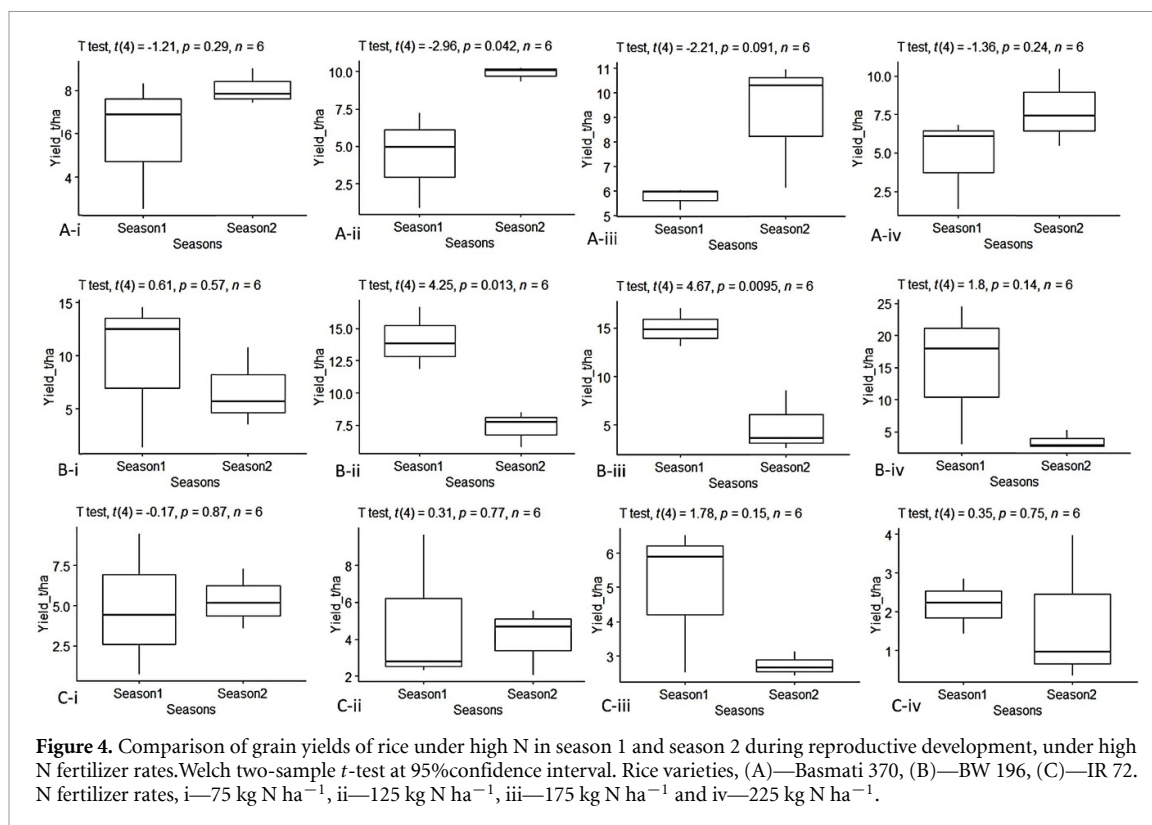
In all the five varieties (IRAT109, MWUR1, MWUR4, NERICA4 and NERICA10), there were positive correlations between N rates and grain yields, total biomass, harvest index, ANR and AE_N, while the

correlation of N rates on NU_tE and NPUE were negative. However, in terms of NHI, some varieties had positive correlations (IRAT109, MWUR4 and NERICA10) with N rates while others had negative correlations (MWUR1 and NERICA4) (supplementary table 5). This trend was similar in season 1 (data not shown).



In season one, both Basmati 370 and IR 72 had negative correlations between the N rates and grain yield, harvest index and NHI, while the correlations of N rates and total biomass and N uptake were positive in these varieties. On the contrary, BW 196 registered a negative correlation for N rates with grain yield and harvest index. However, this variety had a negative correlation of N rates with the harvest index and NHI, while the correlation of N rates to total biomass and N uptake were positive. In season two, both Basmati

370 and IR 72 showed negative correlations for the N rates with grain yield, harvest index and NHI. The correlation of N rates to total biomass and N uptake were also negative in these varieties. Just like the other varieties, BW 196 registered a negative correlation on N rates with grain yield and harvest index. However, this variety had a positive correlation of N rates with the NHI, while the correlation of N rates to total biomass and N uptake was negative (supplementary tables 5–7).



4. Discussion

4.1. Grain yield and yield components as affected by nitrogen rates and forms in different rice varieties

The optimal management of N is critical for high yields in rice and there are recommendations for three stages of application, including 40% before transplanting followed by two 30% doses at the panicle initiation and grain filling stages, respectively (Olfati *et al* 2012). The split N applications undertaken in our experiment considered these key rice phenological stages that differentially coincide with these critical rice N demands (supplementary figures 2 and 3). The split application was more significant at Mwea than at the Ahero site. In Mwea, the interaction between split application and fertilizer sources (urea or sulphate of ammonium) were significantly high, though the advantage of splitting was more pronounced for urea. Urea has been reported to have a lower fertilizer use efficiency compared with other N sources (Zaman *et al* 2008) since it is highly susceptible to loss pathways, particularly with NH₃ emissions as soon as it is applied to croplands, especially under warm climatic conditions like at the Ahero site, hence the advantage of split application. Interestingly, the rice yield for the control treatment (unfertilized plots) was much higher (three folds) for the Mwea site than those of Ahero. Being a research centre, the residual N (both organic and inorganic forms) is expected to be higher. Notably, researchers (Liu *et al* 2004, Feng *et al* 2006) had previously postulated luxury consumption of N,

a probable nexus between higher N concentration in rice straw and high indigenous N supply of soil (INS).

In the current study, the average grain yield in the control (unfertilized) plots at Mwea was higher than 3.5 t ha⁻¹, while at Ahero it was 1.2 t ha⁻¹, and the lower grain yield at the Ahero site may be attributed to the lower yield potential and N uptake efficiency of the rice genotypes under very hot conditions, probably with poor pollen fertilization. The splitting of N inputs throughout the growing season of rice crops contributes to the maintenance of synchrony between the crop N demand and N availability that leads to the harvesting of a considerable grain yield (Kumar *et al* 2018). According to Arthanari *et al* (2007), rice crops require a sustained supply of N in the soil until the reproductive stages to enhance maximum yields. A lack of adequate N is a major constraint among many local farmers, especially in Kenya (unless receiving fertilizer subsidies or getting supplies from cooperative societies). As reported by Li *et al* (2008), N in soils at the heading stage helps plants to have higher photosynthetic rates, delayed leaf senescence and significantly increases grain filling. In another study done by Sheng *et al* (2002), the strategy of stressed panicle fertilizer application including application of 30% at tillering and 70% at panicle initiation without any prior application of basal fertilizer, resulted in improved NUE and high grain yield due to maintenance of the soil N supply. The rice crop is known to have variable demand of N at major critical growth stages and this may explain the slight yield

advantage at Mwea under split application (supplementary table 2).

The lower grain production with increased fertilizer application in different seasons had been reported earlier at the Mwea irrigations scheme by Njinju *et al* (2018). Their results showed the negative impact of increasing N on grain filling and HI in Basmati 370 and BW 196 varieties, especially when N rates were above 75 kg ha⁻¹. Their work concentrated only on N with respect to yield, but did not relate to the implication of declining yield at higher N to NUE and N management. Surprisingly, in the current study, the Basmati 370 variety yielded higher than the two varieties (BW 196 and IR 72), particularly in the second season (figure 5). The trends were, however, inconsistent with the first season where BW 196 and IR 72 had higher yields. Basmati's booting and flower initiation coincided with a warmer period as compared to the two varieties during the second season, while the opposite occurred in season 1 (figure 4—see supplementary figures 2 and 3). Whereas the differences in temperatures may appear marginal, the cumulative degree days are substantial, particularly towards the reproductive stages of growth. Such a marginal role of temperatures on the yield of different rice varieties have been reported by Yang *et al* (2019), albeit with warm temperatures. At the Mwea site, the increase in grain yield with N showed stagnation at some point but was more prominent with higher fertilizer rates (supplementary figure 6). The plateauing/levelling off of yield with N application is not unique to N and rice production. Typically, crop yields and nutrient uptake rates have been reported to show gradual decline with additional nutrient supply (reactive N in our case), reaching a ceiling and eventually declining with further addition (supplementary figures 4 and 5). The level of this ceiling is determined by the environment-genetic yield potential. At low levels of nutrient supply, rates of increase in yield and nutrient (N) uptake are large because the nutrient of interest is the primary factor limiting growth—Liebig's law of minimum (Mengel and Kirkby 2001). This could imply poor utilization of N by the crop at the higher supply of N (see supplementary tables 9 and 10) especially during a window of cold season during the rice booting stage, due to curvilinear return to the conversion of plant N to grain as the yield approaches the ceiling at higher levels (Djaman *et al* 2016). For the BW 196 and IR 72 varieties, N application was optimal at around 75 kg ha⁻¹ in the second season and additional N beyond this point led to a decrease in grain yields and possible loss to the environment. These findings indicate that the current N fertilizer amount (75 kg N ha⁻¹) is sufficient for IR 72 and BW 196 in the second season at the Mwea site and implies that the additional N is not efficiently utilized but lost through leaching, emissions or volatilization or any other pathway into water bodies or the atmosphere (Bijay-Singh *et al*

1995, Lassaletta *et al* 2014). The maturity period is therefore a crucial varietal 'cold-escaping' determinant, especially at the critical stage of growth, hence higher yields. Unfortunately, higher N rates have the potential to extend the vegetative stages of certain rice varieties; with the possibility of critical biological stages coinciding with a cold (or even a hot) period, hence poor N uptake and utilization with consequent low NUE and possible N losses. This information is not only important for economic reasons but also important to avoid environmental hazards associated with the over-application of N fertilizers as this also affects NUE as propounded by Lassaletta *et al* (2014). The synchrony of the crop planting dates and N rates is therefore important in planning for proper N utilization and improved yield, especially during the off-season when water is plentiful but coincides with a cold period (Samejima *et al* 2020). This could probably be achieved through transplanting rather than direct planting to shorten the period the plant is in the field, with the hope of escaping the cold period.

It is not only low temperatures that affect rice production. High temperatures during some parts of season one and some sections of season two (at the Mwea site) could have affected the process of grain yield, resulting in low R^2 values. This is concurrent with the argument by Shi *et al* (2017) who demonstrated that high temperatures impair grain filling, leading to poor seed set and reduced seed grain weight. At high temperatures, there is a higher possibilities of N loss through volatilization hence reducing the N available for enhanced grain and biomass formation. As reported by Lai *et al* (2019), higher soil temperatures may trigger processes of denitrification and lead to high emission of nitrous oxide to the environment. Therefore, with the current study, a high rate of fertilization could have resulted in more environmental loss and less yield due to variations in temperatures (either soil and/or ambient).

4.2. Variation in yield and N uptake among different varieties

There were clear differences in yield responses of different rice varieties when supplied with different N rates (figures 1, 4 and 5). This was not surprising since N levels have been previously reported to affect the yield of many rice varieties (Flint-Garcia *et al* 2003, Jahan *et al* 2020). Yoshida *et al* (2006) reported a greater production of spikelet, possibly due to less translocation of photoassimilates from leaves to spikelet under increased N rates, instead of being channeled to the grains. Their results agree with our current work where more N led to more grains but after some level, there was a higher percentage of unfilled grains and less of filled grains (having reached the yield plateau) especially for moderate and high N rates at the Mwea site (supplementary figure 6). Varietal differences in

Table 5. NUE characteristics of rice varieties under high N fertilizer levels.

Variety	N rates (kg ha ⁻¹)	N uptake kg ha ⁻¹	NHI
Season 1			
Basmati 370	75	251.48 ± 35.02 b	0.50 ± 0.10 a
	125	233.80 ± 35.43 b	0.39 ± 0.15 a
	175	485.87 ± 46.59 b	0.35 ± 0.03 a
	225	461.02 ± 35.86 b	0.32 ± 0.10 a
BW 196	75	354.65 ± 101.56 b	0.51 ± 0.15 a
	125	484.92 ± 33.44 b	0.62 ± 0.02 a
	175	771.30 ± 37.06 a	0.57 ± 0.03 a
	225	921.91 ± 236.10 a	0.48 ± 0.15 a
IR 72	75	222.45 ± 45.41 b	0.44 ± 0.18 a
	125	225.53 ± 64.92 b	0.43 ± 0.09 a
	175	387.37 ± 47.85 b	0.38 ± 0.11 a
	225	391.85 ± 37.32 b	0.19 ± 0.04 a
Influence and interaction		Nr*** Var*** NrXVar*	Nr ^{ns} Var* NrXVar ^{ns}
Season 2			
Basmati 370	75	328.64 ± 54.03 bc	0.58 ± 0.10 a
	125	350.32 ± 25.50 bc	0.61 ± 0.03 a
	175	618.06 ± 69.20 a	0.43 ± 0.03 a
	225	510.32 ± 103.27 ab	0.51 ± 0.02 a
BW 196	75	266.70 ± 51.64 bc	0.60 ± 0.19 a
	125	209.42 ± 20.97 c	0.75 ± 0.01 a
	175	185.18 ± 66.66 c	0.78 ± 0.01 a
	225	207.00 ± 105.22 c	0.74 ± 0.17 a
IR 72	75	165.43 ± 43.70 c	0.75 ± 0.07 a
	125	162.50 ± 28.76 c	0.54 ± 0.12 a
	175	184.15 ± 47.29 c	0.52 ± 0.16 a
	225	191.26 ± 111.97 c	0.28 ± 0.06 a
Influence and interaction		Nr ^{ns} Var*** NrXVar ^{ns}	Nr ^{ns} Var* NrXVar*

Means with same letters within a column are not significantly different under Student–Newman–Keuls test mean separation at a 95% level of confidence. Nr—N fertilizer rates, Var—rice varieties, NrXVar—interaction between N fertilizer rates and rice varieties. * (p -value ≤ 0.05), ** (p -value ≤ 0.01), *** (p -value ≤ 0.001), ns (nonsignificant).

yields and N rates had previously been reported by Matsunami *et al* (2013) in their previous experiment with 70 rice varieties. These results seem to concur with our results and are also in agreement with those of Gweyi-Onyango (2018). Moreover, Gewaily *et al* (2018) reported differential responses of varieties with N rates, with the optimal N rate being observed at 220 kg N ha⁻¹ for late maturing varieties as compared to 165 kg ha⁻¹ as optimal for early maturing varieties. In their experiment, the early maturing variety had a lower yield than the late maturing varieties. In our current study, the yield declined with fertilizer rates beyond 125 kg ha⁻¹ for the ‘high rate’ treatments. Unlike our case where the cold period seemed to limit yield (despite the high N uptake) (figure 4, table 5) the warm temperature in Egypt did not seem to limit the yield of rice in the study by Gewaily *et al* (2018). However, Yang *et al* (2019) reported the negative effect of temperatures, depending on the growth duration of the genotype in question.

The N uptake also varied among varieties, with Basmati having a higher N uptake during the second

season, with uptake increasing with N rates (reaching an optimal value at 175 kg ha⁻¹ and leveling off thereafter). However, in the first season, BW 196 was the most superior variety in terms of N uptake. BW 196 and Basmati showed a similar response to N rates, N uptake and grain yields. However, the low yielding variety (IR 72) showed consistently lower yields, which was also reflected in low N uptake in both seasons (figure 4 and table 5). The higher uptake rates coincided with higher grain yields during the season when a particular variety had the highest grain yield (BW 196 during the first season and Basmati during the second season). Our current findings are in agreement with other findings which showed that rice genotypes show significant variability for N uptake (external efficiency) and N utilization (internal efficiency) with yield being predominantly determined by the N uptake process (Singh *et al* 1998, Witcombe *et al* 2008). N uptake is key in the determination of NUE, hence the choice of varieties may be a key consideration in the proper management of N.

4.3. Nitrogen utilization, physiological use efficiencies, apparent recovery and agronomic efficiency

The values of NUE in this study (table 4) were relatively lower compared to what was reported by De-Xi *et al* (2007) that ranged from 30.9% to 45.9%, which can be attributed to low soil N status and insufficiency of the applied N inputs. The values reduced as N levels increased, with 78 kg N ha⁻¹ eliciting the lowest values. Low NUE values with an increase in N were reported by Elrys *et al* (2020). They calculated five scenarios and recommended S2 (EqDamount that was able to achieve self-sufficiency) which was 77 kg N ha⁻¹ per year. Therefore the 78 kg N ha⁻¹ in our study is only for one season, meaning this is double the amount. But other than 77 kg N ha⁻¹, they proposed the need for the application of additional organic N (37 kg animal manure and 11 kg BNF). The integration of inorganic and organic N may therefore be more sustainable than our approach where we only looked at inorganic N. However, the findings of Elrys *et al* (2020) were general in terms of regions and crops. In most rice farming, intensification is practiced and is one of the high valued crops that is supplied with a higher amount of N, hence it is possible to supply N rates beyond the 77 kg N ha⁻¹ per year projection. The findings of the current study can be used to develop appropriate N management strategies for a rice-based cropping system in Kenya to prevent further degradation of the soil quality status that can be achieved through advocating for the application of the right source of N fertilizers applied at the right time. To achieve optimal NUE , plants should have enhanced uptake of N from the soils and use it more efficiently in yield production (Ju *et al* 2015). Our results agree with those of Eagle *et al* (2000) who reported extremely low N utilization efficiencies in rice that were probably influenced by the extreme losses, particularly in flooded environments without proper water regulations. The study also confirmed that with an increase in soil N supply, a decrease in utilization efficiency has an implication on N management. With high availability of N, additional N uptake is partitioned to the straw and less is made available to the grain, hence resulting in low efficiencies. Contrary to this, with low N, especially in unfertilized plots (as evident from this study) (table 4 season 1—Nericas 4 and 10 as well as IRAT109), the little available N is distributed to the grain, contributing to high utilization and high NUE ratios (Eagle *et al* 2000). According to Xu *et al* (2016), fertilizer application should be done judiciously; considering the 4 R principles (right rate, right time, right place, and right form) to ensure the applied N sufficiently meets the specific crop needs. Due to existing challenges among the rural farmers, low N inputs and NUE remain a grey area requiring more research. Therefore, the focus on strategies and technologies for NUE improvement

among local farmers remains a key area of concern in light of environmental management, since this has the potential to reduce N loss.

Our results on AE_N (tables 3 and 4) varied with varieties as well as locations. These findings agree with those of Djaman *et al* (2016) who reported AE_N values ranging from 26% to 105% depending on rice varieties and locations. However, the current findings are contrary to the results of Thind *et al* (2018) who reported a higher AE_N and ANR when fertilizers were applied in three splits in rice fields. These differences could have been influenced by test varieties, stated soil physiochemical properties like bulk density, structure, texture, and organic matter, as they effect the NUE components (Koudjega *et al* 2019). Besides, our low efficiencies could be due to the method used to apply the fertilizer, either in split or in full doses, as clearly demonstrated by Baral *et al* (2020), where the deep placement of urea in lowland rice was effective in promoting plant N uptake, reducing loss and consequently resulting in higher ANR and AE_N values. This is not surprising since previous reports show that the recovery of N in soil–plant systems seldom go above 50%, which means that the N applied gets lost through different pathways (Abbasi *et al* 2003). This increasing gap between the N applied and taken up by crops has been attributed to a monumental reduction in NUE , as reported by the excellent publication of Raza *et al* (2018) in Pakistan. Moreover, Jing *et al* (2007) argued that N fertilizer recovery is not only dependent on crop growth and genotype, but rather on management practices like the adoption of 4 R stewardship in nutrient management and the surrounding environmental conditions that have effects on the volatilization and leaching losses. The 4 R stewardship ‘implies applying the right source of fertilizer (N for our case), at the right rate, at the right time, in the right place’ (Xu *et al* 2016, Ahmad *et al* 2018). For fertilizer NUE , there is the need to create more awareness to match N supply as close as possible with the demands of the specific crops and environments; facts that are also in concurrence with the findings of Yang *et al* (2019) who looked at the effects of warmer temperatures on rice growth and yields. According to Kombali *et al* (2016), fertilizer N recovery can be optimized through the application of frequent smaller doses.

From our findings, rice varieties respond differently to N in different seasons, and these observations are in agreement with other reports that point out the influence of N form, timing, crop variety N needs and the environment on NUE (Djaman *et al* 2018, Gweyi-Onyango 2018, Ntinyari and Gweyi-Onyango 2018), hence these factors play pivotal roles in determining yield and NUE and are linked with other associated factors that may affect N management. The fertilizer subsidy can increase availability and access (Marenja and Barrett 2009)

at the right time, which has a direct effect on yield, as demonstrated by the excellent reviews of Masso *et al* (2017). Besides, there have been reported cases of fertilizer adulteration and inoculants (Jefwa *et al* 2014) and this definitely affects crop growth performance and consequently introduces errors in the estimation of NUE with the potential of affecting the management and policy advice at local and regional scales. Indeed, previously suggested interventions in SSA, such as improved seeds, balanced fertilisation, organic inputs, liming materials, and water management (e.g. Ahero site) have the potential to double NUE, and particularly AE_N , when novel agronomic practices are adopted, as argued by Vanlauwe *et al* (2015).

5. Conclusions

This is the first study to have attempted to evaluate the NUE from the perspectives of rice varieties and seasons in Kenya. N fertilizer management is very important for improving NUE, crop productivity and the reduction of N losses to the environment. Improving NUE to a desirable range remains critical as high values indicate that soil mining is contributing to the declining soil N status and fertility levels. In the current study, cropping season (warm vs cool), rice varieties, N application methods, rates and source had a significant impact on the NUE and its components. Results indicated that an interaction of cropping season and rice varieties is crucial in maintaining rice productivity and NUE in a rice-based cropping system in the study regions of Kenya. Limited or low N conditions provide a better opportunity for selecting for NUE, particularly for double cropping seasons where the cold period becomes a challenge. Whereas it is implicit that most rice varieties are bred for higher N responses, we conclude that most of the N applied beyond 125 kg N ha^{-1} is not fully utilized by the plant (unless there is integration between inorganic and organic N inputs) and hence may be an environmental threat and have cost implications for the farmers. The findings of the current study can therefore be used to develop appropriate N management strategies for the rice-based cropping system. However, additional studies under various N management practices using similar cultivars and N rates in different seasons and at different sites in Kenya would give better insights.

Data availability statement

Option #1: the data that support the findings of this study are openly available at the following URL/DOI: [insert web link or DOI to the data].

All data that support the findings of this study are included within the article (and any supplementary files).

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References

- Abbasi M K, Shah Z and Adams W A 2003 Effect of the nitrification inhibitor nitrapyrin on the fate of nitrogen applied to a soil incubated under laboratory condition *J. Plant Nutr. Soil Sci.* **166** 513–8
- Ahmad M, Almad A S, Jan I and Zia A 2018 Application of the 4R nutrient stewardship concept for growing off-season tomatoes in high tunnels *J. Soil Sci. Plant Nutr.* **18** 989–1001
- Arthanari P M, Ramasamy S and Amanullah M M 2007 Nutrient uptake as influenced by post panicle initiation nutrient management in rice plant organ *Res. J. Agric. & Biol. Sci.* **3** 621–24
- Balasubramanian V, Alves B, Aulakh M, Bekunda M, Cai Z, Drinkwater L, Mugendi D, Van Kessel C and Oenema O 2004 Crop, environmental, and management factors affecting nitrogen use efficiency *Agriculture and the Nitrogen Cycle* ed A R Mosier, J K Syers and J Freney (Metro Manila) SCOPE, 65 pp 19–33
- Baral B R, Pande K R, Gaihre Y K, Baral K R, Sah S K, Thapa Y B and Singh U 2020 Increasing nitrogen use efficiency in rice through fertilizer application method under rainfed drought conditions in Nepal *Nutrient Cycling Agroecosyst.* **118** 1–12
- Bijay-Singh Y S and Sekho S G 1995 Fertilizer-N use efficiency and nitrate pollution of groundwater in developing countries *J. Contam. Hydrol.* **20** 167–84
- De-Xi L I N, Xiao-Hui F A N, Feng H U, Hong-Tao Z H A O and Jia-Fa L U O 2007 Ammonia volatilization and nitrogen utilization efficiency in response to urea application in rice fields of the Taihu Lake region, China *Pedosphere* **17** 639–45
- Djaman K, Bado V B and Mel V 2016 Yield and nitrogen use efficiency of aromatic rice varieties in response to nitrogen fertilizer *Emir. J. Food Agr.* **28** 126–35
- Djaman K, Mel V C, Ametonou F Y, El-Namaky R, Diallo M D and Koudahe K 2018 Effect of nitrogen fertilizer dose and application timing on yield and nitrogen use efficiency of irrigated hybrid rice under semi-arid conditions
- Dobermann A 2007 Nutrient use efficiency—measurement and management *Fertilizer Best Management Practices* (Paris: International Fertilizer Industry Association)
- Eagle A J, Bird J A, Horwath W R, Linquist B A, Brouder S M, Hill J E and Van Kessel C 2000 Rice yield and nitrogen utilization efficiency under alternative straw management practices *Agron. J.* **92** 1096–103
- Edmonds D E, Abreu S L, West A, Caasi D R, Conley T O, Daft M C and Patel N K 2009 Cereal nitrogen use efficiency in sub Saharan Africa *J. Plant. Nutr.* **32** 2107–22
- Elrys A S, KAbdel-Fattah M, Raza S, Chen Z and Zhou J 2019 Spatial trends in the nitrogen budget of the African agro-food system over the past five decades *Environ. Res. Lett.* **14** 124091
- Elrys A S, Metwally M S, Raza S, Alnaimy M A, Shaheen S M, Chen Z and Zhou J 2020 How much nitrogen does Africa need to feed itself by 2050? *J. Environ. Manage.* **268** 110488
- Emitiyagoda G A M S S, Abeysiwardena D D Z and Silva S 2010 Grain yield and yield variability of rice under high management in different Agro-climatic Zones in Sri Lanka *Annals Sri Lanka Dep. Agric.* **12** 63–77

- Estudillo J P and Otsuka K 2013 Lessons from the Asian green revolution in rice *An African Green Revolution—finding Ways to Boost Productivity on Small Farms* ed K Otsuka and D F Larson (Dordrecht: Springer) pp 17–42
- Fageria N K and Baligar V C 2003 Methodology for evaluation of lowland rice genotypes for nitrogen use efficiency *J. Plant Nutr.* **26** 1315–33
- Feng T F E N G, Jingping Y and Hongxin S 2006 Effect of N fertilizer and N use efficiency under different N levels of application in high-fertility paddy field *J. Zhejiang Univ.*
- Flint-Garcia S A, Thornsberry J M and Buckler E S 2003 Structure of linkage disequilibrium in plants *Annu. Rev. Plant Biol.* **54** 357–74
- Fróna D, Szenderák J and Harangi-Rákos M 2019 The challenge of feeding the world *Sustainability* **11** 5816
- Gewaily E E, Ghoneim A M and Osman M M A 2018 Effects of nitrogen levels on growth, yield and nitrogen use efficiency of some newly released Egyptian rice genotypes *Open Agric.* **3** 310–8
- Good A G, Shrawat A K and Muench D G 2004 Can less yield more? Is reducing nutrient input into the environment compatible with maintaining crop production? *Trends Plant Sci.* **9** 597–605
- Gweyi-Onyango J P 2018 Effects of nitrogen levels on yield and nitrogen utilization efficiencies of two rice varieties in Kirinyaga County, Kenya *Afr. J. Horticultural Sci.* **14** 23–34
- Han M, Okamoto M, Beatty P H, Rothstein S J and Good A G 2015 The genetics of nitrogen use efficiency in crop plants *Annu. Rev. Genet.* **49** 269–89
- Hegewisch K C and Abatzoglou J T 2020 Data download' web tool *NW Climate Toolbox* (available at: https://climate.northwestknowledge.net/NWTOOLBOX/formattedDownloads.php?fbclid=IwAR2sLTY82aZRA_3iEHdd5N_r-bE1QJEiEKns3JsJ5Y0t1J19Qu1mOWC-egU) (Accessed 5 August 2020)
- Horwitz W 2010 *Official Methods of Analysis of AOAC International. Volume I, Agricultural Chemicals, Contaminants, Drugs* ed W Horwitz (Gaithersburg, MD: AOAC International)
- Jahan A, Islam A, Sarkar M I U, Iqbal M, Ahmed M N and Islam M R 2020 Nitrogen response of two high yielding rice varieties as influenced by nitrogen levels and growing seasons *Geology, Ecology, and Landscapes* **1**–8
- Jefwa J M et al 2014 Do commercial biological and chemical products increase crop yields and economic returns under smallholder farmers' conditions? *Challenges and Opportunities for Agriculturalintensification of Humid Highland Systems of sub-Saharan Africa* ed B Vanlauwe, P Van Asten and G Blomme (Cham: Springer) pp 81–96
- Jian-Feng C, Jiang H Y, Liu Y B, Dai T B and Cao W X 2011 Methods of identifying and screening of rice genotypes with high nitrogen efficiency *Rice Sci.* **18** 127–35
- Jing Q, Bouman B A M, Hengsdijk H, Van Keulen H and Cao W 2007 Exploring options to combine high yields with high nitrogen use efficiencies in irrigated rice in China *Eur. J. Agron.* **26** 166–77
- Ju C, Buresh R J, Wang Z, Zhang H, Liu L, Yang J and Zhang J 2015 Root and shoot traits for rice varieties with higher grain yield and higher nitrogen use efficiency at lower nitrogen rates application *Field Crops Res.* **175** 47–55
- Kajisa K 2016 On the determinants of low productivity of rice farming in Mozambique: pathways to intensification *In Pursuit of an African Green Revolution* (Berlin: Springer) pp 13–38
- Kombali G, Rekha B, Sheshadri T, Thimmegowda M N and Mallikarjuna G B 2016 Optimization of water and nutrient requirement through drip fertigation in aerobic rice *Int. J. Bio-Resour. Stress Manage.* **7** 300–4
- Koudjega K, Ablade K A, Lawson I Y D, Abekoe M K, Owusu-Bennoah E and Tsatsu D K 2019 Reducing ammonia volatilization and improving nitrogen use efficiency of rice at different depths of urea supergranule application *Commun. Soil Sci. Plant Anal.* **50** 974–86
- Kumar K A, Swain D K and Bhadoria P B S 2018 Split application of organic nutrient improved productivity, nutritional quality and economics of rice-chickpea cropping system in lateritic soil *Field Crops Res.* **223** 125–36
- Lai T V, Farquharson R and Denton M D 2019 High soil temperatures alter the rates of nitrification, denitrification and associated N₂O emissions. *J Soils Sediments* **19** 2176–189
- Lassaletta L, Billen G, Anglade G B and Garnier J 2014 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland *Environ. Res. Lett.* **9** 105011
- Li Y L, Fan X R and Shen Q R 2008 The relationship between rhizosphere nitrification and nitrogen-use efficiency in rice plants *Plant Cell Environ.* **31** 73–85
- Liu L J, Sang D Z, Liu C L, Wang Z Q, Yang J C and Zhu Q S 2004 Effects of real-time and site-specific nitrogen managements on rice yield and nitrogen use efficiency *Agric. Sci. China* **3** 262–68
- Magoti R, Kikuta M, Chemining'wa G, Kinama J, Kimani J, Samejima H and Makihara D 2019 Growth of rice varieties in different kenyan soil types under water-deficit conditions *J. Agric. Sci.* **11** 1–11
- Marenya P P and Barrett C B 2009 Soil quality and fertilizer use rates among smallholder farmers in western Kenya *Agric. Econ.* **40** 561–72
- Masso C, Baijukya F, Ebanyat P, Bouaziz S, Wendt J, Bekunda M and Vanlauwe B 2017 Dilemma of nitrogen management for future food security in sub-Saharan Africa—a review *Soil Res.* **55** 425–34
- Matsunami M, Matsunami T, Kon K, Ogawa A, Kodama I and Kokubun M 2013 Genotypic variation in nitrogen uptake during early growthamong rice cultivars under different soil moisture regimes *Plant Prod. Sci.* **16** 238–46
- Mengel K and Kirkby E A 2001 *Principles of Plant Nutrition* (Dordrecht: Kluwer Academic Publishers)
- Ministry of Agriculture 2008–2018 National rice development strategy (available at: www.jica.go.jp/english/our_work/thematic_issues/agricultural/pdf/kenya_en.pdf)
- Njinju S M, Samejima H, Katsura K, Kikuta M, Gweyi-Onyango J P, Kimani J M, Yamauchi A and Makihara D 2018 Grain yield responses of lowland rice varieties to increased amount of nitrogen fertilizer under tropical highland conditions in central Kenya *Plant Prod. Sci.* **109** 1–12
- Ntinyari W and Gweyi-Onyango J P 2018 Impact of nitrogen forms and levels on yield and quality of rice in kirinyaga and kisumu counties kenya *Asian J. Soil Sci. Plant Nutr.* **3** 1–7
- Olfati J A, Khasmakhi-Sabet S A and Shabani H 2012 Nutrient Solutions on Yield and Quality of Basil and Cress *International Journal of Vegetable Science* **18** 298–304
- Rakotoson T, Dusserre J, Letourmy P, Ramontal R, Cao T V, Ramanantsoanirina A and Raboin L M 2017 Genetic variability of nitrogen use efficiency in rainfed upland rice *Field Crops Res.* **213** 194–203
- Raza S, Zhou J, Aziz T, Afzal M R, Ahmed M, Javaid S and Chen Z 2018 Piling up reactive nitrogen and declining nitrogen use efficiency in Pakistan: a challenge not challenged (1961–2013) *Environ. Res. Lett.* **13** 034012
- Saito K, Nelson A, Zwart S J, Niang A, Sow A, Yoshida H and Wopereis M C S 2013 Towards a better understanding of biophysical determinants of yield gaps and the potential for expansion of the rice area in Africa *Realizing Africa's Rice Promise* (Cotonou) pp 188–203
- Samejima H, Katsura K, Kikuta M, Njinju S M, Munji K J M, Yamauchi A and Makihara D 2020 Analysis of rice yield response to various cropping seasons to develop optimal cropping calendars in Mwea, Kenya *Plant Prod. Sci.* **23** 297–305
- Sheng H J, Qian X Q and Wang X Z 2002 Effects of applying integrated fertilizer companion on population quality and

- grain yield in rice *J. Yangzhou University Agricultural and Life Sciences Edition* **23** 47–50
- Shi W, Yin X, Struik P C, Solis C, Xie F, Schmidt R C, Huang M, Zou Y, Ye C and Jagadish S V 2017 High day- and night-time temperatures affect grain growth dynamics in contrasting rice genotypes. *J. Exp. Bot.* **68** 5233–245
- Singh U, Ladha J K, Castillo E G, Punzalan G, Tirol-Padre A and Duqueza M 1998 Genotypic variation in nitrogen use efficiency in medium- and long-duration rice *Field Crops Res.* **58** 35–53
- Thind H S, Singh Y, Sharma S, Goya L, Singh V and Singh B 2018 Optimal rate and schedule of nitrogen fertilizer application for enhanced yield and nitrogen use efficiency in dry-seeded rice in north-western India *Arch. Agron. Soil Sci.* **64** 196–207
- Tsujimoto Y, Rakotoson T, Tanaka A and Saito K 2019 Challenges and opportunities for improving N use efficiency for rice production in sub-Saharan Africa *Plant Prod. Sci.* **22** 413–27
- USDA 2018 Production, supply and distribution online (available at: <https://apps.fas.usda.gov/psdonline/app/index.html#/app/home>)
- Van Bueren E T and Land Struik P C 2017 Diverse concepts of breeding for nitrogen use efficiency. A review *Agron. Sustain. Dev.* **37** 1–24
- Vanlauwe B, Descheemaeker K, Giller K E, Huising J, Merckx R, Nziguheba G, Wendt J and Zingore S 2015 Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation *Soil* **1** 491–508
- Walkley A and Black I A 1934 An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method *Soil Sci.* **37** 29–38
- Witcombe J R, Hollington P A, Howarth C J, Reader S and Steele K A 2008 Breeding for abiotic stresses for sustainable agriculture *Phil. Trans. R. Soc. B* **363** 703–16
- Xu G, Fan X and Miller A J 2012 Plant N assimilation and use efficiency *Annu. Rev. Plant Biol.* **63** 153–82
- Xu X, He P, Zhao S, Qiu S, Johnston A M and Zhou W 2016 Quantification of yield gap and nutrient use efficiency of irrigated rice in China *Field Crops Res.* **186** 58–65
- Yang T, Zeng Y, Sun Y, Zhang J, Tan X, Zeng Y and Pan X 2019 Experimental warming reduces fertilizer nitrogen use efficiency in a double rice cropping system *Plant Soil Environ.* **65** 483–9
- Yoshida H, Horie T and Shiraiwa T 2006 A model explaining genotypic and environmental variation of rice spikelet number per unit area measured by cross-locational experiments in Asia *Field Crops Research* **97** 337–43
- Zaman M, Nguyen M L, Blennerhassett J D and Quin B F 2008 Reducing NH₃, N₂O and NO₃-N losses from a pasture soil with urease or nitrification inhibitors and elemental S-amended nitrogenous fertilizers *Biol. Fertil. Soils* **44** 693–705
- Zhou M, Brandt P, Pelster D, Rufino M C, Robinson T and Butterbach-Bahl K 2014 Regional nitrogen budget of the Lake Victoria Basin, East Africa: syntheses, uncertainties and perspectives *Environ. Res. Lett.* **9** 105009