Chapter 15
Rice Response to Nitrogen and Supplemental Irrigation Under Low Phosphorus and Potassium in Upland Production Systems in East Africa

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Abstract Throughout upland rice ecologies, low soil fertility and moisture stress are the major factors limiting productivity and profitability. We conducted field experiments using 36 combinations of NPK fertilizer on a popular upland rice variety in East Africa (NERICA 4) to establish upland rice crop nutrient requirements under supplemental irrigation (SI) and rainfed (RF) conditions. NPK was applied in a factorial design by partially employing nutrient omission technique. The overall effect of NPK on the grain yield was more striking in SI, with 55% yield increase as compared to 40% in RF. Application of nitrogen (N), phosphorus (P) and potassium (K) fertilizers singly, in SI, increased the grain yield of NERICA 4 by 43%, 5% and 0.4%, respectively. In contrast, N increased grain yield by 20% in RF, and P and K had no significant effect on grain yield. Application of 120 kg N ha^{-1} alone, without P and K, however, led to a 44% decrease in agronomic efficiency (AE) in RF and a marginal increase in SI. Although maximum biomass was obtained with 120:40:40 kg NPK ha^{-1} in both SI and RF, the grain yield was not significantly different from 80:40:40 kg NPK ha^{-1}. Besides, the harvest index (HI) dropped by eight units in RF and increased only marginally in SI at 120:40:40 kg NPK ha^{-1}.

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The net profit, due to NPK, was 33% higher in SI than RF at 80:40:40 kg NPK ha^{-1}. Our data show that N is the most limiting nutrient, and applying N beyond 80 kg N ha^{-1} at the current P and K recommendation of 40 kg ha^{-1} for upland rice is less profitable.

Keywords Nitrogen · Upland rice · Rainfed · Agronomic efficiency · Grain yield

15.1 Introduction

Throughout upland rice ecologies, low rice yields are mainly attributed to moisture stress, low soil fertility and negative interactions between water and nutrient availability. Plant water stress brought about by either high atmospheric evaporation or decreased solution water potential causes reduced nutrient uptake by its effect on the rate of water flow through plants (Greenway and Klepper 1969; Haefele et al. 2010), or through active ion uptake mechanisms and passive efflux of ions (Erlandsson 1979). Upland rice production systems, where moisture levels are often below field capacity, are the most affected, and farmers rarely achieve yields higher than 2.5 tons ha^{-1}. This is exacerbated by limited or unbalanced plant nutrition. Moreover, negative interaction between water and nutrient availability has been reported in upland systems (Haefele et al. 2010). Among the essential plant nutrients, nitrogen (N), phosphorus (P) and potassium (K) are critical elements for plant growth and development (Dobermann and Fairhurst 2000; Miller and Cramer 2004). Low supply of N, P and K is sometimes highlighted as an even more important constraint than water availability (Fukai et al. 1998; Suriya-arunroj et al. 2000; Linquist and Sengxua 2001). Deficiency of N, P and K in upland rice limits tillering, panicle formation and grain filling, curtailing yield output per hectare (Wang et al. 2002; Yamah 2002).

In most African countries, where farmers have traditionally relied on fallow periods, fertilizer use is negligible and often rare. In fact, fertilizer use in Africa is estimated to have stagnated at 6–12 kg ha^{-1} year^{-1} for the last 10 years (Sommer et al. 2013). Uganda, for instance, is among the lowest fertilizer users in the world, and soil nutrient depletion continues to be one of the major agricultural constraints (Musiime et al. 2005). According to the State of Uganda Population report 2010 (The Republic of Uganda/UNFPA 2010), it is estimated that between 1996 and 2000, nutrient fertilizer usage was 0.37 kg ha^{-1}, while nutrient mining was estimated to be 87 kg ha^{-1} year^{-1} by 2008, with most upland areas at the risk of degradation.

The total area under upland rice in Uganda has increased from about 6000 ha in 2002 to about 60,000 ha in 2012, and upland rice dominates the new rice growing areas, suggesting the need for measures to sustain productivity. To our knowledge, the benefits of plant nutrition in upland rice production systems have remained obscure for decades, partly because of limited information on nutrient management, and limited empirical evidence of how fertilizer use rates compare to economically profitable levels. On the other hand, most smallholder farmers operate under varying conditions within the agricultural landscapes. This variability is explained largely by soil fertility gradients induced by either varying inherent soil fertility or management. Thus, soil analysis often falls short of accuracy due to the heterogeneous nature of the fields from which sampling is carried out. To overcome this, nutrient omission trials have been suggested as a tool to identify which of the macro-nutrients, N, P and K, are limiting crop growth and productivity. In this study, we investigated the effect of 36 combinations of NPK on rice yields in rainfed (RF) and supplemental irrigation (SI) upland rice systems. The 36 combinations were applied in a factorial design, in a nutrient omission technique aimed at establishing the crop needs under natural conditions. We used a popular upland rice variety (NERICA 4) that was released in 2003 for commercial production in most East African countries.

15.2 Materials and Methods

15.2.1 Site Information

Field experiments were conducted at the National Crops Resources Research Institute, Namulonge (0° 32′ N, 32° 37′ E, 1150 m above sea level), Uganda. Namulonge is located within the tropical wet and mild dry climate with slightly humid (65%) conditions. The area receives bimodal rainfall with two seasons having approximately the same length (3 months each). Rainfall amounts range from 800 to 1200 mm of annual precipitation and temperatures range from 16 to 28 °C. The soils represent a transition zone between red and yellow ferallitic soils derived from a basement complex. Before planting, soil analysis was done to provide an estimate of the nutrients that would be available to the crop. All soil analysis measurements were done according to the method described by Okalebo et al. (1993). The soil type at the experimental site was sandy-clay loam. Textural analysis values were 22% clay; 16% silt and 62% sand. The chemical properties at 0–20 cm soil depth were: pH 5.3; organic matter 31.5 g kg^{-1}; extractable phosphorus (P), 0.82 mg kg^{-1}; potassium (K), 88.6 mg kg^{-1}; calcium (Ca), 1.6 $cmol_c$ kg^{-1}; and magnesium (Mg), 1.13 $cmol_c$ kg^{-1}. Average annual rainfall amount was higher in 2008 than in 2009 (Fig. 15.1a) but did not cause a significant difference in crop performance in both years, most likely because of timely planting of the experiments. Temperature trends were relatively consistent with a minor increase in January for both years (Fig. 15.1b).

15.2.2 Treatments and Field Management

A factorial design in a split plot arrangement with three replications was used to determine the effect of NPK fertilizer and SI on NERICA 4 in 2008 and 2009. Trials were conducted in RF, and SI in which plants were irrigated with 20 mm of water using sprinklers every five days during windows of dry weather starting from panicle

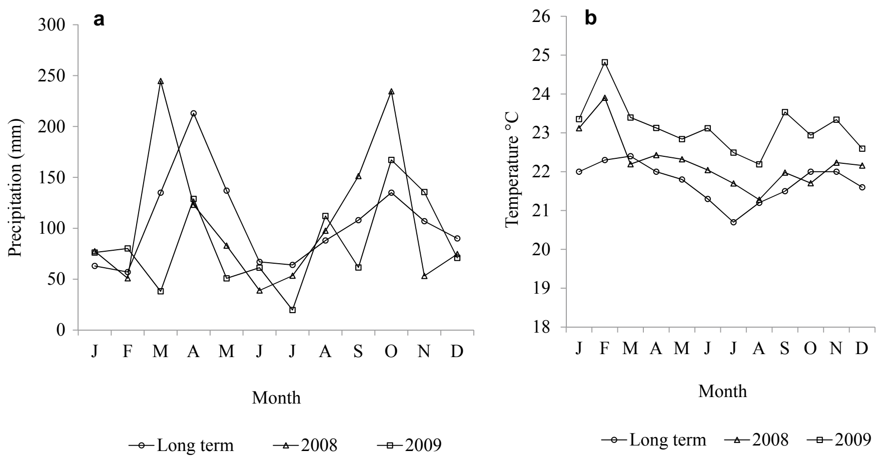

Fig. 15.1 Monthly average temperatures (**a**) and precipitation (**b**) of the two production years in comparison with the long term average

initiation stage. Thirty-six treatment combinations consisting of four levels of N (0, 40, 80 and 120 kg N ha^{-1}), and three levels of each of P and K (0, 20 and 40 kg ha^{-1}) were tested. The nutrients were supplied to the soil in the form of urea for N, triple super phosphate (TSP) for phosphorus and muriate of potash for potassium. Full quantity of P was applied and incorporated in the seedbed at planting. Potassium along with ½ fraction of N was applied at three weeks after planting. The remaining quantity of N was applied at panicle initiation stage. In each year, the experimental plot size was 10.5 m^2 consisting of eight rows, 5 m long with intra row spacing of 0.3 m. The plots received identical cultural treatments of ploughing, cultivation, seed rate, sowing method and pest control.

15.2.3 Sampling and Data Analysis

Four middle rows in each plot were selected and 1 m from either side had randomly selected plants tagged for recording plant height, tillers/m^2 and panicles/m^2. At maturity, panicles were harvested from the tagged plants and data on grain number per panicle was recorded. Grain yield, adjusted to moisture content of 14%, was also determined from the four middle rows using the formula in Fig. 15.2. Dry matter was determined after drying the straw to constant weight. Harvest index was calculated as a percentage of kernals over dry matter yield according to Fageria (2009). Agronomic efficiency (AE) was calculated based on the yield increase due to fertilizer application according to Haefele et al. (2010). All the data was subjected to analysis of variance following the split-plot model using SAS Statistical software (Version 9.3). The least significant difference was used to compare treatments within a factor and only

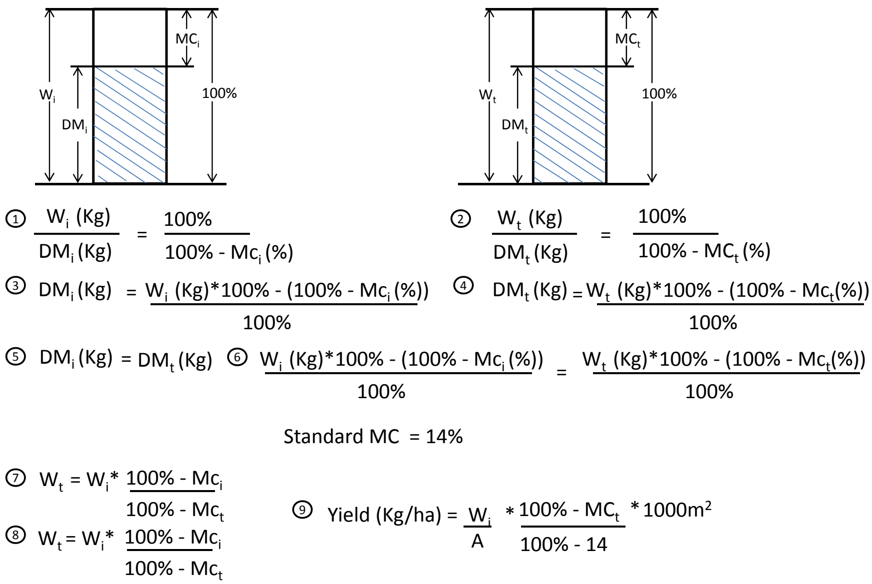

Fig. 15.2 Formula used to obtain grain yield per hectare standardized to 14% grain moisture. A four-row plot, with average row width of 30 cm was harvested. Where W_i is the initial weight of harvested grain with MC at 100%; MC_i is moisture content at harvest; MC_t is moisture content adjusted to 14%. W_t is the grain weight adjusted to 14% MC. DM is dry matter, which stays constant irrespective of MC. DM_i is dry matter at harvest; DM_t is dry matter at 14% moisture content (MC). A is the areas harvested

when the F-test of the variable was significant for that factor. The data on economic attributes was analyzed to assess the benefit of NPK at 80:40:40 with and without SI separately, in order to calculate the gross and net returns. Percentage grain yield difference between SI and RF due to NPK application was calculated using the formula:

$$YI_p = [(YI_{SI} - YI_{RF}) / YI_{SI} * 100] \quad (15.1)$$

where:

YI_p is percentage yield increase, and
YI_{SI} is yield increase in SI, and YI_{RF} is yield increase in RF.

15.3 Results

15.3.1 Grain Yield, Growth and Yield Component Attributes

NPK (120:40:40) increased grain yield by 55% and 40% in SI (Fig. 15.3a) and RF (Fig. 15.3b), respectively. However, the grain yield at 120 kg N ha^{-1} was not significantly different from 80 kg N ha^{-1} in RF even when P and K were applied at 40 kg ha^{-1}. Single application of N, P and K fertilizers in SI increased the grain yield of NERICA 4 from 2.46 to 4.31 tons ha^{-1} for N, 2.46 to 2.58 tons ha^{-1} for P and 2.46 to 2.47 for K; translating into 43%, 5%, and 0.4% yield increase due to N, P, and K, respectively. Interestingly, the grain yield gap was twice higher than the biomass gap when the two production systems (SI and RF) were compared (Figs. 15.3 and 15.4), and the biomass was more correlated to grain yield than the harvest index (HI) in SI compared to RF. At NPK rates of 120:40:40 kg ha^{-1}, HI dropped by eight units in RF (Fig. 15.6a). Moreover, the effect of lower NPK rates on HI was superior to higher rates in RF, with 40:40:40 NPK treatments producing the highest HI (0.45). Conversely, HI continued to increase in SI and was 11.5% and 20.5% higher in 40:40:40 kg ha^{-1} and 120:40:40 kg ha^{-1}, respectively. Despite the declining HI in RF at higher NPK rates, biomass was similar in RF at 80–120 kg N ha^{-1} (Fig. 15.4a), whereas that of SI continued to increase (Fig. 15.4b). At 0–40 kg ha^{-1} of P and K, biomass production was not significantly different from zero nitrogen addition (0 N)

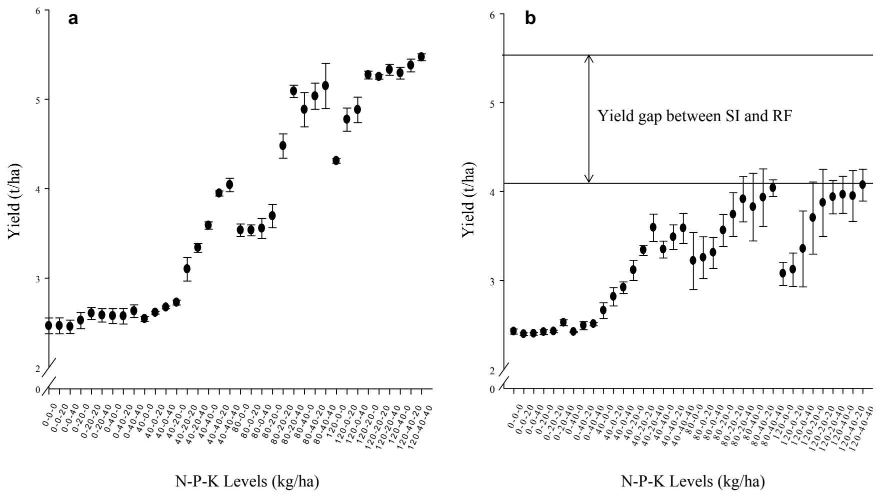

Fig. 15.3 Grain yield increase in relation to incremental rate of NPK fertilizer under supplemental irrigation (**a**) and rainfed (**b**) conditions. Yield gap is twice the biomass gap when the two production systems (SI and RF) are compared. The yield gap is the difference between the highest mean grain yields between SI and RF. Symbols indicate means and bars indicate standard errors. ($LSD_{(0.05)}$ = 0.78 and 0.17 for supplemental irrigation and rainfed conditions, respectively)

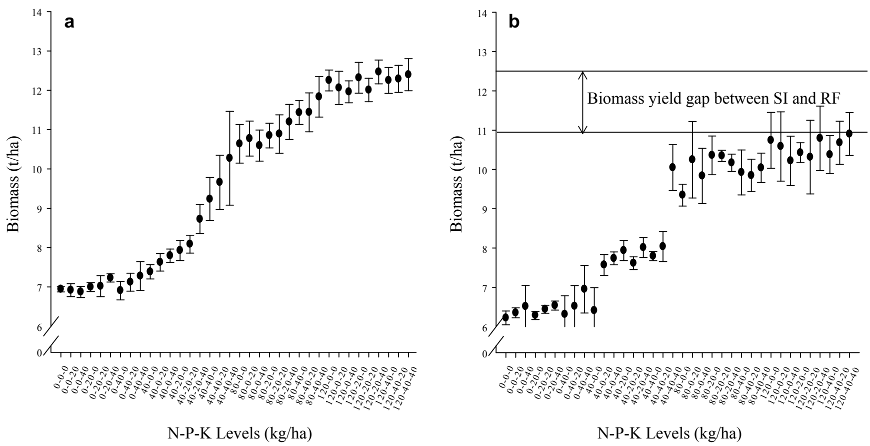

Fig. 15.4 Increase in biomass in relation to incremental rate of NPK fertilizer under supplemental irrigation (**a**) and rainfed (**b**) conditions. The biomass gap is the difference between the highest biomass yields between SI and RF. Symbols indicate means and bars indicate standard errors. ($LSD_{(0.05)} = 0.07$ and 0.10 for supplemental irrigation and rainfed conditions, respectively)

in both SI and RF; the same was true for 0–40 kg N ha^{-1} without P and K. Agronomic efficiency (AE) increased from 18 kg kg^{-1} to 24 kg kg^{-1} in SI (Fig. 15.5a). In contrast, average AE remained at suboptimal levels of 17 kg kg^{-1} and declined at N rates beyond 40 kg ha^{-1} in RF, which was similar to the pattern observed with HI. Productivity decline in terms of AE was also observed in SI when N fertilizer levels exceeded 80 kg ha^{-1}. Moreover, N application without P and K decreased AE by 30% and 47% in SI and RF, respectively (Fig. 15.5b). Panicle number (per m^2), tiller number, grain number (per panicle) and 1000 grain weight were also significantly influenced by both SI and NPK treatments. The panicle number (per m^2) ranged from 168 to 254 while tiller number ranged from 176 to 266 in SI across NPK application rates, which translated into 33% increase in tiller and panicle number (Fig. 15.6a). In RF, panicle number ranged from 167 to 223 while tiller number ranged from 176 to 239, which translated into 26% and 24% increase in tiller and panicle number, respectively. Grain number (per panicle) and 1000 grain weight also increased progressively with the increasing NPK levels. Interestingly, these yield parameters were also significantly influenced by PK in both SI and RF, except HI which dropped by 14% and 5% with increasing NK and NP, respectively (Fig. 15.6b). In general SI significantly augmented the effect of NPK on yield components than RF, and a combination of all the three nutrients was highly significant than when one was omitted.

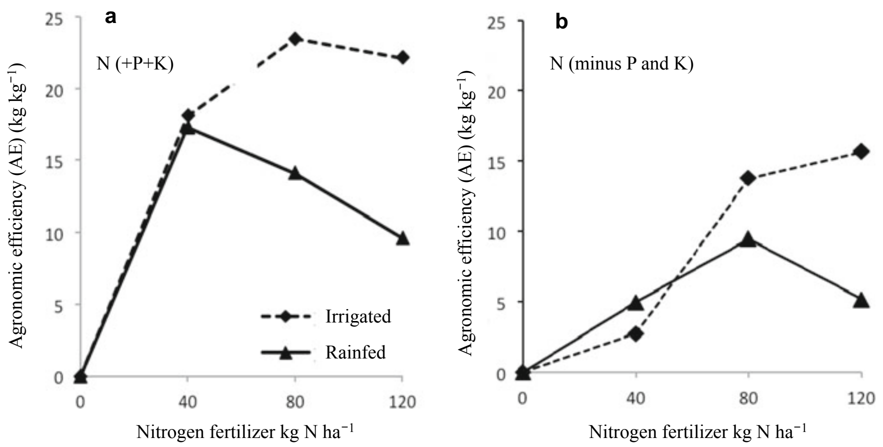

Fig. 15.5 Agronomic Efficiency (AE) of nitrogen fertilizer when applied with P and K, N (+ P + K) and without P and K, N (minus P and K) in supplemental irrigation (irrigated) and rainfed conditions. ($LSD_{(0.05)}$ = 2.26 and 3.67 for supplemental irrigation and rainfed conditions, respectively)

15.3.2 Economic Attributes

The values of the economic attributes (gross and net return) increased significantly with the rates of NPK applied in both SI and RF conditions (Table 15.1). However, the economic returns were more evident in SI compared to RF. The highest value of gross as well as net return was recorded at 120:40:40 NPK application rates in SI, whereas the RF crop had significantly higher returns at 80:20:20 NPK application. For comparison between the two systems, both gross and net returns were calculated based on NPK application rates of 80:40:40. Using this rate, gross and net returns of US$2127 and US$1323 were obtained under SI, respectively, whereas, RF conditions produced a gross and net return of US$1583 and US$1001, respectively. Average difference in net return between SI and RF at 80:40:40 NPK was US$322 ha^{-1}. This increase was 33% higher than the net returns obtained under RF conditions.

15.4 Discussion and Conclusions

Upland rice production in Africa suffers from low nutrient supply and moisture stress, which limit crop productivity and profitability. We examined the effects of supplementary irrigation (SI) and 36 NPK fertilizer application rates on the grain yield of the rice cultivar, ‘NERICA 4’, in Namulonge, Uganda over a period of two years. Several combinations were included to determine a suitable combination of N, P and K needed to improve upland rice productivity and profitability.

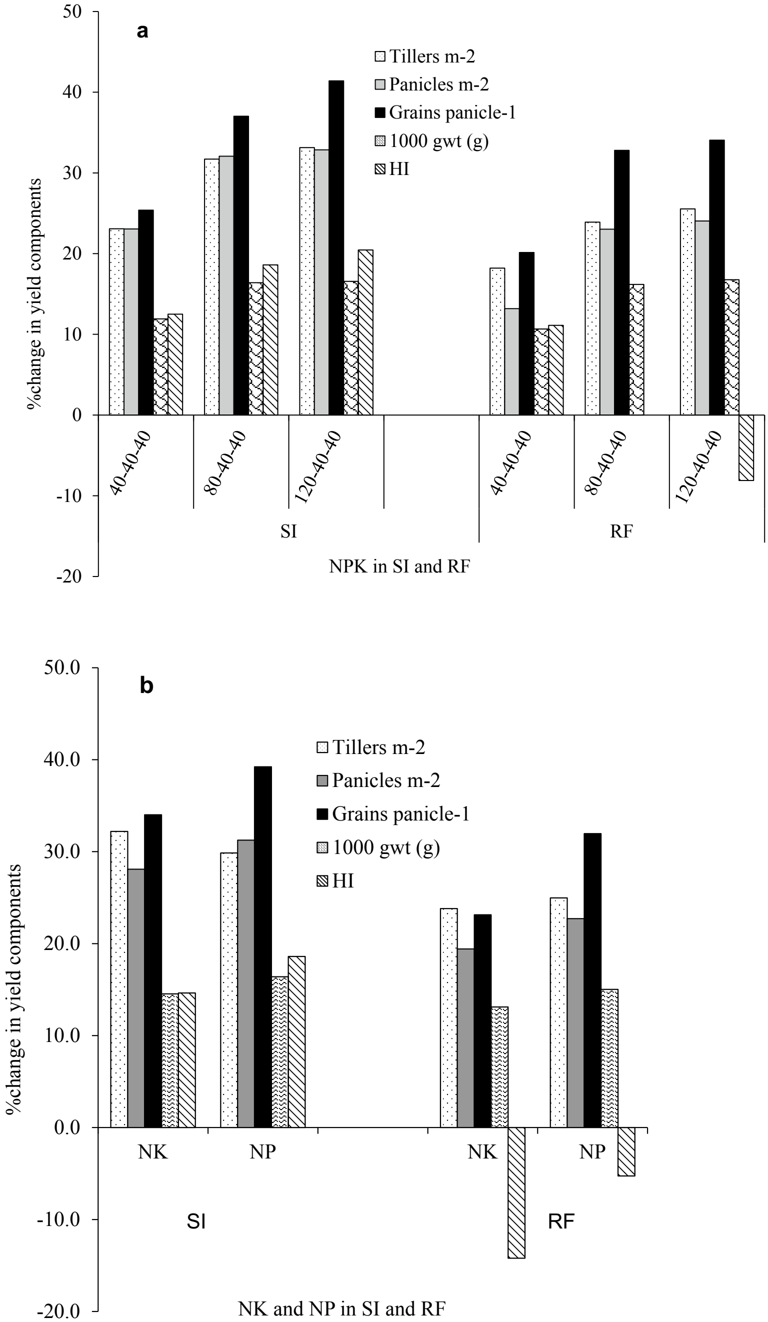

Fig. 15.6 Effect of NPK fertilizer on growth and yield components of NERICA 4 under supplemental irrigation (SI) and rainfed (RF) conditions. The percentage (%) change in each yield component is shown. **a** Compares the effect of all the three nutrients, N, P and K in varying amounts on yield components under SI and RF, whereas **b** compares the effect of NK and NP on yield components (legend)

Table 15.1 Effect of water treatments in respect with increasing NPK levels on economic returns due to grain yield of field grown NERICA 4

Fertilizer material	Price (US$)	Analysis (N-P-K)	N (%)	P_2O_5 (%)	K_2O (%)	Amount of fertilizer material needed (kg ha^{-1})	Costs ha^{-1} (US$)
Urea	38.9	46-0-0	46	0	0	174	135.3
Triple super phosphate	38.9	0-46-0	0	46	0	87	67.2
Muriate of potash	50	0-0-60	0	0	60	67	67
Other costs (US$)							
Seeds and labor							312.2
Additional cost, labor and fuel for SI							222.2
Total cost (SI)							**804**
Total cost (RF)							**581.8**
Selling price of rice kg^{-1}							0.39
Gross income (SI)							2127
Gross income (RF)							1583
Net profit (SI)							1323
Net profit (RF)							1001
Difference between SI and RF							**322**

Climatic measurements were collected in an attempt to explain the results of this study. However, the climatic influence on grain yield was not significant, and the data were negligibly different between the two years, and thus were not considered in the interpretation of the findings of this study.

The nutrient content of the soil at the experimental site was apparently insufficient for optimum crop yields, as reflected by the soil properties. In effect, the crop considerably responded to NPK in both SI and rainfed (RF) conditions, exhibiting significantly higher values of most of the crop-assessment attributes when compared to no NPK application.

Even though in RF the yield response was in a favorable range, the yield difference of 15% between SI and RF was substantial, and suggests that rice growers will need to match the crop nutrition with soil moisture to increase nutrient uptake at the time of crop nutrient need. Crop nutrient requirements change as plants develop. For example, rice has a greater N and P requirement in the early stage right through flowering, which decreases gradually until the dough stage; whereas the demand for K is lower at earlier growth of the plant, but increases from flowering until ripening

(Dobermann and Fairhurst 2000). Synchronizing these growth stages with nutrient and moisture supply will greatly improve rice productivity in uplands.

We found that increasing P and K levels at low N increased the grain yield only marginally, suggesting that adequate N supply is needed for productive utilization of P and K by the crop. Considering the percentage yield difference due to N (43%) as compared to 5% and 0.4% due to P and K, respectively, N is apparently the most limiting in Namulonge, and potentially has a synergistic effect on P and K uptake. A similar trend could be encountered across upland rice farming systems, considering the large significant difference in grain yield between zero and the other NPK rates used in this study.

Plots that were treated with a minimal difference between NPK ratios (e.g., 80:40:40) had significantly higher grain yields than plots with wide difference between the ratios (e.g., 120:0:20). This suggests that the practice of balanced nutrition is crucial for farmers to achieve optimum rice grain yield in uplands. Thus, the balanced application of NPK is likely to have a positive impact across upland rice production areas in East Africa.

We also found a reduction in grain yield of 24% when N was singly applied at 120 kg N ha^{-1}, even though there was an increase in the biomass. Because of this negative response, it is apparent that excessive addition of N fertilizer had a considerably negative effect on crop productivity when it is not balanced with P and K. Thus, it is not worth applying large amounts of N when soil is low in available P and K, as this may not only limit crop yields, but also cause financial losses to the grower. In fact, unbalanced supply of N, P and K is sometimes even highlighted as a more important constraint than water availability (Fukai et al. 1998; Suriya-arunroj et al. 2000; Linquist and Sengxua 2001). Besides this, some studies have shown that P and K increase total N uptake as well as grain yield (Horie et al. 1997; Inthapanya et al. 2001; Saito et al. 2006). Moreover there is a strong interaction between N and K in crop growth, thus crop response to applied N decreases when the exchangeable K content of the soil is below a critical target level (Belay et al. 2002; Cai and Qin 2006; Wang et al. 2007).

Our data show a significantly low response of grain yield to P and K when applied singly, which is consistent with the above findings. This is also consistent with the findings of George et al. (2001), who reported that application of only P had little effect on grain yield irrespective of increased P uptake. Both N and P are often associated with positive effect on tillers and panicles, and high yielding upland cultivars under high-input conditions are characterized by moderate panicle number in the Philippines ($\geq$ 300 panicles/m^2), tillering number in Brazil ($\geq$ 250 tillers/m^2), and by higher harvest index (HI) and intermediate height (Pinheiro and de Castro 2000; Wang et al. 2002; Saito et al. 2006).

Although it has not been previously reported in Uganda, it is not surprising to find such responses in cultivars adapted to conventional low-input systems, such as those existing in East Africa. In this study, NERICA 4 produced a maximum HI of 0.46, which was relatively higher than the HI reported by Saito et al. (2006) in Laos. However, the HI of NERICA 4 is still lower than 0.50, which is normally reported for improved semi-dwarf cultivars (Mae 1997). Moreover, HI dropped by eight units in RF and increased only marginally in SI at high NPK levels, which was also consistent with the low agronomic efficiency (AE). This might suggest that NERICA 4, despite its adaptation to low input systems, has comparatively a better yield performance. However, the low HI, despite having enhanced vegetative growth, may suggest limitation in the translocation of photosynthates to the grains at higher N, possibly explaining the double difference between the yield gap and the biomass gap. Thus, development of cultivars with a high correlation of nutrient and water use efficiency with HI and biomass in upland rice production systems remains to be explored.

Nevertheless, our data demonstrated that NPK significantly influenced the yield attributes of NERICA 4, including tiller and panicle number, 1000 grain weight and grains per panicle in both RF and SI. Moreover, AE of NERICA 4 was 30% higher in SI than in RF conditions, indicating that application of NPK considerably increased productivity in SI compared to RF. The low AE in RF is likely due to reduced photosynthetic rate as a consequence of limited moisture availability during short periods of dry weather, in which we applied water for the SI treatment. These findings point out the significance of SI in upland rice production and could be considered as a management strategy in semi-intensive upland rice systems. The contribution of SI and RF to gross and net return was consistent with NPK yield response trends (Table 15.1). Supplemental irrigation resulted in additional 33% economic returns at 80:40:40 NPK, which rationalizes the significance of moisture in rice mineral nutrition.

Overall, our data show that a dose of 80 kg N ha^{-1} has a profound influence on grain yield of upland rice in RF and SI. Although we found a slight grain yield increase by applying 120 kg N ha^{-1} in SI, it was insufficient to justify application of an additional 40 kg N ha^{-1} at the lower rates of P and K. Thus, applying nitrogen levels above 80 kg N ha^{-1} at the current P and K recommendation of 40 kg ha^{-1} for NERICA 4 could be counterproductive, and may contribute to excess nitrogen with negative consequences on the environment. The low AE and HI at higher NPK rates suggests the need for improvement of NERICA 4 or deployment of cultivars with AE values > 25 kg kg^{-1}.

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