Upland rice response to fertilizer in Uganda

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Abstract

Upland rice (Oryza spp.) yields are low in Uganda, partly because of inadequate fertilizer use. Yield response to nitrogen, phosphorus, and potassium application and economically optimal nutrient rates (EOR) were determined. Three on-station trials and two clusters of on-farm trials were conducted in Uganda at about 1000 m. Mean grain yield, with hulls, was 1.3 and 3.7 t ha⁻¹ with 0 and 100 kg ha⁻¹ N applied, respectively. Grain yield response to applied P compared with N was less, and mean yield was not increased with K application. Depending on fertilizer cost relative to grain price (CP), mean EOR ranged from 54 to 92 kg ha⁻¹ N and 17 to 30 kg ha⁻¹ P. Equations were determined for yield response, estimation of EOR, and the benefit:cost ratio (BC) for fertilizer N and P use. Grain N concentration and N harvest index at EOR were 1.55 and 55%, respectively. Mean recovery efficiency, partial factor productivity, and agronomic efficiency declined with increasing N rate and were 75%, 41 kg kg⁻¹, and 28 kg kg⁻¹, respectively, at the EOR. Fertilizer N and P use can be highly and moderately profitable, respectively, for upland rice production in Uganda. Maximizing net return on finance-constrained investment in fertilizer use needs to consider CP and smallholder investment capacity rather than net return ha⁻¹.

Key words: economic, fertilizer use, nitrogen, phosphorus, potassium, use efficiency.

Introduction

Upland rice production is of less importance in Uganda compared with maize (Zea mays L.) and sorghum (Sorghum bicolor L. Moench), but production has increased substantially during the past decade due to high market value. The increased production has been achieved more through expansion of area sown than increased yields. Rice production in Uganda equals about 75% of consumption (Government of the Republic of Uganda, 2009). Smallholders are more likely to apply fertilizer to rice compared with other cereals because of the high market value of rice. However, levels of nutrient application are low and mean grain yield in Uganda is estimated to be 1.5 Mg ha⁻¹ (FAOSTAT, 2011). Inadequate control of numerous constraints may contribute to the low yield as found in Tanzania with biotic constraints, low input use, and low availability of soil N and P constraining productivity (Mghase et al., 2010). Little, if any, fertilizer is applied for upland rice production in Uganda, as in other sub-Saharan African countries, because of high costs of fertilizer use relative to the price of rice (Otsuka and Kalirajan, 2006). Yet soil nutrient depletion is high and a major cause of land degradation with estimated mean depletion rates for nitrogen (N), phosphorus (P) and potassium (K) of -21, -8 and -43 kg ha⁻¹ year⁻¹, respectively, in Uganda (Wortmann and Kaizzi, 1998).

Currently there are no fertilizer recommendations for upland rice production in Uganda. Research findings from elsewhere are that nutrient application needs are highly variable and situation specific. Research in Uganda found that upland rice grain yield can often be increased by more than 100% with application of N and P, and the crop is responsive to Azolla spp. and to a preceding green manure crop of Mucuna pruriens L. (Kaizzi, 2002; Kaizzi et al., 2007). Yield increases of 2.1 – 5.2 Mg ha⁻¹ in response to 80 - 120 kg ha⁻¹ of applied N were reported in Uganda (Onaga et al., 2012). Miyamoto et al. (2012) found that paddy yield could be increased by 46 kg ha⁻¹ per 1 kg ha⁻¹ of applied N. In the Ivory Coast, yield was maximized with just 50 kg ha⁻¹ of NPK fertilizer 12:24:18 or with 12 kg ha⁻¹ urea-N applied with the low responsiveness attributed to soil water deficit stress during grain fill (Galabi et al., 2011).
Kone et al. (2011) encountered situations of reduced grain yield and root development with N application which was attributed to mid-season soil water deficits. In Benin, yields were less with no N compared with N applied in diagnostic trials (Kone et al., 2009). On the dry savannah land of northern Nigeria, grain yield increased linearly with N rates up to 90 kg ha-1 (Kamara et al., 2010). Upland rice yields were increased from 1.7 to 2.3 t ha-1 with a Bray-1 soil test P of 4 mg kg-1 with P application (Oikeh et al., 2010), and from 0.98 to 1.27 Mg ha-1 with Bray-1 of 2 to 3 mg kg-1 (Sahrawat, 2000) with 45 kg ha-1 P applied. Oikeh et al. (2008) determined 60 and 26 kg ha-1 to be the optimal rates of N and P application, respectively, for upland rice production by smallholders in Nigerian forest agro-ecosystems.

The objectives of this research were to quantify the yield response of upland rice to N, P, and K, to determine economically optimal nutrient rates for N, P, and K (EONR, EOPR, and EOKR) at different CP, and to evaluate efficiency of applied N use by upland rice in Uganda.

**Materials and methods**

*Site characteristics and experimental design*

Fertilizer response trials were conducted at five site-seasons in western Uganda across three cropping seasons from 2009 to 2010 (Table 1). Three site-seasons were on the Bulindi research station and two site-seasons were clusters of single sets of treatments evaluated on-farm with three farms per cluster providing replication. The research area was in the Western Mid-Altitude Farmlands Agroecological Zone (Wortmann and Eledu, 1999).

### Table 1: Characteristics for research sites at Bulindi for three seasons, and for clusters of on-farm trials conducted at Kwera and Kiziranfumbi, to determine upland rice response to applied N, P, and K in Uganda

<table>
<thead>
<tr>
<th>Site-seasona</th>
<th>Soil properties</th>
<th>Previous crop</th>
<th>Sowing date</th>
<th>Harvest date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand Clay OM pH P K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>g kg-1 mg kg-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulindi 2009B</td>
<td>154 506 46 5.9 4.9 418 FL‡</td>
<td>Sept. 18 -20</td>
<td>Jan. 12 -15</td>
<td></td>
</tr>
<tr>
<td>Bulindi 2010A</td>
<td>326 505 44 5.9 4.6 235 CR</td>
<td>Mar. 17 - 19</td>
<td>June 8 - 21</td>
<td></td>
</tr>
<tr>
<td>Kwera</td>
<td>405 406 36 6.0 6.2 231 CR</td>
<td>Sept. 1 - 10</td>
<td>Jan 15 - 30</td>
<td></td>
</tr>
<tr>
<td>Kiziranfumbi</td>
<td>503 298 54 7.1 3.7 132 CR</td>
<td>Sept. 1 - 10</td>
<td>Jan 15 - 30</td>
<td></td>
</tr>
</tbody>
</table>

*a The rainfall is bimodal, with planting for season A and B occurring in March and April and in late August and September, respectively; ‡ The latitude, longitude, and elevation of the research locations, respectively, were: Bulindi, 1o30’N, 31o29’E, 1021 m, Acric Ferralsol; Kwera, 1o49’N, 32o58’E, Petric Plinthsoil; and Kiziranfumbi, 1o21’N, 31o12’E, Acric Ferralsol. CR = cereal, FL = fallow.

All Bulindi trial sites received >50 mm rainfall in the two weeks before sowing and received 430 mm or more of rainfall by 100 days after sowing (Fig. 1). Rainfall was less in season 2010B compared with other seasons with only 55 mm from 23 to 55 days after sowing. The rainfall and soils of the site-seasons were considered representative of the niches within agroecological zones where upland rice production occurs in Uganda.
The soils were Acric Ferralsols except for pre-dominantly Petric Plinthso at the Kwera on-farm location (Table 1). The soils at all site-seasons had rooting depths greater than 1.0 m. Surface soil samples for the 0- to 20-cm depth consisting of 10 cores per site-season were collected before planting and fertilizer application to determine basic soil properties. Sand, clay, and soil organic matter content ranged from 154 to 503, 298 to 506 (Bouyoucos, 1936), and 36 to 54 (Walkley and Black, 1934) g kg⁻¹ soil, respectively. Mehlich-3 P (Mehlich, 1984) ranged from 3.7 to 7.9 mg kg⁻¹ soil.

The experimental design was a randomized complete block design of three replicates for the Bulindi trials, and with five or six single replication trials per on-farm cluster. The nutrient rates evaluated were: 0 (N0), 50, 100, and 150 kg N ha⁻¹; 0, 12.5, 25.0, and 37.5 kg P ha⁻¹; and 0, 30, 60, and 90 kg K ha⁻¹ (Table 2). The incomplete factorial arrangement limited the treatment number in consideration of Liebig’s law of the minimum, proposed by J. von Liebig in 1840, expecting N and K to be the most and least limiting of the three nutrient deficiencies. The N0 treatment occurred only with no P and K applied, and P and K effects were tested only with N applied. Similarly, no K was applied for the zero-P treatment. There was confounding of P and K treatments. The K effect was determined in the statistical analysis by subtracting at the plot level the K minus treatments from the corresponding K plus treatments after verifying that the P × K interaction was not significant; K level effect on these differences was determined.

**Table 2** The N-P-K rates (kg ha⁻¹) of fertilizer trials conducted for upland rice in Uganda.

<table>
<thead>
<tr>
<th>0-0-0</th>
<th>50-0-0</th>
<th>50-12.5-0</th>
<th>50-25-0</th>
<th>50-37.5-0</th>
<th>50-12.5-30</th>
<th>50-25-60</th>
<th>50-37.5-90</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-0-0</td>
<td>100-0-0</td>
<td>100-12.5-0</td>
<td>100-25-0</td>
<td>100-37.5-0</td>
<td>100-12.5-30</td>
<td>100-25-60</td>
<td>100-37.5-90</td>
</tr>
<tr>
<td>150-0-0</td>
<td>150-12.5-0</td>
<td>150-25-0</td>
<td>150-37.5-0</td>
<td>150-12.5-30</td>
<td>150-25-60</td>
<td>150-37.5-90</td>
<td></td>
</tr>
</tbody>
</table>

Varieties were a sub-plot factor including Nerica4 and Superica. Nerica-4 is a genotype derived from the interspecific hybridization of WAB 56-104 (Oryza sativa, tropical japonica type) and CG 14 (Oryza glaberrima). Superica-1 (O. sativa) is a Ugandan release. Each variety has a maturity period of 120 days. The plot size was 4 by 6 m.
The N, P, and K sources were urea, triple super phosphate, and potassium chloride, respectively. Fertilizer P was applied pre-plant. Fertilizer N and K were applied with 25% pre-plant, 25% at tiller formation, and 50% at panicle initiation. The fertilizers were surface broadcast applied at planting and incorporated. The side dress application of N and K was band-applied to the side of the row and covered.

**Crop management and data collected**

Site preparation included disk plowing at 15 to 20 cm depth followed by secondary disk tillage at 10 cm depth. The previous crop and sowing dates varied (Table 1). Seeding rates were selected to achieve final plant populations of 50 plants m–2, with spacing of 20 cm by 20 cm. In-season weed control was by weeding with hand hoes twice or thrice depending on weed intensity. During the season, chloropyrifos 5% (DursbanTM) was applied for control of the stem borer complex and the African rice gall midge (Orseolia oryzivora Harris and Gagné (Diptera: Cecidomyiidae).

The plants were cut at ground-level from the inner rows in a 1.5 x 2.0 m area and air dried for at least 3 d. The panicles were threshed and the harvested grain weight was determined. After adding the panicle remnants, the straw was weighed to determine the straw yield. The harvested grain was weighed, and grain yield calculated. Grain yield was adjusted to 140 g kg–1 water content. Oven-dried plant samples were ground to pass a 0.5-mm sieve and analyzed for total N in a single digest by a wet-ashing technique with colorimetric determination (Anderson and Ingram, 1993; Okalebo et al., 2002). The harvest index (HI) was calculated. Straw and grain N concentrations were used in the calculation of N uptake in grain and total biomass, the N harvest index (NHI), and other N use efficiency (NUE) values.

**Data analysis**

The data analyses were done by site-season and combined across site-seasons using Statistix 9 (Analytical Software, Tallahassee, FL) with site-seasons and replications as random variables and varieties and nutrient rates as fixed variables. When significant nutrient rate effects occurred, an asymptotic yield function was determined: Yield (Mg ha–1) = a – bcN, where a was near maximum yield, b was the gain in yield due to nutrient application, and cN determined the shape of the curvilinear response where c was a curvature coefficient and N was the nutrient rate. The regression analyses by site-season and combined across site-seasons were done with plot data. Upland rice response to applied N was determined across all P levels after verifying a lack of N x P rate interaction, and response to applied P was determined with the zero N treatment omitted from the analysis. There were no grain yield increases due to applied K.

The EONR and EOPR, or the nutrient application rates that gave the greatest net return ha–1 to fertilizer use, were calculated for a range of CP. A grain price of US$0.40 kg–1 (Uganda Sh. 2400 US$–1) was used for the economic analysis. Equations were developed using non-linear regression analysis to relate EOR to CP. Benefit:cost ratio was considered to be the value of increased yield relative to cost of fertilizer use for the given application rate. Polynomial functions were determined for each crop-nutrient combination to estimate BC with application rate and CP as independent variables. Differences and relationships were considered significant at P ≤ 0.05.

Nonlinear functions that related total N in the aboveground biomass at harvest (UN) to the N rate and grain yield were determined. Asymptotic regression analysis, using individual plot data, related NUE parameters to N rate. Exceptions were for straw N concentration and uptake which had linear and quadratic relationships to N rate, respectively, and for RE and agronomic efficiency of N use (AE) which had linear and quadratic relationships to N rate, respectively. The NUE parameters included grain N concentration and content, HI, NHI, internal efficiency (IE) of total plant N taken up from soil and fertilizer, partial factor productivity (PFP), and physiological efficiency (PE), recovery efficiency (RE), and (AE) for fertilizer N use (Cassman et al. 2002). The NUE components were calculated as: IE = Y/UN (kg kg–1) where Y is grain yield (kg ha–1); PFP = Y/N rate; NHI = grain N/UN; RE = (UN+N –
UNN0)/N rate; PE = (Y+N – YN0)/(UN+N – UNN0); and AE = (Y+N – YN0)/N rate. The units for IE, PE, AE, and PFP were kg grain kg⁻¹ N, and kg N kg⁻¹ N for NHI.

Results

Yield response to N, P and K

The mean upland rice paddy grain yield at N0 was 1.42 Mg ha⁻¹ and was more in on-farm trials than at Bulindi (Table 3). The predicted mean maximum grain yield was 3.67 t ha⁻¹ (Table 4), with no significant yield increase for >100 kg ha⁻¹ N applied.

Table 3: Nitrogen application effect on upland rice grain and straw yield in Uganda. The results are the means of two varieties as there was no variety by N rate or P x N rate interaction

<table>
<thead>
<tr>
<th>Site-season</th>
<th>N rate, kg ha⁻¹</th>
<th>N rate, kg ha⁻¹</th>
<th>Grain yield, t ha⁻¹</th>
<th>Straw yield, t ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>50</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Bulindi 2009B</td>
<td>0.75cb</td>
<td>2.19b</td>
<td>2.45ab</td>
<td>2.48a</td>
</tr>
<tr>
<td>Bulindi 2010A</td>
<td>1.00b</td>
<td>2.56a</td>
<td>2.55a</td>
<td>2.62a</td>
</tr>
<tr>
<td>Bulindi 2010B</td>
<td>0.99b</td>
<td>3.27a</td>
<td>3.56a</td>
<td>3.36a</td>
</tr>
<tr>
<td>Kiziranfumbi</td>
<td>1.79c</td>
<td>4.59b</td>
<td>5.02ab</td>
<td>5.18a</td>
</tr>
<tr>
<td>Meana</td>
<td>1.42b</td>
<td>3.39a</td>
<td>3.71a</td>
<td>3.62a</td>
</tr>
<tr>
<td>SE</td>
<td>0.26</td>
<td>0.53</td>
<td>0.63</td>
<td>0.59</td>
</tr>
</tbody>
</table>

aThe N rate x site-season interaction was significant for straw yield due to a relatively greater increase in straw yield in season 2010B compared with the other seasons; bDifferent letters in a row under grain or straw yield indicate statistically significant differences at α ≤ 0.05

The N x P rate and N rate x site-season interactions were not significant for grain yield but there was a relatively greater increase in straw yield in Season 2010B due to N application compared with the other seasons.

Table 4: The coefficients for the upland rice grain yield response functions to applied N and the economically optimal N rates (EONR) for different cost of fertilizer N use to grain value ratios (CP)

<table>
<thead>
<tr>
<th>Site-season</th>
<th>Response coefficients</th>
<th>EONR at five N:grain price ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>Bulindi, 2009B</td>
<td>2.65</td>
<td>1.90</td>
</tr>
<tr>
<td>Bulindi, 2010A</td>
<td>2.59</td>
<td>1.56</td>
</tr>
<tr>
<td>Bulindi, 2010B</td>
<td>3.57</td>
<td>2.40</td>
</tr>
<tr>
<td>Kiziranfumbi</td>
<td>5.59</td>
<td>3.44</td>
</tr>
<tr>
<td>Combined</td>
<td>3.67</td>
<td>2.40</td>
</tr>
<tr>
<td>SE</td>
<td>0.36</td>
<td>0.59</td>
</tr>
</tbody>
</table>
Upland rice grain yield increased in response to N for all site-seasons (Table 3, 4). The predicted overall mean grain yield increase was 2.40 t ha⁻¹. Grain yield was significantly increased by application of >50 kg ha⁻¹ N for only two of the five site-seasons but this was not sufficient to result in a N rate x site-season interaction. Combined across all site-seasons, the grain yield response to applied N was

\[ Y = 3.67 - 2.40(0.958^N) \]  
Eq. 1

\[ Y = 3.39 - 2.12(0.968^N) \] with no P or K applied  
Eq. 2

The b and c coefficients of equations 1 and 2 were not significantly different at α = 0.05 using a z-test. Upland rice straw yield was increased by 50 kg ha⁻¹ N application for the three site-seasons where measured, with an additional increase by applying more N at two of the site-seasons.

Nitrogen was profitable for all site-seasons and all CPs, and the site-season EONR ranged from 38 to 150 kg ha⁻¹ depending on the CP (Table 4). The mean EONRs determined from the analysis combined across all site-seasons ranged from 54 and 92 kg ha⁻¹ with CPs of 10 and 2, respectively (Fig. 2).

Net returns to applied N were more sensitive to the N rate as the CP increased. The mean EONR can be estimated from the CP according to

\[ EONR, \text{ kg ha}^{-1} = 107.2 - 8.78CP + 0.339CP^2 \]  
Eq. 3

The P x K rate interaction was not significant but the P rate x site-season interaction was significant for grain yield with P, in the presence of N, resulting in increased upland rice grain yield for three of the five site-seasons (Table 5).

<table>
<thead>
<tr>
<th>Site-seasons</th>
<th>P rate, kg ha⁻¹</th>
<th>P rate, kg ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grain yield, t ha⁻¹</td>
<td>Straw yield, t ha⁻¹</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>12.5</td>
</tr>
<tr>
<td>Bulindi, 2009B</td>
<td>2.21b</td>
<td>2.25</td>
</tr>
<tr>
<td>Bulindi, 2010A</td>
<td>2.36b</td>
<td>2.53b</td>
</tr>
<tr>
<td>Bulindi, 2010B</td>
<td>3.03b</td>
<td>3.29b</td>
</tr>
<tr>
<td>Kwerer</td>
<td>4.53</td>
<td>4.73</td>
</tr>
<tr>
<td>Kiziranfumbi</td>
<td>4.44b</td>
<td>5.66a</td>
</tr>
<tr>
<td>Meansa</td>
<td>3.31c</td>
<td>3.69ab</td>
</tr>
<tr>
<td>SE</td>
<td>0.50</td>
<td>0.65</td>
</tr>
</tbody>
</table>

aThe P rate x site-season interaction was significant for grain yield with greater response to P rate for some site-seasons compared with others. The grain yield response function to applied P was: Yield = 3.79 – 0.556*0.947P.
bDifferent letters in a row under grain or straw yield indicate statistically significant differences at α ≤ 0.05.

Yield increased with up to 25 kg ha⁻¹ P for two site-seasons. In the combined analysis, grain yield was increased by 0.38 t ha⁻¹ with 12.5 kg ha⁻¹ P. The yield response function from the combined analysis was

\[ Y = 3.79 - 0.556(0.947^P) \]  
Eq. 4

Applying Eq. 4, EOPR was determined to be related to CP, with CP for fertilizer P at 4-12, as

\[ EOPR, \text{ kg ha}^{-1} = 53.4 - 4.69CP + 0.134CP^2 \]  
Eq. 5
Straw yield was increased with P at Bulindi in the 2010B season only with no additional increase with >12.5 kg ha⁻¹ P applied. Mehlich-3 P was low at 4-8 mg kg⁻¹, but there was no indication of relationship between soil test P and grain yield response to P. Grain and straw yield were not affected by K for any site-season.

The BC of fertilizer use was greater with N than P, and decreased as CP increased. The BC was related to nutrient application rate and CP for N applied at ≤100 kg ha⁻¹ and P at ≤50 kg ha⁻¹ as follows:

\[
N \text{ rate} \leq 100 \text{kg ha}^{-1} : BC_N = 56.52 - 0.541N - 9.983CP + 1.83E10^{-4}N^2 + \\
0.425CP^2 + 0.0326NCP
\]  
Eq. 6

\[
P \text{ rate} \leq 40 \text{kg ha}^{-1} : BC_P = 10.67 - 0.172P - 0.383CP + 1.01E10^{-3}P^2 + \\
0.0513CP^2 + 8.54E10^{-3}PCP
\]  
Eq. 7
Figure 2: Upland rice yield response to applied N and P, and economically optimal N and P rates for different ratios of fertilizer use cost to grain price ratios (CP)
Nitrogen use efficiency

Plant UN ranged from 31 to 89 kg ha\(^{-1}\) for N0 and with 150 kg ha\(^{-1}\) N applied and was 79 kg ha\(^{-1}\) at EONR (Table 6). Variation in UN accounted for 82 and 74% of the variation in biomass and grain yield, respectively. Grain yield increased by a mean of 14.7 kg (kg UN)\(^{-1}\) for N0 and by 27.6 kg kg\(^{-1}\) UN across all N rates.

### Table 6: Mean effect of N rate on components of N use efficiency by upland rice averaged for 5 site-seasons in Uganda

<table>
<thead>
<tr>
<th>Component</th>
<th>Units</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>Pr</th>
<th>EONRa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain N concentration</td>
<td>g kg(^{-1})</td>
<td>14.2</td>
<td>15.6</td>
<td>16.1</td>
<td>16.8</td>
<td>***</td>
<td>15.5</td>
</tr>
<tr>
<td>Straw N concentration</td>
<td>g kg(^{-1})</td>
<td>5.60</td>
<td>5.32</td>
<td>6.08</td>
<td>6.05</td>
<td>***</td>
<td>5.6</td>
</tr>
<tr>
<td>Grain N content</td>
<td>kg ha(^{-1})</td>
<td>13.2</td>
<td>41.4</td>
<td>46.7</td>
<td>47.9</td>
<td>***</td>
<td>43.6</td>
</tr>
<tr>
<td>Straw N content</td>
<td>kg ha(^{-1})</td>
<td>18.0</td>
<td>32.3</td>
<td>41.6</td>
<td>41.2</td>
<td>***</td>
<td>35.6</td>
</tr>
<tr>
<td>Plant N content</td>
<td>kg ha(^{-1})</td>
<td>31.2</td>
<td>73.7</td>
<td>88.3</td>
<td>89.2</td>
<td>***</td>
<td>78.7</td>
</tr>
<tr>
<td>Harvest index</td>
<td>kg kg(^{-1})</td>
<td>0.24</td>
<td>0.31</td>
<td>0.30</td>
<td>0.30</td>
<td>***</td>
<td>0.30</td>
</tr>
<tr>
<td>N harvest index</td>
<td>kg kg(^{-1})</td>
<td>0.44</td>
<td>0.57</td>
<td>0.54</td>
<td>0.54</td>
<td>***</td>
<td>0.55</td>
</tr>
<tr>
<td>Recovery efficiency</td>
<td>kg kg(^{-1})</td>
<td>0.85</td>
<td>0.57</td>
<td>0.38</td>
<td>0.38</td>
<td>***</td>
<td>0.75</td>
</tr>
<tr>
<td>Agronomic efficiency</td>
<td>kg kg(^{-1})</td>
<td>34.4</td>
<td>19.7</td>
<td>12.7</td>
<td>12.7</td>
<td>***</td>
<td>28.1</td>
</tr>
<tr>
<td>Internal efficiency</td>
<td>kg kg(^{-1})</td>
<td>31.0</td>
<td>36.5</td>
<td>33.6</td>
<td>32.6</td>
<td>***</td>
<td>35.4</td>
</tr>
<tr>
<td>Partial factor productivity</td>
<td>kg kg(^{-1})</td>
<td>52.8</td>
<td>28.9</td>
<td>18.9</td>
<td>18.9</td>
<td>***</td>
<td>41.4</td>
</tr>
<tr>
<td>Physiological efficiency</td>
<td>kg kg(^{-1})</td>
<td>40.3</td>
<td>37.5</td>
<td>32.6</td>
<td>32.6</td>
<td>ns</td>
<td></td>
</tr>
</tbody>
</table>

aThe EONR was 66 kg ha\(^{-1}\) for a fertilizer N use cost to farm-gate grain price ratio of 6; ns, no significant effect at \(\alpha \leq 0.05\); *** Significant effect at \(\alpha \leq 0.001\)

Internal efficiency (IE), or the efficiency of converting UN to grain yield, is a function of NHI and grain N concentration. The linear effect of NHI and grain N concentration accounted for 72 and 11% of the variation in IE, respectively. Grain N concentration, NHI, and IE at an EONR = 66 kg ha\(^{-1}\) for CP = 6 were 15.5 g kg\(^{-1}\), 55% and 35.4 kg grain (kg UN)\(^{-1}\), respectively, which were higher than for the 0N rate (Table 6). The IE decreased with increased N rates. Mean NHI was high in comparison to HI. Upland rice NHI was similar and less than NHI reported for sorghum and maize, respectively, at EONR in Uganda, although EONR was higher for upland rice compared with sorghum and maize (Kaizzi et al. 2012 a,b).

Mean PFP declined with increased N rate and was 41 kg kg\(^{-1}\) at EONR compared with 79 and 83 kg kg\(^{-1}\) for sorghum and maize, respectively, although EONR was calculated for relatively low grain values for maize and sorghum compared with rice which is typical in Uganda (Kaizzi et al. 2012 a,b). Mean AE decreased with N rate and was estimated to be 28 kg kg\(^{-1}\) at EONR compared with 52 and 64 kg kg\(^{-1}\) for sorghum and maize, respectively. Mean PE of fertilizer N was not affected by N rate which is consistent with the results of the sorghum and maize studies. The following equations, determined from plot data of the three site-seasons at Bulindi, represent the N rate effect on various components of NUE for upland rice in Uganda.

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\[ UN, \text{kg ha}^{-1} = 91.82 - 60.89(0.977^N) \]  
\[ \text{Grain } N \text{ concentration, kg kg}^{-1} = 17.50 - 3.47(0.992^N) \]  
\[ \text{GrainUN, kg ha}^{-1} = 47.60 - 34.42(0.968^N) \]  
\[ Stover N \text{ concentration, kg kg}^{-1} = 5.32 - 0.0060N \]  
\[ StoverUN, kg ha}^{-1} = 17.73 - 0.356N - 0.00129N^2 \]  
\[ HI, \text{kg kg}^{-1} = 0.303 - 0.691(0.613^N) \]  
\[ NHI, \text{kg kg}^{-1} = 0.547 + 0.106 - 0.106(0.609^N) \]  
\[ IE, \text{kg kg}^{-1} = 23.63 + 0.0797N - 0.000570N^2 \]  
\[ AE, \text{kg kg}^{-1} = 57.6 - 0.564N + 0.00177N^2 \]  
\[ RE, \text{kg kg}^{-1} = 104.7 - 0.446N \]  
\[ PFP, \text{kg kg}^{-1} = 12.9 + 101(0.981^N) \]

**Discussion**

Inadequate rainfall was not an apparent constraint to grain yield in the Bulindi trials as yield was highest in the 2010B season when rainfall was least and less well-distributed compared with 2009B and 2010A. The indigenous soil N supply was apparently low as indicated by a mean grain yield of 1.46 t ha\(^{-1}\) and 31 kg ha\(^{-1}\) UN with N0, even though SOM was always >36 g kg\(^{-1}\). In comparison, UN with N0 was 31 and 46 kg ha\(^{-1}\) by sorghum and maize, respectively, in Uganda with generally less SOM concentration (Kaizzi et al. 2012a,b). In contrast, UN by irrigated maize in Nebraska at N0 averaged 175 kg ha\(^{-1}\) with similar or lower SOM levels (Wortmann et al. 2011). The difference in UN at N0 for Uganda compared with irrigated maize in Nebraska indicates greater recalcitrance of the SOM in Uganda with lower soil organic N mineralization rates, possibly associated with older soil surfaces and less annual return of organic material to the soil in Uganda compared with irrigated maize production areas in Nebraska. The organic matter of Uganda soils is probably valuable for enhanced soil physical properties including wet soil aggregate stability, water infiltration and percolation, water holding capacity, and cation exchange capacity (Tisdall and Oades 1982; Woomer et al. 1994), but apparently has low organic nutrient mineralization rates.

The large response of upland rice grain yield to N application was consistent with earlier results from Uganda (Kaizzi 2002; Kaizzi et al. 2007; Onaga et al. 2012), and with the responses of maize and sorghum in Uganda (Fig. 3; Kaizzi et al. 2012a,b). Yield with N applied and at N0 was more and less for maize and sorghum compared with upland rice. The coefficient values for b of 2.14 and 2.40 and for c of 0.94 and 0.96 for maize and upland rice, respectively, were not significantly different resulting in similar curve shape although with the plateau reached with a higher N rate for upland rice compared with maize.
The high market value of upland rice compared with maize and sorghum results in relatively lower CPs and higher EONRs for upland rice. Upland rice response to applied P, with N applied, was more gradual and to a higher P rate compared with maize and sorghum which had little response beyond 10 kg ha\(^{-1}\) P. The significant but small increase in upland rice yield to P application, with N applied, was generally consistent with the responses reported by Oikeh et al. (2008) and Sahrawat (2000).

Depending on CP, the mean EONR and EOPR for upland rice ranged from 54 to 92 and 17 to 37 kg ha\(^{-1}\), respectively. In reality, the CP of fertilizer use must include fertilizer procurement and application costs, the interest rate or opportunity cost of the money used for fertilizer purchase, and the nutrient price. These added costs can be very high when fertilizer is not easily available. Opportunity cost for resource-poor people with little access to money is often 100% of the actual value due to other high priority uses of available funds and other investment opportunities (CIMMYT 1988). A BC ≥1 is therefore required for such an investment to be attractive to such finance-constrained farmers.
The value of grain used in determining CP, whether used for consumption by the producers or marketed, must consider the added costs of harvesting, processing, storage, and marketing the increased production.

Finance-constrained farmers commonly do not have enough money to apply fertilizer at EOR to maximize net returns ha^{-1}. Fertilizer application at less than EOR to more land is expected to give more total production and higher net returns compared with applying at EOR to less land. Optimizing the choice of crop-nutrient-rate combinations, in consideration of CPs, is needed to maximize net returns on their constrained investment.

Considering 12 other crop nutrient combinations in Uganda using common CP values, Kaizzi et al. (2012c) found that the decreasing order of BC for fertilizer nutrients applied at EOR was groundnut (Arachis hypogaea L.) P > bean (Phaseolus vulgaris L.) N, maize N > soybean (Glycine max L.) P > sorghum N > groundnut K > maize P > bean P > soybean K, and > K applied to maize or sorghum. The BC for N applied to upland rice at EOR is greater than for any of the above and the BC for applied P to upland rice is less than for soybean P but greater than for sorghum N. This ordering could change with changes in relative CP due to changed grain values or nutrient costs. The upland rice EONR allows for BC >2, but BC >2 at EOPR only if CP ≤4. The results demonstrate that N application to upland rice can increase farm productivity with high profitability, and N application to upland rice should have priority over the 14 other crop-nutrient response function evaluated here and in Kaizzi et al. (2012 a,b,c). Phosphorus application for upland rice can be profitable when CP is not too high and/or when applied at less than EOPR. Improved input supply and marketing efficiency, fertilizer subsidies, and improved access to credit could greatly affect CP and therefore the BC of fertilizer use for upland rice production.

Recovery of applied N in the aboveground upland rice biomass was 75% at EONR which is a good recovery rate and intermediate between the RE reported for maize and sorghum (Kaizzi et al. 2012 a,b). The RE of sorghum was >100% as sorghum performance was poor at N0 and applied N apparently boosted plant vigor and root growth to recover nitrate-N that was otherwise lost to leaching beyond the root zone. Other fertilizer N use efficiency components were low at EONR for upland rice compared to maize and sorghum including AE and PFP, but this is largely due to the higher EONR of upland rice associated with its higher market value compared with maize and sorghum.

Conclusion

Upland rice increased by 178% with N applied at the EONR for a CP of 6. Yield can be further increased with P application but the results demonstrate that N deficiency is much more limiting than P or K deficiency. The yield response to applied N indicates that N application for upland rice production is highly profitable and a priority fertilizer application option relative to other crop-nutrient options of finance-constrained smallholder farmers of Uganda. The recovery of applied N is high if properly applied at EONR or less, implying little residual effect for the following crop but also little lost to the environment.

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