# Increasing smallholder rice production in East Africa:

## *fertilisers or good agronomic practices?*


Thomas Awio

**Propositions**

1. Enhancing lowland rice productivity requires managing water first, weeds second, and only then fertilisation.
   (this thesis)

2. Micro-nutrient fertilisers can easily be omitted in East African lowland rice production.
   (this thesis).

3. Unproductive tillers act as weeds.

4. For sub-Saharan Africa, food production for income is more important than for own nutrition security.

5. Sustainable agricultural development requires innovations that provide solutions to farmers' problems rather than innovator's problems.

6. Social activities are important in writing a scientific paper also during a pandemic.

7. Common sense is not that common in politics.

8. A sustainable society is one that acknowledges rights and values of all humans.

Propositions belonging to the thesis, entitled
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Thomas Awio
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# Increasing smallholder rice production in East Africa: fertilisers or good agronomic practices?

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*Dedicated to my wife Consolate, and our children Maria Abigail and Mark Raphael.*

# Abstract

Meeting the demand for staple food crops, especially cereals, is one of the challenges sub-Saharan Africa (SSA) continues to grapple with. Low crop productivity in SSA is the main contributor to the inability to meet the food demand. Increasing crop productivity in smallholder farming systems, hence closing the gap between potential and actual farm yields, is needed to meet the food demand on existing arable land. In order to address the low soil fertility that limits crop productivity, farmers apply NPK fertilisers. Yet, fertilisation with only NPK is not always resulting in better yields on farmers' fields. Crop responses to NPK fertilisation can be influenced by other nutrients, recommended agronomic practices (RAP) and inherent soil fertility. However, there is little attention to secondary and micro-nutrient fertiliser use by smallholder farmers, while farmers' application of RAP tends to be sub-optimal. Also, variation in inherent soil fertility level exists among farmers' fields because of crop management differences. Improved understanding of the role of secondary and micro-nutrients, RAP, and inherent soil fertility is therefore required to design management packages to enhance grain yield and NPK use efficiency. The aim of this thesis is to quantify for lowland rice the effect of secondary and micro-nutrients, RAP under researcher supervision and as applied by farmers, and inherent fertility on rice yield and NPK use efficiency, and to identify feasible options to improve productivity.

Researcher- and farmer-managed joint on-farm experiments were conducted under irrigated and rainfed lowland conditions in Tanzania and Uganda. For the researcher-managed on-farm trials conducted between 2015 and 2017, treatments tested included RAP combined with: zero fertilisation as a control, NPK fertilisation with and without secondary and micro-nutrients (S, Mg, B, Cu, Mn, Zn), and/or treatments where B, Mn and Zn were omitted one at a time from the NPK + secondary and micro-nutrient treatment. Treatments for the joint on-farm trials conducted in 114 farmers' fields in Uganda in 2019 included farmers' practice (FP) as a control, RAP with and without NPK, and farmer-selected best practices geared towards intensification (farmers' intensification practice, FIP). One year after the joint on-farm trials, a follow-up evaluation study using a semi-structured questionnaire and field observations was conducted. For the researcher- and farmer-managed joint trials, data were collected on grain yield and yield components. Plant sample analyses were also made for the joint on-farm trials to determine N, P and K tissue concentrations. While data on socio-economic, crop management practices and grain yield were collected during the follow-up evaluation study.

Grain yield improved due to NPK fertilisation by ca. 32 and 29% in Tanzania during 2015 and 2016, and by 24 and 100% in Uganda during 2016 and 2017, respectively. Applying NPK + secondary and micro-nutrients further increased grain yield in Tanzania by 7 and 11% during 2015 and 2016, respectively, but not in Uganda. Fertilisation had major effects only when water supply was adequate, and not under drought. Secondary and micro-nutrient application without NPK gave yields similar to control plots, and lower than NPK fertilisation alone. This study showed good water management as the first step to increasing lowland rice productivity, under also good crop management, and further yield gains can be achieved with NPK fertilisation. Secondary and micro-nutrients can be omitted by farmers in these areas.

Grain yield increased by ca. 12% due to FIP or RAP without fertilisation, while RAP+NPK application resulted in 33% extra yield, compared to FP. RAP gave higher net income (ca. USD 220 $ha^{-1}$) than RAP+NPK (ca. USD 50 $ha^{-1}$). Timing of weeding and of fertiliser application contributed most to yield variation among fields. The exploitable yield gap across treatments and under FP was 24 and 29%, respectively. We concluded that different yield gap levels can be exploited by lowland rice farmers as yield gap can be reduced by RAP, FIP, and RAP+NPK, although fertiliser application poses a risk to profit. For farmers with good water management, timely weeding should be combined with other crop management practices to realise yield gains.

Inherent soil fertility varied greatly among farmers' fields. Apparent N recovery, and agronomic and physiological N efficiencies reduced with increasing inherent N supply. Physiological efficiencies of P and K also decreased with increasing indigenous supply. Delaying weeding beyond recommended weeding time, and the interaction between inherent supply and delayed weeding reduced use efficiencies of fertiliser nutrients. Delayed fertilisation reduced apparent N recovery and P physiological efficiency. Thus increasing fertiliser nutrient use efficiency in smallholder farms requires site-specific fertilisation strategies based on inherent fertility and proper weed management, coupled with fertiliser application at correct crop stage.

Farmers who had lower yields during joint on-farm trials improved their management practices and hence had higher yield gains (1358 kg $ha^{-1}$) one year later, compared with farmers who had middle (473 kg $ha^{-1}$) and top (−91.7 kg $ha^{-1}$) yields. Farmers who participated in the trials had higher yield (4125 kg $ha^{-1}$) than the non-participants (3893 kg $ha^{-1}$). Three farm types were identified that differed in application of RAP, but with small differences in household characteristics. We concluded that exposing farmers to RAP through joint learning has the potential benefit of increasing smallholder rice yields. Lack of differences among households could indicate that wealth is not crucial in innovation adoption in this production system.

Results in this thesis have demonstrated the possibility of smallholder farmers in SSA to increase rice productivity, firstly through good water management and then following recommended crop management practices. Fertilisation with NPK can further enhance yield, however, appropriate rates based on field-specific nutrient demands need to be applied since fertiliser costs may make fertilisation uneconomical. Secondary and micro-nutrients may be applied with NPK but the additional yield gain is limited, so their omission has no income penalty. Enhancing fertiliser nutrient use efficiencies requires field-specific nutrient application based on inherent fertility, proper weed management, and timing of fertiliser application.

**Keywords:** Recommended agronomic practices, NPK fertilisation, micro-nutrients, joint experimentation, exploitable yield gap, lowland rice, grain yield and nutrient use efficiency.

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# 1

# CHAPTER 1.

## General introduction

## 1.1 General background

One of the challenges of sub-Saharan Africa (SSA) is meeting the demand for staple food crops, especially cereals, where self-sufficiency in cereal production is the lowest globally (Saito et al., 2019; van Ittersum et al., 2016). This is particularly the case for rice (*Oryza sativa*) for which the consumption rate is growing more swiftly than for any other staple food crop (Arouna et al., 2021; Bado et al., 2018a,b). Moreover, the population of SSA continues to grow, with the projection that the population will nearly double to 2.1 billion by 2050 compared with the 1.2 billion in 2022 and peak at an estimated 3.8 billion by 2100 (United Nations, 2019, 2022; Vollset et al., 2020). As a result, cereal demand is expected to triple by 2050. Yet, yields are very low, and current cereal consumption is already dependent on considerable cereal imports. This makes the continent to be at the greatest risk of food insecurity, compared with other regions of the world (van Ittersum et al., 2016).

For SSA to meet the projected food demand on existing agricultural land, there is a need to increase crop yields per unit of available cultivable land, thereby closing the gap between potential yield and actual farm yields (Lobell et al., 2009; Mauser et al., 2015; Mueller et al., 2012; Pradhan et al., 2015). Otherwise, if crop productivity per unit area cannot be improved, the projected cereal demand will have to be met either through crop area expansion, reliance on cereal imports, or both (van Ittersum et al., 2016; van Oort et al., 2015). Yet, arable cropland will be inadequate for crop area expansion as a single solution (Chamberlin et al., 2014). Likewise, import dependence is not a sustainable option because of low incomes, weak non-agricultural exports, and, hence, lack of adequate foreign currency by most SSA countries to pay the import bills. Moreover, global food prices will also likely increase with the growing populations. These constraints are on top of the lack of infrastructure to store and distribute food efficiently (Arment, 2020; Manitra et al., 2012; van Ittersum et al., 2016). Therefore, increasing productivity per unit land area, hence closing the yield gap, is the only viable solution that SSA needs to pursue in order to meet the growing food demand of its rising population. This will avoid land expansion for agricultural production and the associated negative environmental consequences such as biodiversity loss, and destruction of ecosystem services and functioning (Chamberlin et al., 2014; Foley et al., 2005; Pradhan et al., 2015; Sala et al., 2000; Zabel et al., 2019).

The yield gap in the context of crop production is the difference between potential yield and actual farm yield (Lobell et al., 2009). Potential yield is the yield obtained when the crop is grown under conditions where it is well adapted without water, nutrients, and biotic stress limitations (Stuart et al., 2016). Actual farm yield is the mean yield farmers attain in a given location. Considering the definition of potential yield, it is clear that under farmers' field conditions achieving potential yield is virtually impossible, because of biotic and abiotic stresses, and reduction in economic gains while trying to reach the maximum yield level. It has been argued that about 80% of potential yield is the maximum possible yield achievable, given local conditions in farmers' fields – referred to as economically attainable or exploitable yield (Lobell et al., 2009; Stuart et al., 2016; van Ittersum et al., 2013). The difference between this attainable yield and actual farm yield is the exploitable yield gap (Stuart et al., 2016), which farmers can close. Closing the exploitable yield gap may require that feasible options for smallholder farmers to improve productivity are identified. These options should be within reach by farmers, where farmers can conveniently implement them to improve their grain yield.



Rice is one of the most important food crops of SSA, the most rapidly growing food commodity mainly driven by urbanisation, and the second largest source of caloric intake after maize (Bado et al., 2018a; Seck et al., 2013; Tsujimoto et al., 2019). As a result, rice has become an important strategic component of food security and a crucial element in the staple food economies of the region, gaining prominence in farming systems and diets. Demand for rice is projected to continue rising due to the high population growth rate; rapid urbanisation as rice is easy to store, prepare and cook; and changes in eating habits (Arouna et al., 2021; Balasubramanian et al., 2007; Seck et al., 2013; Tanaka et al., 2017; Tsujimoto et al., 2019). Rice can boost food security and nutrition, foster rural development and support sustainable land use. Improving rice productivity is, thus, not only important to improve food security, but also to improve household income, alleviate poverty, and promote socio-economic growth of rice farmers (Seck et al., 2013; Tanaka et al., 2015).

Rice belongs to the family *Poaceae,* which comprises twenty-two species of the genus *Oryza*, of which *O. sativa* (Asian rice) and *O. glaberrima* (African rice) are the most important cultivated species, grown for human consumption (Muthayya et a., 2014). Rice roots have aerenchyma tissue which makes it function well in soils with low oxygen content (Steffens et al., 2011; Surajit, 1981). In fact, rice is the only major annual food crop that thrives in a water saturated or submerged soil during part or all of its growth cycle (Surajit, 1981). Rice cultivation in SSA is believed to have begun 2,000–3,000 years ago, when people grew African rice, native to Africa (Linares, 2002). The Asian rice, domesticated in tropical and sub-tropical Asia, was then introduced to Africa in the 16th century, where it has now largely replaced *O. glaberrima* (Cubry et al., 2018; Linares, 2002; Sangeetha et al., 2020). In the last five decades, total rice production in SSA has increased seven-fold from 4.6 to 32.0 million metric tons per year (FAO, 2021). The rise in production is a result of an increase in land area under cultivation rather than yield increase (Figure 1.1). Rice in SSA is mostly grown by smallholder farmers, and yields are generally low. This low grain yield is caused by several factors, including sub-optimal crop management practices, low levels of production technologies and dominance of the rainfed ecology, amongst others. According to FAO (2021), average grain yield in SSA showed a slight increase from 1.4 to 2.4 t $ha^{-1}$ over the past five decades (Figure 1.1). At present, an average farmer in SSA harvests ca. 50% less rice $ha^{-1}$ compared with the global average yield of 4.7 t $ha^{-1}$.

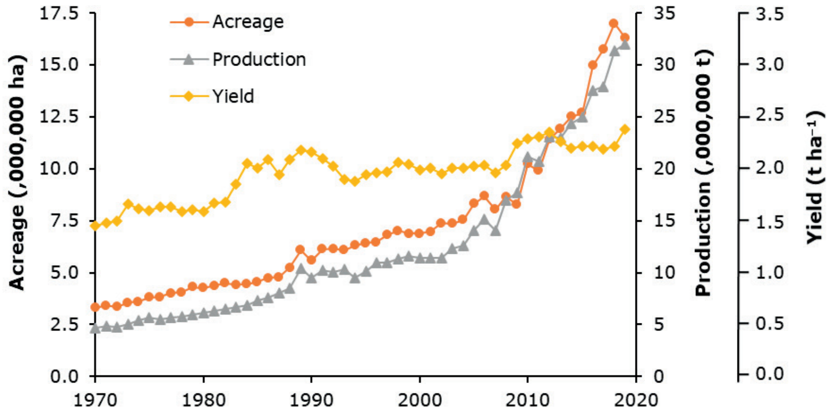


**Figure 1.1** Rice acreage, yield and production in sub-Saharan Africa from 1970 to 2019 (data source: FAO, 2021).

In East Africa (comprising Burundi, Kenya, Rwanda, Tanzania and Uganda) during the same period, rice production increased from 0.2 to 4.1 million metric tons per year. The increase in production is attributed to both the rise in area under production which increased about seven-fold, from 0.2 to 1.2 million hectares per year, and a steady increase in grain yield by ca. 88% from 2.0 to 3.7 t $ha^{-1}$ (FAO, 2021); with an average farmer harvesting ca. 55% more rice $ha^{-1}$ than in the rest of SSA although less than the global average by ca. 21%. Yield estimates within the region range from 1.5 to 6.8 t $ha^{-1}$

among countries (FAO, 2021). Likewise for Uganda and Tanzania, over the same period, production has increased tremendously from 11,000 to 220,000 and 132,000 to 3,475,000 metric tons per year, respectively. The increase is also associated with around five- and seven-fold increase in acreage and a stable rise in yield which roughly quadrupled from 0.7 to 2.8 and 0.9 to 3.3 t ha$^{-1}$, respectively, for Uganda and Tanzania (Figure 1.2). Although these yields are slightly above the average yield for SSA, they are still much lower than rice yields reported for other rice growing regions, notably, Asia at 4.9 t ha$^{-1}$ (FAO, 2021). Despite the observed low yields, there is potential for higher yields to be realised in SSA as several on-farm experiments have shown average yields of 2.8 to 9.8 t ha$^{-1}$ with improved soil, crop and water management practices (Haefele et al., 2000; Kwesiga et al., 2020; Niang et al., 2018; Saito et al., 2019; Senthilkumar et al., 2018; Wanyama et al., 2015). The current low yields could be an indication that at present the potential of local production resources in SSA is being exploited at low levels.



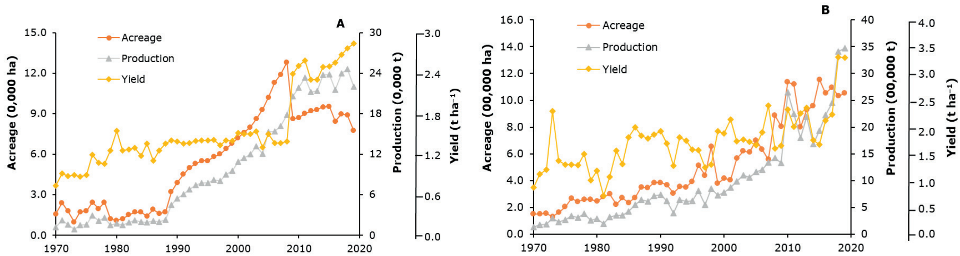


**Figure 1.2** Rice acreage, yield and production for Uganda (**A**) and Tanzania (**B**) from 1970 to 2019 (data source: FAO, 2021). Difference in estimation methods could explain the large drop in estimated acreage and increase in yield for Uganda between 2008 and 2009.

Two major rice agro-ecologies, depending on soil, climate and water supply, are lowland (or wetland) and upland (or dryland). The lowland system can involve irrigated, rainfed or floating (deep-water) rice (Khush, 1997). Under irrigated and rainfed lowland, rice is grown in bunded fields which are kept flooded most of the growing season with irrigation or rainwater, and rice seedlings transplanted or rice seeds directly sown in wet or dry soil (GRiSP, 2013). In upland systems, rice is grown in non-bunded fields under dryland conditions (no flooded soil) without irrigation, and rice seeds are directly sown. Deep-water (floating) rice is found in flood-prone environments, where fields occasionally suffer from excess water and uncontrolled deep flooding. Of these rice production systems, more than 90% of the global rice production area is accounted for by irrigated and rainfed lowland (GRiSP, 2013). Irrigated lowland rice is estimated to account for nearly 55% of global rice area, contributing to about 75% of the global rice production. Rainfed lowland rice is estimated to occupy approximately 30% of the global rice area and contributes about 19% of global rice production (GRiSP, 2013). While rainfed upland rice makes up about 9% of global rice area, with 4% contribution to total global rice production, and the remaining area and production is made up of deep-water and floating rice. Considering the important contribution of irrigated and rainfed lowlands to rice production and these being the major production agro-ecologies in East Africa and SSA at large, this thesis focused on study sites in irrigated and rainfed lowlands.

## 1.2 Rice-based production systems in East Africa

Of the total rice area and production in SSA, East Africa accounts for 7.6 and 12.7% respectively. In the region, rice is the second most important staple among cereals, in terms of total production, after maize, with an average consumption growth rate of 4% per annum and estimated consumption of 1.8 million metric tons in 2012 (FAO, 2021; KilimoTrust, 2014). It is the fifth most important crop within the region after cassava, maize, sweet potato and banana. Tanzania is the largest producer and consumer of rice in East Africa, where annual consumption is estimated at 1.18 million metric tons (almost 65% of the region's production) and the highest per capita consumption of 25 kg per year (KilimoTrust, 2014; Lazaro et al., 2017). Kenya is the second largest consumer with annual consumption at 370,000 metric tons and per capita consumption of 9.5 kg per year. While Uganda, Rwanda and Burundi annually consume 167,000, 83,000 and 58,000 metric tons, with per capita consumption at 8, 4 and 4 kg per year, respectively (KilimoTrust, 2014).

Rice production in East Africa covers a wide range of ecosystems; from dryland/upland, floodplains, inland valley swamps to irrigated ecologies (Dianga et al., 2021; Grotelüschen et al., 2021; Kwesiga et al., 2019; Sekiya et al., 2020), categorised majorly as rainfed upland, rainfed lowland, and irrigated ecosystems (GRiSP, 2013). Rainfed (i.e., floodplains and inland valley swamps) or irrigated lowlands are generally wetlands, characterised by nutrient rich soils and year-round water or soil moisture availability due to a high water table and surface water. Kenya, Rwanda, Tanzania and Uganda combined have an area of about 17 million ha of wetlands (Leemhuis et al., 2016). While Swamy & Kumar (2014) estimated about 70% of East Africa's cultivated rice area to be in the rainfed lowland. This thesis focuses on the rainfed and irrigated lowland ecosystems in Uganda and Tanzania. Swampy bottomlands of small inland valleys in Uganda are the main rice-producing environments, where production is dependent on seasonal rainfall and sub-surface interflows from adjacent valley slopes (Grotelüschen et al., 2021). In Tanzania, the Kilombero floodplain is the most important lowland rice-growing area, with production being largely concentrated in the alluvial fans and is dependent on seasonal rainfall and overbank flooding of the Kilombero river and its tributaries (Kato, 2007).

### 1.3 An overview of constraints to rice production in sub-Saharan Africa



Many abiotic and biotic constraints limit potential productivity of rice in various smallholder farms in SSA. Abiotic stresses include mainly drought, flood, and variable rainfall; poor soil fertility; acidity or alkalinity; salinity; and extreme temperatures. While the biotic constraints are weeds; pests, mainly birds, insects, snails and rodents; and diseases such as rice blast, rice yellow mottle virus and bacterial leaf blight, among others (Balasubramanian et al., 2007; Nhamo et al., 2014; Séré et al., 2013). With the currently observed changing climate scenarios, the effects of some of these constraints are expected to be further aggravated, reducing rice yields in all production ecosystems (Praveen & Sharma, 2019; van Oort & Zwart, 2018; Wang et al., 2022).

Lack of water resources or drought, especially during periods of low rainfall, is a major production constraint to rice cultivation in rainfed agro-ecosystems due to inadequate quantity and/or poor distribution of rainfall (Balasubramanian et al., 2007; Dramé et al., 2013). The amount and reliability of rainfall are therefore the two most important constraints to rainfed rice production. Drought can occur at any stage during the rice cropping season, where the most devastating effects are observed for occurrence shortly before flowering, which can cause considerable grain yield loss (Dramé et al., 2013). In SSA, up to 37% of rice area is estimated to be affected by drought, with associated rice yield loss of up to 29% (Diagne et al., 2013; Noelle et al., 2018; van Oort, 2018). In East Africa, van Oort (2018) reported more severe drought stress than in other regions. Suvi et al. (2021) observed that nearly 70% of farmer respondents in Tanzania considered drought an important constraint in rice production. In the lowland agro-ecosystems (irrigated or rainfed), poor water control can likewise limit rice intensification due to submergence, and development of salinity, acidity or nutrient toxicity (Balasubramanian et al., 2007; Sahrawat, 2005), making water management a critical aspect in wetland rice cultivation. In Uganda, Musiime et al. (2005) reported that over 80% of rice farmers considered other constraints to rice production, including soil nutrient depletion, weeds, pests and diseases, being linked to water management.

Soil fertility is another major biophysical factor that affects rice productivity. Low rice yields and large yield gaps in SSA have been majorly attributed to nutrient deficiencies and poor nutrient management practices (Diagne et al., 2013; Haefele et al., 2013; Saito et al., 2013). Bationo et al. (2006) reported that African soils have poor inherent fertility as they are very old, highly weathered and leached, with 16% of Africa's land including rice growing agro-ecologies having low fertile soils and 55% being unsuitable for cultivation. The poor soil fertility is associated with low organic carbon content, and low N and P availability (Saito & Futakuchi, 2009). In addition, poor crop management practices result in increased soil erosion and nutrient depletion (e.g., lower soil organic C content and N supply), leading to rice productivity decline (Becker & Johnson, 2001a). Soil nutrient depletion continues to be among the main rice production constraints (Waddington et al., 2010), where for instance in Uganda over 80% of rice farmers perceive nutrient depletion as one of the critical factors responsible for decreased crop yields (Musiime et al., 2005). Saito and Futakuchi (2009) reported 54% rice grain yield reduction across cultivars due to low soil fertility in West Africa. Likewise in Uganda, Kankwatsa et al. (2019) showed that rice grain yields were on average 37% lower in low fertile soils without fertiliser amendments compared to amended soils. Improved soil fertility management practices could thus help raise farmers' rice yields in SSA, as shown by previous studies, for instance those of Haefele et al. (2000, 2001, and 2013). In East Africa, nitrogen (N), phosphorus (P), and potassium (K) fertilisers are applied in order to address the low fertility problem; however, low response to the applied NPK has been reported (Saito et al., 2019). Considering that crop response to fertiliser application can be influenced by different factors, including inherent soil fertility or soil indigenous nutrient supply (Kihara & Njoroge, 2013; Vanlauwe et al., 2006), understanding the causes of such low response to NPK application in East African lowland rice is necessary to enhance NPK use efficiency, rice growth and grain yields. Indigenous nutrient supply is defined as "*the total amount of a particular nutrient that is available to crops from the soil during a cropping cycle*" (Witt & Dobermann, 2002), which can be derived from incorporated crop residues, residual nutrients from previous applications, irrigation or flood water, and biological fixation, among other sources (Cui et al., 2008; Dobermann et al., 2003; Witt & Dobermann, 2002). Assessing the contribution of inherent soil fertility to fertiliser nutrient use efficiency in these lowlands is important to enhance NPK use efficiency and rice productivity.

Weeds are the most serious biotic constraint to rice production in all rice agro-ecologies of Africa (Diagne et al., 2013). The dominant problem weeds in rice-based production systems in Africa are perennial and annual grasses and sedges such as *Echinochloa spp., Cyperus spp., Imperata cylindrica, Oryza longistaminata,* and *Eleusine indica,* among others, and the parasitic weeds *Striga spp*. and *Rhamphicarpa fistulosa* (Rodenburg & Johnson, 2013; Rodenburg et al., 2010). Weeds can cause considerable yield and financial losses to farmers due to competition with crops for nutrients, water and sunlight, and costs of control measures, respectively. Weeds may also reduce the quality of harvest as some produce seeds that are similar to rice grains, while other species can be alternative hosts for pests and diseases (Rodenburg & Johnson, 2013). Weeds reduce fertiliser nutrient use efficiency due to competition with crops for the applied nutrients, resulting in reduced crop growth and yield. In SSA, rice yield loss of at least 2.2 million metric tons per year due to weeds are estimated, with yield losses of 28–74%, 28–89%, and 48–100% reported in, respectively, transplanted lowland rice, direct-seeded lowland rice, and upland rice (Rodenburg & Johnson, 2009). Farmers' estimates indicate at least 60% yield loss in rainfed lowland rice due to *R. fistulosa,* and farmers reported abandoning rice fields when these become heavily infested (Rodenburg et al., 2011). Increasing rice productivity per unit area will in other words require proper weed management practices such as proper land preparation including levelling and bunding, timely weeding, use of weed suppressive cultivars, timely water and nutrient management (Rodenburg & Johnson, 2013). For instance, in upland rice, improved weed management by weeding more than once increased rice productivity by 43-52% (Ogwuike et al., 2014; Touré et al., 2011). Likewise under irrigated rice systems, rice yield increases of up to 270% are reported with good weed control (Zwart, 2013). Studies show that by applying basic measures such as bunding and timely weeding to improve weed control, farmers in SSA could increase their rice yields by up to 23% (Becker & Johnson, 2001b; Becker et al., 2003). Next to nutrients and weeds, pests and diseases constrain rice production, although not discussed in this thesis. It is important to monitor disease nutrition interaction and develop and apply appropriate management strategies to deal with the effects.

## 1.4 Micro-nutrients in rice production systems

Whereas N, P and K fertilisation has been reported to improve rice grain yields (see e.g., Haefele et al., 2001; Haefele et al., 2002; Niang et al., 2018; Saito et al., 2019; Tanaka et al., 2013; Wanyama et al., 2015), there are indications that micro-nutrients co-limit productivity, and their application together with NPK can increase NPK use efficiency, and hence crop yields (Atique-ur et al., 2014; Dicko et al., 2018; Dimkpa & Bindraban, 2016; Kihara et al., 2017). Studies have indeed shown that rice yields were in cases co-limited by micro-nutrients. For instance in SSA, studies where boron (B), zinc (Zn), copper (Cu), magnesium (Mg) and sulphur (S) were applied in combination with NPK reported increased yields of rice compared with yields realised when only NPK was applied (Kihara et al., 2017; Vanlauwe et al., 2015; Wortmann et al., 2019). Despite the growing evidence that micro-nutrients can co-constrain productivity, less attention has been paid to micro-nutrient fertilisation in East Africa compared with NPK. Kihara et al. (2016) noted that generally in SSA most research has focused on N and P as key nutrients limiting crop production leaving out other nutrients such as K, S and some micro-nutrients that could greatly constrain production. The fact that crop yields can increase by supplying micro-nutrients suggests that increased use efficiencies of N, P and K and, hence, reduced nutrient losses to the environment are possible. In view of the above, there is need for better understanding of how fertilisation of rice crops in lowland rice ecologies of East Africa can be made more effective and efficient. Previous studies on micro-nutrients in East Africa have focused mainly on upland crops, and knowledge of the relevance of micro-nutrients in lowland rice where farmers seem to find low yield gains from NPK fertilisation (Saito et al., 2019) is limited.

Among the micro-nutrients, Zn is the most important micro-nutrient in rice nutrition and its deficiency is recognised as the most frequent and widespread globally, affecting many crops, with rice yields reported to be restricted by Zn deficiency in millions of hectares worldwide (Alloway, 2008a,b; Joy et al., 2015). In rice, Zn deficiency results in stunted growth, reduced tillering, delayed maturity and lower yields (Alloway, 2008b). Boron deficiency is the second most widespread micro-nutrient problem reported as the major reason for panicle sterility and poor grain quality in rice. Copper, iron (Fe) and manganese (Mn) deficiencies are reported to vary in importance around the world. Copper deficiency is reported to affect vegetative growth, cause male sterility resulting in grain yield losses of up to 20% or more, and can lead to shrivelled grains and reduced viability of seeds in cereals (Alloway, 2008a; Atique-ur et al., 2015;

Graham, 2008). Deficiencies of secondary nutrients – calcium (Ca), Mg and S have also been reported in crop plants. Collectively, their deficiency has been shown to affect overall plant growth and development, nutrient uptake and grain yield (Chorianopoulou & Bouranis, 2022; Grzebisz et al., 2023).

## 1.5 Good agronomic practices and the associated benefits to increasing rice productivity

Good/recommended agronomic practices (RAP) in rice production are cultivation practices that are suited for a particular environment and aim at helping farmers improve rice yields (Mkanthama, 2013; Oo & Usami, 2020). Recommended agronomic practices are considered as integrated crop, soil, water, weed, pest and disease management practices (Senthilkumar et al., 2018), and are seen as a basket containing several good farming practices from where farmers can choose the most appropriate practices for their production environment (Mkanthama, 2013). RAP for lowland rice production may comprise a package of practices including, but not limited to, fine field tillage using hand hoe, animal- or tractor-drawn implements; bunding and levelling before transplanting or sowing; use of improved varieties and high quality seeds; nursery establishment and management; timely and line transplanting or sowing; timely weed, pest and disease management; timely fertilisation; good water management; and timely harvesting (Mkanthama, 2013; Oo & Usami, 2020; Senthilkumar et al., 2018). For any given agro-ecosystem (irrigated or rainfed), RAP appropriate for farmers in such agro-ecosystem need to be implemented in a logical sequence as these interact to cause the overall effect on crop growth and yield.

The benefits of following RAP in rice production have been shown to include economic, environmental, and social gains from on-farm practices, such as reduced seed rate, uniform and vigorous seedling establishment, increased fertiliser use efficiency and reduced environmental pollution, and improved rice yields (International Rice Research Institute - IRRI, 2010; Oo & Usami, 2020). In SSA, it is indicated that application of RAP has the potential to increase yields, and that RAP should be considered an important component of any strategy aimed at boosting rice yields and ensuring sustainable and efficient exploitation of Africa's wetlands (Nhamo et al., 2014; Rodenburg et al., 2014). For instance, Nhamo et al. (2014) reported rice yield gains of ca. 87% and 92%, respectively, from use of bunds to control water and improved weed management practices compared with farmers' practice. Similarly, Krupnik et al. (2012), Senthilkumar et al. (2018), Raes et al. (2007), Rodenburg and Johnson (2009), Touré et al. (2009), and Becker and Johnson (2001b) reported improved rice grain yields due to a combination of fine tillage, bunding, timely weeding and fertilisation, attributing the gains to a lower weed biomass and increased fertiliser nutrient use efficiency. In SSA where farmers apply very low fertiliser amounts (Bado et al., 2018a,b), efforts to increase rice yields may need to be focused first on RAP components considered as available and feasible options for farmers to intensify production.

Although RAP can increase nutrient use efficiency and grain yield, its effectiveness varies when applied under researcher- and farmer-management. Studies show that RAP applied under researcher management resulted in higher nutrient use efficiency and grain yield compared to application under farmers' management (Becker & Johnson, 2001b; Niang et al., 2018; Tsujimoto et al., 2019). The difference in RAP effects between researcher- and farmer-management may be attributed to the difference in efficiency with which implementation is done. This could mean that exposing farmers to RAP in a participatory manner, where farmers are guided in RAP implementation ensuring learning-by-doing, can help farmers improve their RAP execution, thereby improving on their crop management practices, and hence increasing grain yield. A follow-up evaluation of such joint learning with farmers may then be necessary to provide insights into how the joint learning later brings about changes in farmers' management practices and related changes in grain yields. Such evaluation may be vital in providing information to make decisions on how improved production practices for rice yield enhancement can be delivered to farmers, ensuring adoption of improved crop management and increase in on-farm rice yields.

In spite of the evident benefits of RAP, smallholder farmers either do not adopt these improved practices or they take a long time to adopt (Mottaleb, 2018). This lack of or slow adoption is attributed to uncertainties about proper application, success of such practices under local farmers' environmental conditions, and high costs (Mottaleb, 2018; Sinyolo, 2020). Studies further indicate that disparity in adoption of improved management practices is related to the differences in household socio-economic characteristics, including, for instance, farm size and income, labour and cash availability, and risk perception. Likewise, training and awareness about the improved practices, and past participation in on-farm trials have been reported to influence adoption (Danlami et al., 2016; Fosso & Nanfosso, 2016; Hassan et al., 2016; Urfels et al., 2021). Increasing rice production, therefore, also requires understanding the level of uptake of improved management practices by smallholder rice farmers together with their socio-economic characteristics and the associated variation in grain yield, as this could help in supporting advisory programmes that can enhance adoption of improved practices, hence increasing rice yields.

## 1.6 Problem statement

Despite the vital role rice plays in rural household food and income security and national economies in SSA, smallholder farm yields are still very low, and in many countries, domestic rice production has not been able to meet the growing demand, resulting in reliance on imports to meet the deficit in demand. The low farm yields are, among other factors, attributed to soil fertility constraints and sub-optimal management. In East Africa, NPK fertilisers are applied in an attempt to address the low soil fertility. However, application of NPK fertilisers only is not always producing better yields. Understanding the contributing factors for the low response to NPK application is thus necessary to enhance NPK use efficiency, rice growth and grain yields. Soil micro-nutrient deficiencies and depletion might result in low NPK uptake and use efficiency as no soil micro-nutrient replenishment is done. Micro-nutrients are reported to enhance NPK uptake and use efficiency, and improve crop yields, where higher rice yields have been shown when micro-nutrients are applied together with NPK fertilisers compared to yields obtained with only NPK application (Kihara et al., 2017; Vanlauwe et al., 2015; Wortmann et al., 2019). In spite of such evidence of likely yield limitation by micro-nutrients, micro-nutrient fertilisation in East Africa has gained little attention, with previous studies focusing mainly on upland crops. The low response to NPK fertilisation may therefore require special attention to micro-nutrient management for improved lowland rice productivity. A balanced micro- and macro-nutrient fertilisation may be needed to enhance uptake and utilisation of NPK and other nutrients for improved rice growth and grain yield. Therefore, there is a need for better understanding of the possible contribution of micro-nutrients in making NPK fertilisation more effective and efficient, and hence their potential role in enhancing rice yields in the East African lowland rice ecologies where limited yield gains are realised from only NPK fertilisation (Saito et al., 2019).

In addition, recommended agronomic practices have been shown to increase fertiliser use efficiency and enhance rice yields on smallholder farms, and to be key in realising yield gains from fertilisation (Becker & Johnson, 2001b; Nhamo et al., 2014; Touré et al., 2009). It is consequently important also to assess the role of recommended agronomic practices, with or without fertilisation, for its contribution to enhancing smallholder farmers' productivity. Considering that weeds can reduce fertiliser nutrient use efficiency because of their competition with crops for the applied nutrients thereby causing reduced crop growth and yield, assessing the contribution of weed and fertiliser management strategies on fertiliser response in lowland rice of East Africa is necessary to enhance fertiliser nutrient use efficiency and grain yields. Moreover, inherent soil fertility is shown to influence crop response to fertiliser application (Kihara & Njoroge, 2013; Vanlauwe et al., 2006), yet inherent fertility level varies between farmers' fields due to their differences in crop management practices. Understanding the role of inherent fertility (indigenous nutrient supply) and crop management practices on NPK use efficiency in lowlands may therefore also be crucial in designing management packages to enhance fertiliser nutrient use efficiency and rice grain yields. While applying recommended agronomic practices has been shown to increase fertiliser use efficiency and enhance rice yields on smallholder farms, their adoption and application depend on a number of factors including socio-economic characteristics of individual farmers. Assessing uptake of improved management practices by smallholder rice farmers after participation in a joint learning, their socio-economic characteristics and the associated variation in grain yield can be useful in obtaining information relevant in decision making regarding delivery of improved practices to farmers for enhancing rice yield. This information may also be crucial in supporting advisory programmes that can enhance adoption of improved practices, resulting in increase in on-farm rice yield.

In light of the above, this study aimed to quantify the magnitude of the effect of micro-nutrients, RAP under researcher supervision and as applied by farmers after participation in joint on-farm trials, and inherent fertility on NPK use efficiency in lowland rice and hence rice yields in East Africa, and to identify feasible options to improve smallholder productivity. Specific objectives were to:

i. Assess the contribution of NPK, and combinations of NPK + secondary and micro-nutrients on lowland rice yield in East Africa (*Chapter 2*).
ii. Evaluate the contribution of recommended agronomic practices on lowland rice yield, and show exploitable yield gaps that farmers can bridge using recommended crop management practices, and different feasible options for farmers to improve productivity (*Chapter 3*).
iii. Quantify the effect of the interaction between indigenous nutrient supply and management practices on nutrient uptake and use efficiency on-farm (*Chapter 4*).

iv. Evaluate how joint experimentation with farmers translates into changes in farmers' management practices and, hence, on-farm rice grain yield (*Chapter 5*).

### 1.7 Study areas and research approaches

The studies of this thesis were conducted in Uganda and Tanzania under irrigated lowland (IL) and rainfed lowland (RL) conditions. In Uganda, researcher- and farmer-managed joint experimentation trials were conducted at the Doho rice irrigation scheme (IL) in Butaleja district (34°02'E and 0°56'N), while in Kibimba rice irrigation scheme (IL) and the Magoola swamp (RL) in Bugiri district (33°45'E and 0°33'N) researcher-managed trials were also conducted. In Tanzania, researcher-managed trials were conducted in the Kilombero valley at Idete - RL (36°30'E and 8°60'S) and in Msufini - IL (36°54'E and 7°47'S). The Doho rice irrigation scheme is the largest public rice irrigation scheme in Uganda (Wanyama et al., 2017), covering 1000 ha of land where more than 4000 smallholder farmers cultivate rice. The scheme receives a bimodal rainfall pattern, with peaks in March–May and August–October, and an average annual rainfall of 1186 mm (Namyenya, 2014). The soils in the area are plinthosols, reddish brown in colour, sandy loam, and loam textured (Tenywa et al., 2016). Bugiri district receives a bimodal rainfall with peaks in April–May and September–November, and an annual average rainfall of ca. 1250 mm. The soils in the district are laterite and ferralitic, with deep reddish brown sandy loams or clay loams (Musiime et al., 2005). Butaleja and Bugiri districts are among the major rice producing areas in Uganda. The Kilombero floodplain is the most important lowland rice-growing area of Tanzania, characterised by fluvisols in the valley bottom, which are brown or grey, sandy loam or clay soils. The area receives a bimodal rainfall in March–May and October–December, with the annual rainfall ranging from 1200 to 1400 mm (Gabiri et al., 2018).

The studies were a combination of multi-locational researcher-managed on-farm experiments conducted in two cropping seasons, participatory on-farm trials conducted in three cropping seasons with over 100 farmers, and a follow-up evaluation study through household surveys and farmers' field assessments. The researcher-managed on-farm experiments in Uganda were conducted in 2016 and 2017, and in Tanzania in 2015 and 2016. In Uganda, for each location and year, trials were arranged in a Randomised Complete Block Design, with four replications, except in Magoola swamp which had only three replications. In Tanzania, ten farmers' fields were used, each field treated as a replicate so ten replicates in each site and year. The participatory on-farm trials were conducted in Doho rice irrigation scheme between January and December 2019 as a follow-up to the two years of researcher-managed on-farm experiments. Treatment allocation within an individual farmer's field was random, and each farmer was considered a replicate. Finally, a further follow-up study was conducted one year after the participatory on-farm trials, between January and May 2021 in order to assess change in management practices and grain yield of farmers after participation in the joint experimentation. A semi-structured questionnaire was used to collect information from farmers, followed by field observations made during field visits to collect information on farmers' crop management practices and grain yield.

## 1.8 Thesis outline

This thesis consists of six chapters. This chapter (Chapter 1) presents the general background to the study and the challenges rice production in SSA faces, and the potential role of NPK and micro-nutrient fertiliser use and recommended agronomic practices in intensifying rice productivity in smallholder farms in East Africa. Following this chapter, there are four research chapters (Chapter 2 to Chapter 5) one addressing each of the above defined objectives (Figure 1.3) and followed by a general discussion (Chapter 6).

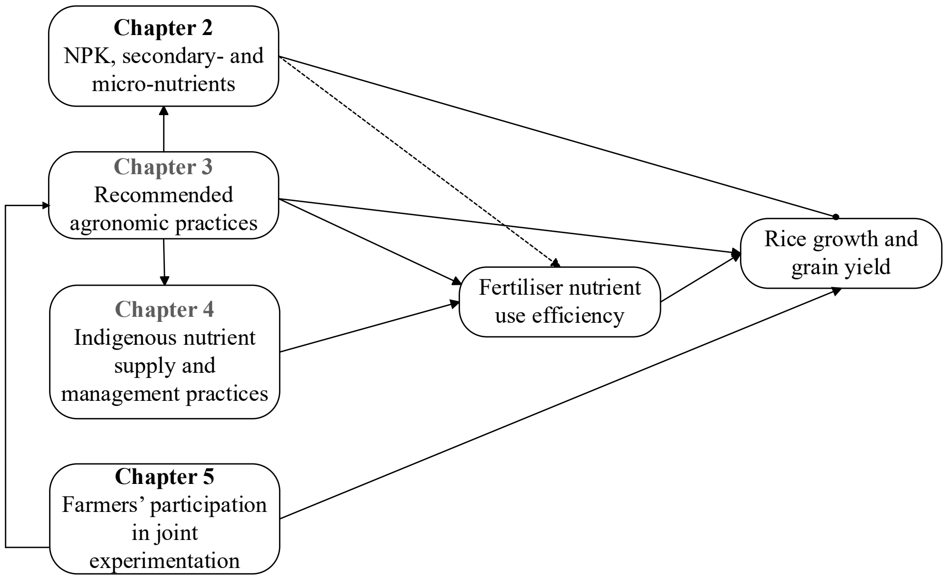


**Figure 1.3** Outline of the thesis. Continuous lines with arrows indicate effects which the study directly assesses. Dashed arrow indicates effect the study does not directly assess but reflects on in the general discussion.

Chapter 2 uses rice yield and yield component data from the researcher-managed on-farm experiments in Uganda and Tanzania to assess rice yield response to NPK and NPK plus secondary and micro-nutrient fertilisation in East African lowlands. Chapter 3 uses rice yield data from participatory on-farm trials in Uganda to evaluate the effect of applying recommended agronomic practices on lowland rice yield, and to show different management options available for smallholder farmers to improve productivity. In Chapter 4, plant analysis and rice yield data from these same participatory on-farm trials are used to quantify the effect of the interaction between indigenous nutrient supply and management practices on fertiliser nutrient use efficiency in lowland rice. Chapter 5 uses socio-economic, management and rice yield data from the follow-up evaluation study to assess the effect of experimenting with farmers on farmers' management practices and rice grain yields. In Chapter 6, a summary of the main findings of this thesis is provided, and the results are combined to provide insights for options for smallholder lowland rice farmers in SSA to increase nutrient use efficiency and rice productivity.



**References**


Alloway, B. J. (2008a). Micronutrients and Crop Production: An Introduction. In *Micronutrient Deficiencies in Global Crop Producttion*. *Springer*, 1-39.

Alloway, B. J. (2008b). Zinc in soils and crop nutrition, 2nd edition. *International Zinc Association and International Fertilizer Industry Association, Brussels, Belgium and Paris, France.*, 139.

Arment, C. J. (2020). Food Dependency in Sub-Saharan Africa: Simply a Matter of 'Vulnerability', or Missed Development Opportunity? *Development and Change, 51*(2), 283-323. DOI: 10.1111/dech.12532

Arouna, A., Fatognon, I. A., Saito, K., & Futakuchi, K. (2021). Moving toward rice self-sufficiency in sub-Saharan Africa by 2030: Lessons learned from 10 years of the Coalition for African Rice Development. *World Development Perspectives, 21*, 100291. DOI: 10.1016/j.wdp.2021.100291

Atique-ur-Rehman, R., Farooq, M., Nawaz, A., & Ahmad, R. (2014). Influence of boron nutrition on the rice productivity, kernel quality and biofortification in different production systems. *Field Crops Research, 169*, 123-131. DOI: 10.1016/j.fcr.2014.09.010

Atique-ur-Rehman, R., Farooq, M., Nawaz, A., Rehman, A., & Iqbal, S. (2015). Soil Application of Boron Improves the Tillering, Leaf Elongation, Panicle Fertility, Yield and its Grain Enrichment in Fine-Grain Aromatic Rice. *Journal of Plant Nutrition, 38*(3), 338-354. DOI: 10.1080/01904167.2014.963120

Bado, V. B., Djaman, K., & Mel, V. C. (2018b). Developing fertilizer recommendations for rice in Sub-Saharan Africa, achievements and opportunities. *Paddy and Water Environment, 16*(3), 571-586. DOI: 10.1007/s10333-018-0649-8

Bado, V. B., Djaman, K., & Valère, M. C. (2018a). Managing Fertilizer Recommendations in Rice-Based Cropping Systems: Challenges and Strategic Approaches. In A. Bationo, D. Ngaradoum, S. Youl, F. Lompo, & J. O. Fening (Eds.), *Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems: Volume 1* (pp. 25-50). Cham: Springer International Publishing.

Balasubramanian, V., Sie, M., Hijmans, R. J., & Otsuka, K. (2007). Increasing Rice Production in Sub-Saharan Africa: Challenges and Opportunities. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 94, pp. 55-133): Academic Press.

Bationo, A., Hartemink, A. E., Lungo, O., Naimi, M., Okoth, P., Smaling, E. M. A., & Thiombiano, L. (2006). *African soils: their productivity and profitability of fertilizer use : background paper for the African Fertilizer Summit 9-13th June 2006, Abuja, Nigeria*. Retrieved from Togo: https://edepot.wur.nl/26759

Becker, M., & Johnson, D. E. (2001a). Cropping intensity effects on upland rice yield and sustainability in West Africa. *Nutrient Cycling in Agroecosystems, 59*(2), 107-117. DOI: 10.1023/A:1017551529813

Becker, M., & Johnson, D. E. (2001b). Improved water control and crop management effects on lowland rice productivity in West Africa. *Nutrient Cycling in Agroecosystems, 59*(2), 119-127. DOI: 10.1023/A:1017585328904

Becker, M., Johnson, D. E., Wopereis, M. C. S., & Sow, A. (2003). Rice yield gaps in irrigated systems along an agro-ecological gradient in West Africa. *Journal of Plant Nutrition and Soil Science, 166*(1), 61-67. DOI: 10.1002/jpln.200390013

Chamberlin, J., Jayne, T. S., & Headey, D. (2014). Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. *Food Policy, 48*, 51-65. DOI: 10.1016/j.foodpol.2014.05.002

Chorianopoulou, S. N., & Bouranis, D. L. (2022). The Role of Sulfur in Agronomic Biofortification with Essential Micronutrients. Plants, 11(15), 1979. DOI: 10.3390/plants11151979

Cubry, P., Tranchant-Dubreuil, C., Thuillet, A.-C., Monat, C., Ndjiondjop, M.-N., Labadie, K., . . . Vigouroux, Y. (2018). The Rise and Fall of African Rice

Cultivation Revealed by Analysis of 246 New Genomes. *Current Biology, 28*(14), 2274-2282.e2276. DOI: 10.1016/j.cub.2018.05.066

Cui, Z., Zhang, F., Chen, X., Miao, Y., Li, J., Shi, L., . . . Bao, D. (2008). On-farm estimation of indigenous nitrogen supply for site-specific nitrogen management in the North China plain. Nutrient Cycling in Agroecosystems, 81(1), 37-47. DOI: 10.1007/s10705-007-9149-8

Danlami, A. H., Islam, R., Applanaidu, S. D., & Tsauni, A. M. (2016). An empirical analysis of fertiliser use intensity in rural Sub-Saharan Africa. International Journal of Social Economics, 43(12), 1400-1419. DOI: 10.1108/IJSE-04-2015-0086

Diagne, A., Alia, D. Y., Amovin-Assagba, E., Wopereis, M. C. S., Saito, K., & Nakelse, T. (2013). Farmer perceptions of the biophysical constraints to rice production in sub-Saharan Africa, and potential impact of research. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa's Rice Promise. . *CAB International, Wallingford, UK*, 46-68.

Dianga, A. I., Musila, R. N., & Kamau, W. J. (2021). Rainfed Rice Farming Production Constrains and Prospects, the Kenyan Situation. *Integrative Advances in Rice Research*, 12. DOI: 10.5772/intechopen.98389

Dicko, M. K., Traoré, L., Kouyaté, Z., Koné, M., Sidibé, B., Kamissoko, N., . . . Diakité, C. H. (2018). Response of Rice, Maize and Millet to Fertilizers in Mali. In A. Bationo, D. Ngaradoum, S. Youl, F. Lompo, & J. O. Fening (Eds.), *Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems: Volume 1* (pp. 139-155). Cham: Springer International Publishing.

Dimkpa, C. O., & Bindraban, P. S. (2016). Fortification of micronutrients for efficient agronomic production: a review. *Agronomy for Sustainable Development, 36*(1), 7. DOI: 10.1007/s13593-015-0346-6

Dobermann, A., Witt, C., Abdulrachman, S., Gines, H. C., Nagarajan, R., Son, T. T., . . . Bartolome, V. (2003). Estimating Indigenous Nutrient Supplies for Site-Specific Nutrient Management in Irrigated Rice. Agronomy Journal, 95(4), 924-935. DOI: 10.2134/agronj2003.9240

Dramé, K. N., Manneh, B., & Ismail, A. M. (2013). Rice genetic improvement for abiotic stress tolerance in Africa. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa's Rice Promise. *CAB International, Wallingford, UK*, 144-160.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., . . . Snyder, P. K. (2005). Global Consequences of Land Use. *Science, 309*(5734), 570. DOI: 10.1126/science.1111772

Food and Agriculture Organisation of the United Nations (2021). Production data: Crops and livestock products. Retrieved from http://www.fao.org/faostat/en/#data/QC. [Accessed 26 October 2021]

Fosso, P. K., & Nanfosso, R. T. (2016). Adoption of agricultural innovations in risky environment: the case of corn producers in the west of Cameroon. Review of Agricultural, Food and Environmental Studies, 97(1), 51-62. DOI: 10.1007/s41130-016-0008-3

Gabiri, G., Burghof, S., Diekkrüger, B., Leemhuis, C., Steinbach, S., & Näschen, K. (2018). Modeling spatial soilwater dynamics in a tropical floodplain, East Africa. *Water (Switzerland), 10*(2). DOI: 10.3390/w10020191

Graham, R. D. (2008). Micronutrient Deficiencies in Crops and their Global Significance. In: B.J. Alloway (ed), Micronutrient Deficiencies in Global Crop Production. *Springer*, 41-61.

GRiSP (Global Rice Science Partnership). (2013). Rice Almanac, 4th edition. *International Rice Research Institute, Los Baños (Philippines)*, 283.

Grotelüschen, K., Gaydon, D. S., Langensiepen, M., Ziegler, S., Kwesiga, J., Senthilkumar, K., . . . Becker, M. (2021). Assessing the effects of management and hydro-edaphic conditions on rice in contrasting East African wetlands using experimental and modelling approaches. *Agricultural Water Management, 258*, 107146. DOI: 10.1016/j.agwat.2021.107146

Grzebisz, W., Zielewicz, W., & Przygocka-Cyna, K. (2023). Deficiencies of Secondary Nutrients in Crop Plants—A Real Challenge to Improve Nitrogen Management. Agronomy, 13(66). DOI: 10.3390/agronomy13010066

Haefele, S. M., Johnson, D.E., Diallo, S., Wopereis, M. C.S., Janin, I. (2000). Improved soil fertility and weed management is profitable for irrigated rice farmers in Sahelian West Africa. *Field Crops Research, 66*(2), 101-113. DOI: 10.1016/S0378-4290(00)00066-6

Haefele, S. M., Saito, K., Ndiaye, K. M., Mussgnug, F., Nelson, A., & Wopereis, M. S. C. (2013). Increasing rice productivity through improved nutrient use in Africa. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa's Rice Promise. *CAB International, Wallingford, UK*, 250–264.

Haefele, S. M., Wopereis, M. C. S., Donovan, C., & Maubuisson, J. (2001). Improving the productivity and profitability of irrigated rice production in Mauritania.

*European Journal of Agronomy, 14*(3), 181-196. DOI: 10.1016/S1161-0301(00)00094-0

Haefele, S. M., Wopereis, M. C. S., & Wiechmann, H. (2002). Long-term fertility experiments for irrigated rice in the West African Sahel: agronomic results. *Field Crops Research, 78*(2), 119-131. DOI: 10.1016/S0378-4290(02)00117-X

Hassan, M. B., Baiyegunhi, L. J. S., Ortmann, G. F., & Abdoulaye, T. (2016). Adoption of striga (striga hermonthica) Management Technologies in Northern Nigeria. Agrekon, 55(1-2), 168-188. DOI: 10.1080/03031853.2016.1159587

International Rice Research Institute. (2010). Bridging the "GAP" makes farmers wealthier. *IRRI Annual Report.*, 44. Retrieved from http://books.irri.org/AR2010_content.pdf

Joy, E. J. M., Stein, A. J., Young, S. D., Ander, E. L., Watts, M. J., & Broadley, M. R. (2015). Zinc-enriched fertilisers as a potential public health intervention in Africa. *Plant and Soil, 389*(1), 1-24. DOI: 10.1007/s11104-015-2430-8

Kankwatsa, P., Muzira, R., Mutenyo, H., & Lamo, J. (2019). Improved Upland Rice: Adaptability, Agronomic and Farmer Acceptability Assessment under Semi-Arid Conditions of South Western Uganda. Open Access Library Journal, Vol.06No.12, 5. DOI: 10.4236/oalib.1105660

Kato, F. (2007). Development of a major rice cultivation area in the Kilombero valley, Tanzania. *African Study Monographs, Suppl.36*, 3-18.

Khush, G. S. (1997). Origin, dispersal, cultivation and variation of rice. *Plant Molecular Biolog, 35*, 25-34.

Kihara, J., & Njoroge, S. (2013). Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. Field Crops Research, 150, 1-8. DOI: 10.1016/j.fcr.2013.05.025

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., . . . Huising, J. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agriculture, Ecosystems & Environment, 229*(Supplement C), 1-12. DOI: 10.1016/j.agee.2016.05.012

Kihara, J., Sileshi, G. W., Nziguheba, G., Kinyua, M., Zingore, S., & Sommer, R. (2017). Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. *Agronomy for Sustainable Development, 37*(4), 25. DOI: 10.1007/s13593-017-0431-0

KilimoTrust. (2014). Expanding Rice Markets in the East African Community. 64.

Krupnik, T. J., Shennan, C., Settle, W. H., Demont, M., Ndiaye, A. B., & Rodenburg, J. (2012). Improving irrigated rice production in the Senegal River Valley through experiential learning and innovation. *Agricultural Systems, 109*, 101-112. DOI: 10.1016/j.agsy.2012.01.008

Kwesiga, J., Grotelüschen, K., Neuhoff, D., Senthilkumar, K., Döring, T. F., & Becker, M. (2019). Site and Management Effects on Grain Yield and Yield Variability of Rainfed Lowland Rice in the Kilombero Floodplain of Tanzania. *Agronomy, 9*(10). DOI: 10.3390/agronomy9100632

Kwesiga, J., Grotelüschen, K., Senthilkumar, K., Neuhoff, D., Döring, T. F., & Becker, M. (2020). Rice Yield Gaps in Smallholder Systems of the Kilombero Floodplain in Tanzania. *Agronomy, 10*(8). DOI: 10.3390/agronomy10081135

Lazaro, E., Sam, A. G., & Thompson, S. R. (2017). Rice demand in Tanzania: an empirical analysis. *Agricultural Economics, 48*(2), 187-196. DOI: 10.1111/agec.12325

Leemhuis, C., Amler, E., Diekkrüger, B., Gabiri, G., & Näschen, K. (2016). East African wetland-catchment data base for sustainable wetland management. *Proc. IAHS, 374*, 123-128. DOI: 10.5194/piahs-374-123-2016

Linares, O. F. (2002). African rice (<em>Oryza glaberrima</em>): History and future potential. *Proceedings of the National Academy of Sciences, 99*(25), 16360-16365. DOI: 10.1073/pnas.252604599

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop Yield Gaps: Their Importance, Magnitudes, and Causes. *Annual Review of Environment and Resources, 34*(1), 179-204. DOI: 10.1146/annurev.environ.041008.093740

Manitra, A. R., Massimo, I., & Marianna, P. (2012). Why has Africa become a net food importer? Explaining Africa agricultural and food trade deficits. *Trade and Markets Division, FAO, Rome.*, 89.

Mauser, W., Klepper, G., Zabel, F., Delzeit, R., Hank, T., Putzenlechner, B., & Calzadilla, A. (2015). Global biomass production potentials exceed expected future demand without the need for cropland expansion. *Nature Communications, 6*, 8946-8946. DOI: 10.1038/ncomms9946

Mkanthama, J. M. (2013). An Analysis of use of Good Agricultural Practices in Rice Production: A Case Study of Bagamoyo and Dakawa Areas, Tanzania. *MSc. Thesis, Kenyatta University of Agriculture and Technology.*, 110.

Mottaleb, K. A. (2018). Perception and adoption of a new agricultural technology: Evidence from a developing country. Technology in Society, 55, 126-135. DOI: 10.1016/j.techsoc.2018.07.007

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature, 490*(7419), 254-257. DOI: 10.1038/nature11420

Musiime, O., Tenywa, M. M., Majaliwa, M. J. G., Lufafa, A., Nanfumba, D., Wasige, J., . . . Kyondha, M. (2005). Constraints to rice production in Bugiri district. *African Crop Science Conference Proceedings, 7*, 1495-1499.

Muthayya, S., Sugimoto, J. D., Montgomery, S., & Maberly, G. F. (2014). An overview of global rice production, supply, trade, and consumption. Ann N Y Acad Sci, 1324, 7-14. DOI: 10.1111/nyas.12540

Namyenya, A. (2014). Farmers' willingness to pay for irrigation water: the case of Doho rice irrigation scheme in eastern Uganda. *MSc. Thesis, Makerere University.*, 90.

Nhamo, N., Rodenburg, J., Zenna, N., Makombe, G., & Luzi-Kihupi, A. (2014). Narrowing the rice yield gap in East and Southern Africa: Using and adapting existing technologies. *Agricultural Systems, 131*, 45-55. DOI: 10.1016/j.agsy.2014.08.003

Niang, A., Becker, M., Ewert, F., Tanaka, A., Dieng, I., & Saito, K. (2018). Yield variation of rainfed rice as affected by field water availability and N fertilizer use in central Benin. *Nutrient Cycling in Agroecosystems, 110*(2), 293-305. DOI: 10.1007/s10705-017-9898-y

Noelle, N. M., Weru, Wambugu Peterson., Rodrigue, Sangare Jean., Karlin, Gnikoua. (2018). The effects of drought on rice cultivation in sub-Saharan Africa and its mitigation: A review. *African Journal of Agricultural Research, 13*, 1257-1271.

Ogwuike, P., Rodenburg, J., Diagne, A., Agboh-Noameshie, A. R., & Amovin-Assagba, E. (2014). Weed management in upland rice in sub-Saharan Africa: impact on labor and crop productivity. *Food Security, 6*(3), 327-337. DOI: 10.1007/s12571-014-0351-7

Oo, S. P., & Usami, K. (2020). Farmers' Perception of Good Agricultural Practices in Rice Production in Myanmar: A Case Study of Myaungmya District, Ayeyarwady Region. *Agriculture, 10*(7). DOI: 10.3390/agriculture10070249

Pradhan, P., Fischer, G., van Velthuizen, H., Reusser, D.E., & Kropp, J.P. (2015). Closing Yield Gaps: How Sustainable Can We Be? *PLoS ONE, 10*(6), e0129487. DOI: 10.1371/journal.pone.0129487

Praveen, B., & Sharma, P. (2019). A review of literature on climate change and its impacts on agriculture productivity. Journal of Public Affairs, 19(4), e1960. DOI: 10.1002/pa.1960

Raes, D., Kafiriti, E. M., Wellens, J., Deckers, J., Maertens, A., Mugogo, S., . . . Descheemaeker, K. (2007). Can soil bunds increase the production of rain-fed lowland rice in south eastern Tanzania? *Agricultural Water Management, 89*(3), 229-235. DOI: 10.1016/j.agwat.2007.01.005

Rodenburg, J., & Johnson, D. E. (2009). Weed Management in Rice-Based Cropping Systems in Africa. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 103, pp. 149-218): Academic Press.

Rodenburg, J., & Johnson, D. E. (2013). Managing weeds in rice of Africa. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa's Rice Promise. *CAB International, Wallingford, UK*, 204-212.

Rodenburg, J., Riches, C. R., & Kayeke, J. M. (2010). Addressing current and future problems of parasitic weeds in rice. *Crop Protection, 29*(3), 210-221. DOI: 10.1016/j.cropro.2009.10.015

Rodenburg, J., Zossou-Kouderin, N., Gbèhounou, G., Ahanchede, A., Touré, A., Kyalo, G., & Kiepe, P. (2011). Rhamphicarpa fistulosa, a parasitic weed threatening rain-fed lowland rice production in sub-Saharan Africa – A case study from Benin. *Crop Protection, 30*(10), 1306-1314. DOI: 10.1016/j.cropro.2011.06.007

Rodenburg, J., Zwart, S. J., Kiepe, P., Narteh, L. T., Dogbe, W., & Wopereis, M. C. S. (2014). Sustainable rice production in African inland valleys: Seizing regional potentials through local approaches. *Agricultural Systems, 123*, 1-11. DOI: 10.1016/j.agsy.2013.09.004

Sahrawat, K. L. (2005). Iron Toxicity in Wetland Rice and the Role of Other Nutrients. *Journal of Plant Nutrition, 27*(8), 1471-1504. DOI: 10.1081/PLN-200025869

Saito, K., & Futakuchi, K. (2009). Performance of diverse upland rice cultivars in low and high soil fertility conditions in West Africa. *Field Crops Research, 111*(3), 243-250. DOI: 10.1016/j.fcr.2008.12.011

Saito, K., Nelson, A., Zwart, S. J., Niang, A., Sow, A., Yoshida, H., & 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. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa's Rice Promise. *CAB International, Wallingford, UK*, 188–203.

Saito, K., Vandamme, E., Johnson, J.-M., Tanaka, A., Senthilkumar, K., Dieng, I., . . . Wopereis, M. C. S. (2019). Yield-limiting macronutrients for rice in sub-Saharan Africa. *Geoderma, 338*, 546-554. DOI: 10.1016/j.geoderma.2018.11.036

Sala, O. E., Stuart Chapin, F., Iii, Armesto, J. J., Berlow, E., Bloomfield, J., . . . Wall, D. H. (2000). Global Biodiversity Scenarios for the Year 2100. *Science, 287*(5459), 1770. DOI: 10.1126/science.287.5459.1770

Sangeetha, J., Thangadurai, D., Fayeun, L. S., Akinwale, J. A., Habeeb, J., Maxim, S. S., . . . Islam, S. (2020). Origin and Evolution of Rice as Domesticated Food Crop. In A. Roychoudhury (Ed.), *Rice Research for Quality Improvement: Genomics and Genetic Engineering: Volume 1: Breeding Techniques and Abiotic Stress Tolerance* (pp. 1-14). Singapore: Springer Singapore.

Seck, P. A., Ali, A.T., Jeanne, Y.C., Aliou D., & Wopereis, M. C.S. (2013). Africa’s Rice Economy Before and After the 2008 Rice Crisis. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., & Jalloh, A. (eds). Realizing Africa's Rice Promise. *CABI*, 436. DOI: 10.1079/9781845938123.0024

Sekiya, N., Oizumi, N., Kessy, T. T., Fimbo, K. M. J., Tomitaka, M., Katsura, K., & Araki, H. (2020). Importance of market-oriented research for rice production in Tanzania. A review. *Agronomy for Sustainable Development, 40*(1), 7. DOI: 10.1007/s13593-020-0611-1

Senthilkumar, K., Tesha, B. J., Mghase, J., & Rodenburg, J. (2018). Increasing paddy yields and improving farm management: results from participatory experiments with good agricultural practices (GAP) in Tanzania. *Paddy and Water Environment, 16*(4), 749-766. DOI: 10.1007/s10333-018-0666-7

Séré, Y., Fargette, D., Abo, M. E., Wydra, K., Bimerew, M., Onasanya, A., & Akator, S. K. (2013). Managing the major diseases of rice in Africa. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa's Rice Promise. *CAB International, Wallingford, UK*, 213-228.

Sinyolo, S. (2020). Technology adoption and household food security among rural households in South Africa: The role of improved maize varieties. Technology in Society, 60, 101214. DOI: 10.1016/j.techsoc.2019.101214

Steffens, B., Geske, T., & Sauter, M. (2011). Aerenchyma formation in the rice stem and its promotion by H2O2. *New Phytologist, 190*(2), 369-378. DOI: 10.1111/j.1469-8137.2010.03496.x

Stuart, A. M., Pame, A. R. P., Silva, J. V., Dikitanan, R. C., Rutsaert, P., Malabayabas, A. J. B., Singleton, G. R. (2016). Yield gaps in rice-based farming systems: Insights from local studies and prospects for future analysis. *Field Crops Research, 194*, 43-56. DOI: 10.1016/j.fcr.2016.04.039

Surajit, K. D. D. (1981). Principles and Practices in Rice Production. *International Rice Research Institute, Los Baños, The Philippines*, 642.

Suvi, W. T., Shimelis, H., & Laing, M. (2021). Farmers' perceptions, production constraints and variety preferences of rice in Tanzania. Journal of Crop Improvement, 35(1), 51-68. DOI: 10.1080/15427528.2020.1795771

Swamy, B. P. M., & Kumar, A. (2014). Sustainable rice yield in water-short drought-prone environments: Conventional and molecular approaches. In: Irrigation Systems and Practices in Challenging Environments. Lee, T. S. (Ed). *IntechOpen*, 384.

Tanaka, A., Diagne, M., & Saito, K. (2015). Causes of yield stagnation in irrigated lowland rice systems in the Senegal River Valley: Application of dichotomous decision tree analysis. *Field Crops Research, 176*, 99-107. DOI: 10.1016/j.fcr.2015.02.020

Tanaka, A., Johnson, J.-M., Senthilkumar, K., Akakpo, C., Segda, Z., Yameogo, L. P., . . . Saito, K. (2017). On-farm rice yield and its association with biophysical factors in sub-Saharan Africa. *European Journal of Agronomy, 85*, 1-11. DOI: 10.1016/j.eja.2016.12.010

Tanaka, A., Saito, Kazuki., Azoma, Komla., Kobayashi, Kazuhiko. (2013). Factors affecting variation in farm yields of irrigated lowland rice in southern-central Benin. *European Journal of Agronomy, 44*, 46-53. DOI: 10.1016/j.eja.2012.08.002

Tenywa. M.M., M., J.G.M., Yazidhi, B., Luswata, K.C., Geofrey, G.I. (2016). The effect of Land Use Practices on Pollution Dynamics in the Highlands of Uganda. In: Management and Area-wide Evaluation of Water Conservation Zones in Agricultural Catchments for Biomass Production, Water Quality and Food Security. *International Atomic Energy Agency*, 79-101.

Touré, A., Becker, M., Johnson, D. E., Koné, B., Kossou, D. K., & Kiepe, P. (2009). Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. *Field Crops Research, 114*(2), 304-310. DOI: 10.1016/j.fcr.2009.08.015

Touré, A., Rodenburg, J., Saito, K., Oikeh, S., Futakuchi, K., Gumedzoe, D., & Huat, J. (2011). Cultivar and Weeding Effects on Weeds and Rice Yields in a Degraded Upland Environment of the Coastal Savanna. *Weed Technology, 25*(3), 322-329. DOI: 10.1614/WT-D-10-00172.1

Tsujimoto, Y., Rakotoson, Tovohery., Tanaka, Atsuko., & Saito, Kazuki. (2019). Challenges and opportunities for improving N use efficiency for rice production in sub-Saharan Africa. *Plant Production Science, 22*(4), 413-427. DOI: 10.1080/1343943X.2019.1617638

United Nations, Department of Economic and Social Affairs, Population Division. (2022). *World Population Prospects 2022: Summary of Results. UN DESA/POP/2022/TR/NO. 3*, 52pp.

United Nations, Department of Economic and Social Affairs, Population Division. (2019). *World Population Prospects 2019: Highlights* (ST/ESA/SER.A/423). 46pp.

Urfels, A., McDonald, A. J., van Halsema, G., Struik, P. C., Kumar, P., Malik, R. K., . . . Krupnik, T. J. (2021). Social-ecological analysis of timely rice planting in Eastern India. Agronomy for Sustainable Development, 41(2), 14. DOI: 10.1007/s13593-021-00668-1

van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. Field Crops Research, 143, 4-17. DOI: 10.1016/j.fcr.2012.09.009

van Ittersum, M. K., van Bussel, L. G. J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., . . . Cassman, K. G. (2016). Can sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences, 113*(52), 14964. DOI: 10.1073/pnas.1610359113

van Oort, P. A. J. (2018). Mapping abiotic stresses for rice in Africa: Drought, cold, iron toxicity, salinity and sodicity. *Field Crops Research, 219*, 55-75. DOI: 10.1016/j.fcr.2018.01.016

van Oort, P. A. J., & Zwart, S. J. (2018). Impacts of climate change on rice production in Africa and causes of simulated yield changes. Glob Chang Biol, 24(3), 1029-1045. DOI: 10.1111/gcb.13967

van Oort, P. A. J., Saito, K., Tanaka, A., Amovin-Assagba, E., Van Bussel, L. G. J., van Wart, J., . . . Wopereis, M. C. S. (2015). Assessment of rice self-sufficiency in 2025 in eight African countries. *Global Food Security, 5*, 39-49. DOI: 10.1016/j.gfs.2015.01.002

Vanlauwe, B., Tittonell, P., & Mukalama, J. (2006). Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutrient Cycling in Agroecosystems, 76(2), 171-182. DOI: 10.1007/s10705-005-8314-1

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., . . . Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *SOIL, 1*, 491–508. DOI: 10.5194/soil-1-491-2015

Vollset, S. E., Goren, E., Yuan, C.-W., Cao, J., Smith, A. E., Hsiao, T., . . . Murray, C. J. L. (2020). Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. *The Lancet*, 1285–1306. DOI: 10.1016/S0140-6736(20)30677-2

Waddington, S. R., Li, X., Dixon, J., Hyman, G., & de Vicente, M. C. (2010). Getting the focus right: production constraints for six major food crops in Asian and African farming systems. *Food Security, 2*(1), 27-48. DOI: 10.1007/s12571-010-0053-8

Wang, B. X., Anouschka, R. H., & Ma, C. S. (2022). Impacts of climate change on crop production, pests and pathogens of wheat and rice. Front. Agr. Sci. Eng., 9(1), 4-18. DOI: 10.15302/J-FASE-2021432

Wanyama, I., Ochwoh, V.A., Nankya, E., & Van Asten. P.J.A. . (2015). Optimisation of major nutrients (N, P and K) for lowland rice production in Eastern Uganda. *International Journal of Agronomy and Agricultural Research, 7*(2), 218-227.

Wanyama, J., Ssegane, H., Kisekka, I., Komakech, A. J., Banadda, N., Zziwa, A., . . . Lubwama, K. F. (2017). Irrigation Development in Uganda: Constraints, Lessons Learned, and Future Perspectives. *J. Irrig. Drain Eng., 143*(5), 10.

Witt, C., & Dobermann, A. (2002). A site-specific nutrient management approach for irrigated, lowland rice in Asia. Better Crops Int, 16(1), 20-24.

Wortmann, C. S., Kaizzi, K. C., Maman, N., Cyamweshi, A., Dicko, M., Garba, M., . . . Serme, I. (2019). Diagnosis of crop secondary and micro-nutrient deficiencies in sub-Saharan Africa. *Nutrient Cycling in Agroecosystems, 113*(2), 127-140. DOI: 10.1007/s10705-018-09968-7

Zabel, F., Delzeit, R., Schneider, J. M., Seppelt, R., Mauser, W., & Václavík, T. (2019). Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. *Nature Communications, 10*(1), 2844. DOI: 10.1038/s41467-019-10775-z

Zwart, S. J. (2013). Assessing and improving water productivity of irrigated rice systems in Africa. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa's Rice Promise. *CAB International, Wallingford, UK*, 265-275.

# 2

# CHAPTER 2.

## Micro-nutrients in East African lowlands: Are they needed to intensify rice production?

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**Abstract**

Rice is a staple food and cash crop for smallholder farmers in sub-Saharan Africa; however, yields are very low, with indications that both macro and micro-nutrients may limit rice productivity in East Africa next to the need for good agronomic practices. Diagnostic on-farm experiments were conducted in Uganda and Tanzania between 2015 and 2017 to assess the contribution of macro, secondary and micro-nutrients on lowland rice yield and identify options by which smallholder farmers can increase productivity. All treatments included good agronomic practices combined with: zero fertilisation as a control, NPK fertilisation with and without secondary and micro-nutrients (B, Mn, Zn, Cu, Mg, S), and/or treatments where B, Mn and Zn were omitted one at a time from the NPK + secondary and micro-nutrient treatment. NPK fertilisation significantly ($p<0.05$) increased grain yield under irrigated condition by ca. 32 and 29% during 2015 and 2016, and 24 and 100% during 2016 and 2017 in Tanzania and Uganda, respectively; however, inconsistent effects were observed under rainfed condition. Observed higher yields corresponded mainly to higher panicle number with an additive effect of grains per panicle indicating major effects were at earlier growth stages supporting higher sink size development. Adding secondary and micro-nutrients to NPK enhanced yield significantly ($p<0.05$) under irrigated condition in Tanzania 2015 and 2016 by 7 and 11%, respectively, while varying results were obtained under rainfed condition. In Uganda, no significant ($p>0.22$) effects of secondary and micro-nutrients were observed in both years and growing conditions. This study indicates that the first step to improving lowland rice productivity is proper water management, under otherwise also good crop management in terms of timely transplanting and weeding, and further yield gains can be realised with NPK fertilisation. Secondary and micro-nutrients were effective only when NPK were applied and on the fluvisols of Tanzania, and were not co-limiting yield on the plinthosols of Uganda.

**Keywords:** Good agronomic practices, NPK fertilisation, micro-nutrients, intensification, lowland rice and grain yield.

## 2.1 Introduction

Rice (*Oryza sativa*) is the most rapidly growing food commodity in sub-Saharan Africa (SSA) driven mainly by urbanisation and changing consumer preference (Seck et al., 2013), and plays a vital role in rural household food security and national economies (Nhamo et al., 2014). Despite its importance, smallholder farm yields are very low, and in many countries domestic rice production has not been able to meet the growing demand (Nhamo et al., 2014; Senthilkumar et al., 2020), and the deficit in demand is met through imports. The low yield is attributed to, among other factors, soil-related constraints, sub-optimal production practices, drought, weeds, pests and diseases (Nhamo et al., 2014; Rodenburg et al., 2019; Senthilkumar et al., 2020). Thus, considering the contribution of rice to regional food security and economy, there is need to understand important yield contributing factors to help increase farm yields.



Good agronomic practices considered as integrated crop, soil, water and weed management practices (Senthilkumar et al., 2018) have been shown to improve rice yields when compared to farmers' practice in different agro-ecologies. For instance, Nhamo et al. (2014) reported rice yield gains of 86.7% and 91.6%, respectively, from use of bunds to control water and improved weed management practices compared to farmers' practice in Eastern and Southern Africa. Similarly, Senthilkumar et al. (2018), Rodenburg and Johnson (2009), Touré et al. (2009), and Becker and Johnson (2001) recorded improved grain yields due to good agronomic practices – fine tillage, bunding, timely weeding and fertilisation, and attributed the gains to a lower weed biomass and increased use efficiency of applied fertiliser nutrients. While these studies report direct effects of good agronomic practices with or without fertiliser inputs on productivity, studies further show increase in yields with NPK application over nonapplication.

Studies have reported over 20% and 140% more yield of rice with NP and NPK application, respectively, compared to yields obtained in plots under farmers' practice without fertilisation (Haefele et al., 2001, 2002). Similarly, 68% more grain yield due to NPK application was recorded, compared to unfertilised fields (Wanyama et al., 2015). Furthermore, improvements in grain yield due to NPK application in rice, maize, sorghum and finger millet have been observed, compared to no fertilisation (Kihara et al., 2016; Ndungu-Magiroi et al., 2017; Saito et al., 2019; Tanaka et al., 2013; Wade et al., 1999). Whereas NPK fertilisation improves grain yields, emerging evidence indicates that micro-nutrients can also constrain productivity, and their application in addition to NPK can enhance NPK use efficiency, leading to higher crop yields (Atique-ur et al., 2014; Dicko et al., 2018; Dimkpa and Bindraban, 2016; Khoshgoftarmanesh et al., 2010; Kihara et al., 2016; Ram et al., 2016; Vanlauwe et al., 2015). Studies with maize, rice, wheat, beans and potato indeed show that yields are co-limited by micro-nutrients. For instance, studies where boron (B), manganese (Mn), zinc (Zn), copper (Cu) and sulphur (S) were applied in combination with NPK reported increased yields of rice, maize, wheat, beans, sorghum, finger millet and potato in SSA compared to yields realised with NPK alone (Cyamweshi et al., 2018; Kihara et al., 2016, 2017; Ndungu-Magiroi et al., 2017; Vanlauwe et al., 2015; Wortmann et al., 2019). In East Africa, there are indications that micro-nutrients limit crop production, although previous studies have focused mainly on upland crops. Knowledge of the relevance of micro-nutrients in lowland rice where farmers seem to find low yield gains from NPK fertilisation (Saito et al., 2019) is limited.

The current study assessed the contribution of NPK, and combinations of NPK + secondary and micro-nutrients on lowland rice yield in East Africa. Assessments were made under irrigated and rainfed lowland conditions with otherwise good agronomic practices on two contrasting soil types: fluvisols in the alluvial floodplain of Kilombero, Tanzania, which are brown or grey, sandy loam or clay soils and the lake deposits of granite plinthosols and laterite of Doho and Bugiri, Uganda, which are reddish brown, sandy loam or loam soils (Beck, 1964; Gabiri et al., 2018; Tenywa et al., 2016). We sought to understand whether there are yield gains from NPK fertilisation alone, or whether there is need for addition of micro-nutrients, to realise optimal yield gains from fertilisation in these lowlands. We hypothesised that micro-nutrients are important in limiting rice productivity and their application with NPK under good agronomic practices enhances grain yield under the different soil types.

## 2.2 Material and methods

### 2.2.1. Field trial set up

On-farm experiments were conducted in Uganda and Tanzania under irrigated lowland (IL) and rainfed lowland (RL) conditions for 2 successive years. In Uganda, trials were conducted at the Kibimba rice irrigation scheme (IL) and the Magoola swamp (RL) in Bugiri district (33°45’E and 0°33’N), and in the Doho rice irrigation scheme (IL) in Butaleja district (34°02’E and 0°56’N) in 2016 and 2017. In Tanzania, trials were conducted in the Kilombero valley at Idete - RL (36°30’E and 8°60’S) and in Msufini -

IL (36°54'E and 7°47'S) in 2015 and 2016. The trials were conducted as researcher-managed, in farmers' fields.

In Uganda, an experimental field at the Kibimba rice irrigation scheme, which is a commercial farm, was used during the 2016 trial, while at the Doho rice irrigation scheme a volunteer farmer's field was used. Soil samples from each field at both locations were collected at 0-20 cm depth before planting and analysed for texture and nutrient contents. In 2017, to assess the effect of NPK and micro-nutrient application under RL condition, Magoola swamp was selected to represent RL ecology. Soil samples from four different farmers' fields within Magoola swamp and six fields within the Doho rice irrigation scheme were collected and analysed for texture and nutrient contents. In all cases, laboratory methods used for soil analyses were Kjeldahl for N; Mehlich 3 for K, S, Mg, Ca, Zn, B, Cu, Mn, Fe; sodium bicarbonate test for P; and hydrometer method for soil texture. The fields from which soil samples were obtained were evaluated and a single field was selected from the four and six sampled fields in Magoola and Doho, respectively, to conduct the trials, aiming for low levels of both macro- and micro-nutrients. Except for B which was below critical level (<0.5mg/kg) in all fields sampled, and Cu and N which were below critical levels (<0.1-0.3mg/kg and <0.2%) in some fields (Fairhurst et al., 2007; Senthilkumar et al., 2018), other nutrients, including, P, K, Zn, Mn, Fe, S, Mg and Ca, were above their critical levels for occurrence of deficiency in rice (Supplementary Table S2.1).

In Tanzania, ten farmers' fields were selected under each agro-ecology during both years, and soil samples were collected from each field and analysed using aforementioned laboratory methods, and all fields were used to conduct the trials. In this case, N and B were below critical levels in all the fields in both years and agro-ecologies, P, K, Mn, S, Mg and Ca were below their critical levels in some fields, while Zn, Cu and Fe were above their critical levels in all fields (Supplementary Table S2.2). Soil texture was silty clay loam in Uganda and, sandy clay loam in IL and sandy loam in RL of Tanzania.

For each location and year in Uganda, trials were arranged in a Randomised Complete Block Design, with four replications, except in Magoola swamp which had only three replications. In Tanzania, each farmer's field was treated as a replicate, ten replicates in each site and year. Rice varieties commonly grown within the trial sites were used; K 98 for Doho, Wita 9 for Kibimba, K 5 for Magoola, and SARO5 for Idete and Msufini. Plot sizes were 20 $m^2$ (4 m x 5 m) in Tanzania 2015 and 2016 and Uganda 2016, and 16

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$m^2$ (4 m × 4 m) in Uganda 2017. Grain yield measurements were taken from a central 6 $m^2$ and 4 $m^2$ harvest area in 2016 and 2017, respectively, in the Uganda trials; and from 12 $m^2$, in the Tanzania trials.

Rainfall data (Supplementary Table S2.3) for all trial locations for the trial duration were collected. In Tanzania 2015, rainfall data were collected from a Delta-T WS-GP1 weather stations at Ifakara and Morogoro. In 2016, data were collected from a Delta-T WS-GP1 installed within 10 km radius at each experimental location. In Uganda, rainfall data for Kibimba 2016 and Magoola 2017 were collected from a Davis Vantage Pro2 weather station at Kibimba rice irrigation scheme. While, data for Doho 2016 and 2017 were retrieved from Climate Hazards Group Infrared Precipitation with Stations (CHIRPS-v2) at a spatial resolution of 0.05° (https://www.chc.ucsb.edu/data/chirps) and data processed using ArcGIS 10.6.1.

### 2.2.2 Treatments and management

The treatments evaluated included no fertilisation as a control and only NPK fertilisation in both countries. In the Uganda trials further treatments were NPK + B, Mn, Zn, S soil applied (+MN soil), NPK + B, Mn, Zn, S foliar applied (+MN foliar), NP + B, Mn, Zn, S soil applied (K omission ), NPK + Mn, Zn, S soil applied (B omission), NPK + B, Zn, S soil applied (Mn omission), NPK + B, Mn, S soil applied (Zn omission), and NPK + commercial micro-nutrient blend of Zn, B, Cu soil applied (+MN blend soil, Table 2.1). However, the last treatment was not included in Magoola in 2017 because the field that was suitable to run the trial was not large enough to accommodate all the treatment combinations.

Treatments for the Tanzania trials in 2015 included NPK + B, Zn, Mg, S soil applied (+MN soil); NPK + foliar application of two commercial micro-nutrient blends of: B, Mn, Zn, Cu, Mg, S, Mo (+MN blend YVT foliar), and B, Zn, Mo, Si (+MN blend OSA foliar); and only foliar application of B, Mn, Zn, Cu, Mg, S, Mo blend without application of NPK (NPK omission foliar). In 2016, additional treatments of NPK + B, Zn, Cu, Mg, S soil applied (+MN soil) and B, Zn, Mg, S soil applied without NPK application (NPK omission soil) were added to the 2015 treatments (Table 2.1).

All treatment plots were managed under good agronomic practices. Components of good agronomic practices included fine field tillage; bunding and levelling before transplanting (at all locations in Uganda and Msufini, Tanzania) or sowing (in Idete, Tanzania); timely and line transplanting (21-day old seedlings at spacing of 20 cm x 20 cm for varieties K 98, K 5 and SARO5, and 25 cm x 25 cm for Wita 9) or dibbling 3 – 4 seeds per hill at 20 cm × 20 cm spacing; timely weeding (14 – 21 days after transplanting – DAT or sowing – DAS and, subsequent weeding done when and as necessary) using a hand hoe; and good water management (sufficient water supply to treatment plots by irrigation), except under rainfed conditions in Magoola and Idete.

All nutrients supplied through soil were applied as basal: 14 DAT for Uganda, and 0 – 4 DAT or DAS for Tanzania. The exceptions to this procedure were N and K that were split into three at 50, 25 and 25%, and applied 14 DAT, at panicle initiation and at flowering, respectively, for Uganda. For Tanzania, N was split into 50, 25, and 25%, and applied at 0 – 4 DAT or DAS, at panicle initiation and at flowering, while K was split into 50 and 50%, and applied at 0 – 4 DAT or DAS and at flowering, respectively. Foliar application for Uganda trials was split into three at 40, 30, and 30%, and applied at 28 DAT, at panicle initiation and at flowering, respectively. At each foliar application, 0.5, 0.04, 0.3, 0.1 and 0.03% Zn, B, Mn, S and surfactant (Silwet gold) in the foliar solution, respectively, were used. For the Tanzania trials, the commercial micro-nutrient products Yara Vita Tracel Bz (contained Zn, B, Mn, Cu, Mg, S, Mo) was foliar applied during maximum tillering, and OSA Rice (had Zn, B, Mo, Si) was applied in three equal portions at maximum tillering, panicle initiation and flowering, as recommended by the manufacturers. Foliar solution contained 1.0 and 0.2% of Yara Vita Tracel Bz and OSA Rice, respectively, and only in 2015, 0.02% surfactant (Integra). All foliar applications were done using a Knapsack sprayer either in the early morning, between 7.00 and 9.00 a.m., or late afternoon, after 4 p.m., except in Doho 2017 when foliar application was done between 10.00 and 10.30 a.m. Nutrient sources for N, P, K, Zn, B, Mn and S used were urea, triple super phosphate, muriate of potash, $ZnSO_4.7H_2O$, borax (11.5% B), $MnSO_4.H_2O$ and sulphur dust, respectively.

### 2.2.3. Measurements

In Uganda, within the harvested net plot of 6 or 4 $m^2$, 12-hill and 9-hill samples were systematically selected in 2016 and 2017, respectively, by taking every $4^{th}$ hill within and between rows to determine yield components (number of tillers and panicles per hill, total grains per panicle, filled grains per panicle, 1000-grain weight), total above-ground plant dry matter per hill and harvest index (HI) based on grain weight and total dry matter of sampled hills. Panicles $m^{-2}$ were derived from grain yield expressed in Mg $ha^{-1}$ and, the observed grains per panicle and 1000-grain weight. Total grain yield was determined by harvesting the remaining panicles from the harvest area using a sickle and combining this grain weight with the grain weight of the sub-sampled hills. In Tanzania, yield component data (tillers and panicles $m^{-2}$ in both years; total grains per panicle, filled grains per panicle and 1000-grain weight in 2015) were the average of data collected from all plants in two areas, each 1 $m^2$ directly adjacent to the harvest area in each treatment plot. In 2016, 1000-grain weight and harvest index were quantified from 12 randomly selected hills outside the harvest area. Filled grains per panicle were then calculated from grain yield in Mg $ha^{-1}$ and, the observed panicles $m^{-2}$ and 1000-grain weight. Total grain yield was based on all panicles from the 12 $m^2$ harvest area cut using a sickle.

Sample hills were threshed, and straw and filled and empty grains were separately oven-dried to constant weight at 70°C. Filled and empty grains were separated by first pouring all grains from the sampled hills of a plot in to a beaker with distilled water. After stirring for 10 – 15 seconds, the empty grains still float at the surface, and were separated from the filled grains at the bottom. Total above-ground plant dry matter was calculated as the sum of straw yield and filled and empty grains expressed in Mg $ha^{-1}$. To obtain grain yield, panicles from harvest area were threshed, sun-dried, and the grains were winnowed to remove empty grains. Grain weight was determined using a digital weighing scale (Mini Crane scale model MNCS-M), and moisture content determined using a digital grain moisture meter (SATAKE Moistex Model SS-7). Measurements were done inhouse under room temperature and recorded to 1 and 2 decimal places for moisture content and grain yield, respectively. Rice grain yield adjusted to 14% moisture content for all sites was expressed in Mg $ha^{-1}$.

All data were subjected to analysis of variance (ANOVA) using Genstat ($19^{th}$ edition) at 5% probability. Data for each location and year were separately analysed using a one-way ANOVA with randomised blocks, taking the different replicates in Uganda and farmers' fields for Tanzania as blocks, and fertiliser combinations as treatments. In addition to testing for an overall treatment effect, groups of comparable treatments were compared using orthogonal contrasts. These were used to test for the differences in yields in the unfertilised controls versus the all other fertilised treatments, yields using only NPK versus NPK with secondary and micro-nutrients and as last contrast between different secondary and micro-nutrient treatments. Where overall differences were not significant, no post-hoc tests were conducted as differences are not considered significant. Where the orthogonal contrast analyses showed yields of NPK, and NPK +

secondary and micro-nutrient plots differed significantly, Tukey's post-hoc test was used to separate treatment means that were significantly different from others.

## 2.3. Results

### 2.3.1. Effect of NPK fertilisation under good agronomic practices on rice grain yield

Overall, NPK fertilisation significantly increased grain yields across locations and years under irrigated conditions, compared to yields from good agronomic practices only ($p<0.05$). In contrast, inconsistent effects were observed under rainfed condition. Under irrigated conditions, yields increased in Doho 2016 and 2017 by 23.6 and 100%, respectively, and in Kibimba 2016 by 43.8% due to only NPK application, compared to yields obtained from unfertilised control plot (Tables 2.2 – 2.4). Whereas in Magoola 2017 under rainfed condition with good agronomic practices, yields were low across all treatments due to drought (Table 2.5 and Supplementary Table S2.3) and NPK fertilisation had a small positive effect, with 87.5% yield difference when NPK was applied, compared to yield from control plots. The yield differences between treatments in Doho and Kibimba under irrigated lowland conditions were explained by a significantly higher number of filled grains $m^{-2}$ while 1000-grain weights either did not differ, or had an inverse relation to yield differences in Doho 2016 (Table 2.2), where more filled grains $m^{-2}$ were accompanied by a slightly lower 1000-grain weight. The significantly higher number of filled grains $m^{-2}$ was mainly explained by the number of panicles $m^{-2}$, with only a small role for grain number per panicle in some trials. The latter was generally in the same direction; so, higher panicle number was accompanied by higher number of grains per panicle. In Magoola under rainfed lowland condition, yield differences were explained by a significantly more filled grains $m^{-2}$ and a slightly positive effect of 1000-grain weight. The higher number of filled grains $m^{-2}$ was explained by the additive effect of panicles $m^{-2}$ and grains per panicle that were both not significant (Table 2.5). HI was 40 – 55% under irrigated conditions, and averaged 20% under rainfed lowland condition.

**Table 2.1** Treatments implemented and nutrient rates during the trials in Uganda 2016 and 2017, and Tanzania 2015 and 2016

| Treatment | Nutrient rates (kg ha$^{-1}$) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Uganda** | **2016** | | | | | | | | **2017** | | | | | | | |
| | N | P | K | B | Mn | Zn | Mg | S | N | P | K | B | Mn | Zn | Mg | S |
| No fertilisation (control) | | | | | | | | | | | | | | | | |
| NPK | 80 | 40 | 40 | | | | | | 100 | 50 | 50 | | | | | |
| +MN soil | 80 | 40 | 40 | 2.0 | 20.0 | 5.8 | | 14.7 | 100 | 50 | 50 | 2.0 | 12.5 | 6.3 | | 10.6 |
| +MN foliar | 80 | 40 | 40 | 1.5 | 15.0 | 4.4 | | 11.0 | 100 | 50 | 50 | 1.5 | 9.4 | 4.7 | | 8.0 |
| K omission | 80 | 40 | | 2.0 | 20.0 | 5.8 | | 14.7 | 100 | 50 | | 2.0 | 12.5 | 6.3 | | 10.6 |
| B omission | 80 | 40 | 40 | | 20.0 | 5.8 | | 14.7 | 100 | 50 | 50 | | 12.5 | 6.3 | | 10.6 |
| Mn omission | 80 | 40 | 40 | 2.0 | | 5.8 | | 14.7 | 100 | 50 | 50 | 2.0 | | 6.3 | | 10.6 |
| Zn omission | 80 | 40 | 40 | 2.0 | 20.0 | | | 14.7 | 100 | 50 | 50 | 2.0 | 12.5 | | | 10.6 |
| +MN blend soil[1] | 80 | 40 | 40 | 0.6 | | 1.8 | | | 100 | 50 | 50 | 2.0 | | 6.3 | | |
| **Tanzania** | **2015** | | | | | | | | **2016** | | | | | | | |
| | N | P | K | B | Mn | Zn | Mg | S | N | P | K | B | Mn | Zn | Mg | S |
| No fertilisation (control) | | | | | | | | | | | | | | | | |
| NPK | 80 | 40 | 40 | | | | | | 80 | 40 | 40 | | | | | |
| +MN soil | 80 | 40 | 40 | 2.0 | | 3.0 | 7.5 | 10.0 | 80 | 40 | 40 | 2.0 | | 3.0 | 7.5 | 10.0 |
| +MN blend YVT foliar[2] | 80 | 40 | 40 | 0.2 | 0.004 | 0.2 | 0.2 | 0.2 | 80 | 40 | 40 | 0.2 | 0.004 | 0.2 | 0.2 | 0.2 |
| +MN blend OSA foliar[3] | 80 | 40 | 40 | 0.005 | | 0.02 | | | 80 | 40 | 40 | 0.005 | | 0.02 | | |
| NPK omission foliar[2] | | | | 0.2 | 0.004 | 0.2 | 0.2 | 0.2 | | | | 0.2 | 0.004 | 0.2 | 0.2 | 0.2 |
| +MN soil[4] | | | | | | | | | 80 | 40 | 40 | 0.4 | | 0.6 | 7.5 | 10.0 |
| NPK omission soil | | | | | | | | | | | | 2.0 | | 3.0 | 7.5 | 10.0 |

[1]Commercial micro-nutrient product (Elfert-F) also included 0.3 kg ha$^{-1}$ Cu, [2]Commercial micro-nutrient product (YaraVita Tracel Bz) also included 0.004 kg ha$^{-1}$ of Cu and Mo each, [3]Commercial micro-nutrient product (OSA Rice) also included 0.002 kg ha$^{-1}$ Mo and 0.03 kg ha$^{-1}$ Si, and [4]Cu rate in the NPK + B, Zn, Cu, Mg, S soil applied treatment in 2016 was 0.3 kg ha$^{-1}$. The use and mentioning of any commercial product does not reflect specific preferences of the research team, these were available on the local market.

**Table 2.2** Grain yield and yield components under irrigated lowland conditions for different fertilisation treatments in Doho, Uganda, 2016.

| Treatment | Grain yield (Mg ha$^{-1}$) | Panicles m$^{-2}$ | Filled grains panicle$^{-1}$ | Filled-grains m$^{-2}$ (x10$^3$) | 1000-grain weight (g) |
|---|---|---|---|---|---|
| Control | 5.5 | 254 | 104 | 26.2 | 21.1 |
| NPK | 6.8 | 330 | 101 | 33.1 | 20.6 |
| +MN soil | 6.6 | 323 | 104 | 33.5 | 19.8 |
| +MN blend soil | 6.7 | 310 | 110 | 33.2 | 20.1 |
| K omission | 7.2 | 344 | 109 | 36.5 | 19.6 |
| B omission | 6.2 | 270 | 119 | 31.4 | 19.9 |
| Mn omission | 6.7 | 298 | 111 | 32.9 | 20.3 |
| Zn omission | 7.1 | 343 | 103 | 35.3 | 20.1 |
| +MN foliar | 6.3 | 296 | 113 | 31.5 | 20.1 |
| Mean | 6.6 | 308 | 108 | 32.6 | 20.2 |
| S.e.d. | 0.53 | 38.6 | 10.6 | 2.9 | 0.50 |
| p-value contrast 1[1)] | **0.01** | **0.05** | **0.56** | **<0.01** | **0.01** |
| p-value contrast 2[1)] | **0.78** | **0.53** | **0.28** | **0.86** | **0.10** |

All plots were managed under good agronomic practices, including water management. +MN soil or foliar = NPK+BMnZnS soil or foliar applied; +MN blend soil = NPK+BZnCu soil applied; K, B, Mn and Zn omission was from the NPK+BMnZnS soil applied treatment. Differences between NPK + secondary and micro-nutrient treatments were not significant ($p>0.05$). [1)]Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients.

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**Table 2.3** Grain yield and yield components under irrigated lowland conditions for different fertilisation treatments in Doho, Uganda, 2017.

| Treatment | Grain yield (Mg ha$^{-1}$) | Panicles m$^{-2}$ | Filled grains panicle$^{-1}$ | Filled-grains m$^{-2}$ (x10$^3$) | 1000-grain weight (g) |
|---|---|---|---|---|---|
| Control | 4.6 | 324 | 70 | 21.9 | 20.8 |
| NPK | 9.2 | 635 | 69 | 44.0 | 21.0 |
| +MN soil | 8.2 | 489 | 81 | 39.8 | 20.5 |
| +MN blend soil | 9.5 | 625 | 73 | 45.4 | 20.9 |
| K omission | 9.2 | 611 | 73 | 44.0 | 21.0 |
| B omission | 8.8 | 522 | 82 | 42.3 | 20.8 |
| Mn omission | 9.1 | 623 | 72 | 44.2 | 20.5 |
| Zn omission | 9.7 | 625 | 74 | 46.0 | 21.2 |
| +MN foliar[1)] | 4.0 | 556 | 35 | 19.4 | 20.5 |
| Mean | 8.0 | 557 | 70 | 38.5 | 20.8 |
| S.e.d. | 0.44 | 49.5 | 4.9 | 2.3 | 0.33 |
| p-value contrast 1[2)] | **<0.001** | **<0.001** | **0.17** | **<0.001** | **0.97** |
| p-value contrast 2[2)] | **0.65** | **0.18** | **0.10** | **0.85** | **0.42** |

All plots were managed under good agronomic practices, including water management. +MN soil or foliar = NPK+BMnZnS soil or foliar applied; +MN blend soil = NPK+BZnCu soil applied; K, B, Mn and Zn omission was from the NPK+BMnZnS soil applied treatment. Differences between NPK + secondary and micro-nutrient treatments were significant ($p<0.05$). [1)] This Foliar treatment was not included in the treatment comparisons as errors were made in timing of the application. [2)] Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients.

**Table 2.4** Grain yield and yield components under irrigated lowland conditions for different fertilisation treatments in Kibimba, Bugiri, Uganda, 2016.

| **Treatment** | **Grain yield ($Mg\ ha^{-1}$)** | **Panicles $m^{-2}$** | **Filled grains $panicle^{-1}$** | **Filled-grains $m^{-2}$ ($x10^3$)** | **1000-grain weight (g)** |
|---|---|---|---|---|---|
| Control | 4.8 | 188 | 120 | 22.8 | 21.1 |
| NPK | 6.9 | 240 | 129 | 31.2 | 22.1 |
| +MN soil | 7.0 | 286 | 114 | 32.6 | 21.4 |
| +MN blend soil | 6.8 | 288 | 115 | 32.9 | 20.6 |
| K omission | 5.8 | 244 | 113 | 26.8 | 21.6 |
| B omission | 7.5 | 317 | 113 | 35.3 | 21.2 |
| Mn omission | 6.1 | 224 | 125 | 28.2 | 21.8 |
| Zn omission | 8.0 | 341 | 109 | 36.9 | 21.7 |
| +MN foliar | 6.9 | 270 | 118 | 32.0 | 21.4 |
| Mean | 6.6 | 266 | 117 | 31.0 | 21.4 |
| S.e.d. | 0.82 | 38.3 | 8.3 | 4.0 | 0.52 |
| p-value contrast 1[1)] | **<0.01** | **0.01** | **0.59** | **<0.01** | **0.35** |
| p-value contrast 2[1)] | **0.94** | **0.17** | **0.03** | **0.76** | **0.07** |

All plots were managed under good agronomic practices, including water management. +MN soil or foliar = NPK+BMnZnS soil or foliar applied; +MN blend soil = NPK+BZnCu soil applied; K, B, Mn and Zn omission was from the NPK+BMnZnS soil applied treatment. Differences between NPK + secondary and micro-nutrient treatments were significant ($p<0.05$).
[1)]Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients.

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**Table 2.5** Grain yield and yield components under rainfed lowland conditions for different fertilisation treatments in Magoola swamp, Bugiri, Uganda, 2017.

| Treatment | Grain yield (Mg $ha^{-1}$) | Panicles $m^{-2}$ | Filled grains $panicle^{-1}$ | Filled-grains $m^{-2}$ (x$10^3$) | 1000-grain weight (g) |
|---|---|---|---|---|---|
| Control | 0.8 | 198 | 19 | 4.0 | 20.5 |
| NPK | 1.5 | 361 | 19 | 6.9 | 21.5 |
| +MN soil | 1.2 | 270 | 22 | 5.8 | 21.5 |
| +MN blend soil | - | - | - | - | - |
| K omission | 2.1 | 628 | 15 | 9.9 | 21.5 |
| B omission | 2.2 | 396 | 27 | 10.3 | 21.5 |
| Mn omission | 2.3 | 320 | 31 | 10.3 | 22.0 |
| Zn omission | 2.2 | 345 | 32 | 10.3 | 21.0 |
| +MN foliar[1)] | 1.0 | 453 | 13 | 4.6 | 20.5 |
| Mean | 1.7 | 371 | 22 | 7.8 | 21.3 |
| S.e.d. | 0.52 | 133.7 | 4.8 | 2.3 | 0.66 |
| p-value contrast 1[2)] | **0.01** | **0.09** | **0.16** | **0.01** | **0.07** |
| p-value contrast 2[2)] | **0.22** | **0.77** | **0.13** | **0.20** | **0.95** |

All plots were managed under good agronomic practices other than water management. +MN soil or foliar = NPK+BMnZnS soil or foliar applied; +MN blend soil = NPK+BZnCu soil applied; K, B, Mn and Zn omission was from +MN soil applied treatment. Differences between NPK + secondary and micro-nutrient treatments were not significant ($p>0.05$). [1)]Foliar treatment was not included in treatment comparisons due to the very low yields attained because of drought that resulted to leaf scorching. [2)]Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients.

In Tanzania in the irrigated lowland at Msufini, yield increased by 31.6 and 28.9% due to NPK application during 2015 and 2016, respectively, compared to yields in the control plot (Tables 2.6 and 2.7). In the rainfed lowland in Idete 2015, with ample rain, 84.6% more yield was recorded due to NPK application (Table 2.6). In 2016, however, rainfall was too low; as such, the 51.2% yield difference with NPK application, compared to the control plot, was not significantly different (Table 2.8). Under irrigated conditions in Msufini, yield differences among treatments were due to a significantly higher number of filled grains $m^{-2}$ and, only in 2016 grains per panicle while 1000-grain weights did not differ. The higher number of filled grains $m^{-2}$ was for the most part explained by the number of panicles $m^{-2}$ and to a lower extent by grain number per panicle in 2015. Under rainfed condition with adequate rain in Idete, differences in yield between treatments were due to higher numbers of grains per panicle, filled grains $m^{-2}$ and 1000-grain weights. The higher number of grains $m^{-2}$ was due to higher number of panicles $m^{-2}$ and more grains per panicle. HI was 48 – 60% under irrigated conditions, and averaged 34% in the rainfed lowland condition.



### 2.3.2. Contributions of secondary and micro-nutrient fertilisation to rice yield gains

Yield gains from secondary and micro-nutrient addition to NPK was significant ($p<0.05$) across years for irrigated lowland in Msufini, Tanzania, and under sufficient rain in 2015 in rainfed lowlands in Idete, Tanzania. However, the yield gains were not that large (Tables 2.6 and 2.7). In the rainfed lowlands in Idete under limited water supply in 2016, no significant difference were observed. In general, yield gains from secondary and micro-nutrient addition to NPK were lower than gains from only NPK application (compared to the unfertilised control). In none of the Ugandan sites did addition of secondary and micro-nutrients to NPK improve grain yield ($p>0.22$), compared to only applying NPK.

In the irrigated lowland in Msufini, yield gains from secondary and micro-nutrients averaged 7.0 and 11.3% in 2015 and 2016, respectively, compared to yield from only NPK fertilisation (Tables 2.6 and 2.7). In the rainfed lowland in Idete 2015 with ample rain, yield gain from secondary and micro-nutrients averaged 26.4%, compared to yield from only NPK fertilisation (Table 2.6). Applying secondary and micro-nutrients only without NPK, either through soil or foliar, resulted to yields that were similar to unfertilised control plots, and lower compared to only NPK fertilisation. This is an indication that NPK are major yield limiting nutrients, rather than secondary or micro-nutrients, in these soils. Soil application of secondary and micro-nutrients along with NPK was more effective, compared to foliar application of secondary and micro-nutrients with NPK. The observed yield differences between treatments under irrigated conditions were explained by a significantly higher number of filled grains $m^{-2}$ and in 2016 also grains per panicle, whereas 1000-grain weight did not vary. The significantly higher number of filled grains $m^{-2}$ was due to the additive effect of panicle number and grains per panicle. Under rainfed condition with adequate rain, the observed yield differences were due to significantly higher grain number per panicle, filled grains $m^{-2}$, and 1000-grain weight.

**Table 2.6** Grain yield and yield components under irrigated and rainfed lowland conditions, for different fertiliser treatments in Msufini and Idete, Kilombero valley, Tanzania, 2015.

| | Msufini - Irrigated Lowland | | | | | Idete - Rainfed Lowland | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Treatment** | **Grain yield (Mg ha$^{-1}$)** | **Panicles m$^{-2}$** | **Filled grains panicle$^{-1}$** | **Filled grains m$^{-2}$ (x10$^{3}$)** | **1000-grain weight (g)** | **Grain yield (Mg ha$^{-1}$)** | **Panicles m$^{-2}$** | **Filled grains panicle$^{-1}$** | **Filled grains m$^{-2}$ (x10$^{3}$)** | **1000-grain weight (g)** |
| Control | 3.1$^{a}$ | 160$^{a}$ | 66$^{a}$ | 10.6$^{a}$ | 29.2$^{a}$ | 2.7$^{a}$ | 176$^{a}$ | 54$^{a}$ | 9.1$^{a}$ | 29.2$^{a}$ |
| NPK | 4.1$^{b}$ | 216$^{b}$ | 65$^{a}$ | 13.8$^{b}$ | 29.4$^{a}$ | 5.0$^{b}$ | 233$^{b}$ | 70$^{ab}$ | 16.4$^{b}$ | 30.2$^{ab}$ |
| +MN soil | 4.6$^{c}$ | 219$^{b}$ | 71$^{a}$ | 15.5$^{c}$ | 29.7$^{a}$ | 6.8$^{c}$ | 242$^{b}$ | 90$^{c}$ | 21.2$^{c}$ | 32.2$^{c}$ |
| +MN blend YVT foliar | 4.2$^{bc}$ | 224$^{b}$ | 67$^{a}$ | 14.4$^{bc}$ | 29.4$^{a}$ | 5.9$^{bc}$ | 251$^{b}$ | 75$^{bc}$ | 18.9$^{bc}$ | 31.2$^{bc}$ |
| +MN blend OSA foliar | 4.2$^{bc}$ | 212$^{b}$ | 69$^{a}$ | 14.2$^{bc}$ | 29.5$^{a}$ | 6.0$^{bc}$ | 232$^{b}$ | 88$^{bc}$ | 19.7$^{bc}$ | 30.6$^{ab}$ |
| NPK omission foliar | 3.3$^{a}$ | 170$^{a}$ | 66$^{a}$ | 11.2$^{a}$ | 29.3$^{a}$ | 3.0$^{a}$ | 176$^{a}$ | 56$^{a}$ | 10.0$^{a}$ | 29.7$^{a}$ |
| Mean | 3.9 | 200 | 67 | 13.3 | 29.4 | 4.9 | 218 | 72 | 15.9 | 30.5 |
| S.e.d. | 0.15 | 11.42 | 3.26 | 0.54 | 0.24 | 0.38 | 13.6 | 6.0 | 1.17 | 0.457 |
| p-value contrast 1[1)] | **<0.001** | **<0.001** | **0.56** | **<0.001** | **0.14** | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| p-value contrast 2[1)] | **0.03** | **0.77** | **0.09** | **0.05** | **0.36** | **<0.001** | **0.43** | **0.01** | **<0.001** | **0.004** |

All plots were managed under good agronomic practices, including water management in Msufini. Idete received adequate rain during the entire crop growth period. +MN soil = NPK+BZnMgS soil applied; +MN blend YVT foliar = NPK+BZnMnCuMgSMo foliar applied; +MN blend OSA foliar = NPK+BZnMoSi foliar applied; NPK omission foliar = BZnMnCuMgSMo foliar applied. [1)]Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients. Values followed by the same letters are not statistically different.

2

**Table 2.7** Grain yield and yield components under irrigated lowland conditions for different fertiliser treatments in Msufini, Kilombero valley, Tanzania, 2016.

| Treatment | Grain yield (Mg ha$^{-1}$) | Panicles m$^{-2}$ | Filled grains panicle$^{-1}$ | Filled grains m$^{-2}$ (x10$^{3}$) | 1000-grain weight (g) |
|---|---|---|---|---|---|
| Control | 3.7$^{a}$ | 177$^{abc}$ | 65$^{a}$ | 11.6$^{a}$ | 32.3$^{a}$ |
| NPK | 4.8$^{b}$ | 195$^{cd}$ | 76$^{bcd}$ | 14.8$^{b}$ | 32.6$^{a}$ |
| +MN soil[1)] | 5.4$^{c}$ | 201$^{d}$ | 82$^{cd}$ | 16.5$^{b}$ | 32.9$^{a}$ |
| +MN soil[2)] | 5.4$^{c}$ | 201$^{d}$ | 81$^{cd}$ | 16.5$^{b}$ | 32.8$^{a}$ |
| NPK omission soil | 4.0$^{a}$ | 172$^{a}$ | 72$^{abc}$ | 12.4$^{a}$ | 32.6$^{a}$ |
| +MN blend YVT foliar | 5.3$^{bc}$ | 199$^{d}$ | 81$^{cd}$ | 16.1$^{b}$ | 32.7$^{a}$ |
| +MN blend OSA foliar | 5.3$^{bc}$ | 194$^{bcd}$ | 85$^{d}$ | 16.5$^{b}$ | 32.6$^{a}$ |
| NPK omission foliar | 4.0$^{a}$ | 176$^{ab}$ | 70$^{ab}$ | 12.4$^{a}$ | 32.4$^{a}$ |
| Mean | 4.8 | 189 | 77 | 14.6 | 32.6 |
| S.e.d. | 0.18 | 5.9 | 3.4 | 0.58 | 0.36 |
| p-value contrast 1[3)] | **<0.001** | **0.002** | **<0.001** | **<0.001** | **0.20** |
| p-value contrast 2[3)] | **<0.001** | **0.40** | **0.02** | **<0.001** | **0.70** |

All plots were managed under good agronomic practices, including water management. [1)]NPK+BZnMgS; [2)]NPK+BZnCuMgS; NPK omission soil = ZnBMgS soil applied; +MN blend YVT foliar = NPK+BZnMnCuMgSMo foliar applied; +MN blend OSA foliar = NPK+BZnMoSi foliar applied; NPK omission foliar = BZnMnCuMgSMo foliar applied. [3)]Contrast 1: Control vs fertilisation, and contrast 2: NPK only vs NPK + secondary and micro-nutrients. Values followed by the same letters are not statistically different.

**Table 2.8** Grain yield and yield components under rainfed lowland conditions for different fertiliser treatments in Idete, Kilombero valley, Tanzania, 2016.

| Treatment | Grain yield (Mg ha$^{-1}$) | Panicles m$^{-2}$ | Filled grains panicle$^{-1}$ | Filled grains m$^{-2}$ (x10$^{3}$) | 1000-grain weight (g) |
|---|---|---|---|---|---|
| Control | 1.2 | 122 | 38 | 4.5 | 27.1 |
| NPK | 1.8 | 168 | 36 | 6.3 | 28.2 |
| +MN soil[1)] | 2.1 | 186 | 37 | 7.2 | 27.9 |
| +MN soil[2)] | 1.6 | 131 | 39 | 5.6 | 27.1 |
| NPK omission soil | 1.0 | 116 | 32 | 3.6 | 27.3 |
| +MN blend YVT foliar | 1.6 | 171 | 31 | 5.7 | 27.0 |
| +MN blend OSA foliar | 1.8 | 155 | 38 | 6.1 | 27.7 |
| NPK omission foliar | 1.1 | 122 | 35 | 4.2 | 27.0 |
| Mean | 1.5 | 146 | 36 | 5.4 | 27.4 |
| S.e.d. | 0.36 | 17.9 | 5.5 | 1.03 | 0.68 |
| p-value contrast 1[3)] | **0.20** | **0.04** | **0.56** | **0.22** | **0.54** |
| p-value contrast 2[3)] | **0.78** | **0.63** | **0.92** | **0.76** | **0.18** |

All plots were managed under good agronomic practices other than water management. [1)] NPK+BZnMgS; [2)] NPK+BZnCuMgS; NPK omission soil = ZnBMgS soil applied; +MN blend YVT foliar = NPK+BZnMnCuMgSMo foliar applied; +MN blend OSA foliar = NPK+BZnMoSi foliar applied; NPK omission foliar = BZnMnCuMgSMo foliar applied. [3)] Contrast 1: Control vs fertilisation, and contrast 2: NPK only vs NPK + secondary and micro-nutrients.

## 2.4 Discussion

In this study, substantial yield gains were observed with NPK fertilisation under good water and crop management, however, NPK effect was minimal under poor water management, despite the otherwise good crop management practices. The yield gains observed could be attributed to improvement mainly in the number of panicles per unit area, with some cases a limited additional positive effect of more filled grains per panicle resulting in higher numbers of filled grains per unit area in fertilised plots, compared to unfertilised control plots. This indicates that NPK fertilisation made the vegetative and early reproductive crop stages more effective, resulting in the production of more reproductive organs and filled grains per unit area. The additional gain of applying NPK under good agronomic practices was significantly bigger when water was sufficient, either in terms of adequate rain or through irrigation. Only minimal effects were observed where water control was poor and crops suffered from drought. This was the case under rainfed conditions in Magoola 2017 and Idete in 2016, where yields were low due to poor grain filling, and the resultant harvest indices were lower than those observed in similar treatments under adequate water supply. The minimal effect of fertiliser application observed in this study due to drought relates with previous studies where limited fertilisation effect and low rice yields have been reported as a result of drought at panicle initiation, flowering or grain filling stage (Banayo et al., 2020; Castillo et al., 2006; Yang et al. 2019). Drought during our study occurred from panicle initiation to grain filling stage in Magoola 2017, and at vegetative, panicle initiation and grain-filling stage in Idete 2016 (Supplementary Table S2.3). The limited fertiliser effect due to drought has been associated with reduced nutrient availability, spikelet sterility and poor grain filling (Cai et al., 2006; Fukai et al., 1999; Haefele et al., 2016). This implies that for fertilisation under good agronomic practices to be effective in improving rice productivity, any problem with water supply, especially in rainfed lowlands, should first be resolved. Otherwise, both fertiliser application and good agronomic practices do not bring about a yield increase. This calls for support to farmers by regional governments to facilitate area specific feasible solutions to the water problem in rainfed lowlands, if smallholder farmers are to benefit from NPK fertilisation under good agronomic practices and, hence, sustainably improve rice productivity in East Africa (Nhamo et al., 2014; Raes et al., 2007; Touré et al., 2009).

In addition to this more often observed positive effect of applying macronutrients, significant and consistent yield gains from addition of secondary and micro-nutrients to NPK application were observed on the fluvisols in Tanzania under good water and crop management. However, the additional overall yield gains from secondary and micro-nutrients were lower than the gains made with NPK application, compared to not applying any fertilisers. The observed yield gains due to secondary and micro-nutrients applied with NPK could be attributed mainly to enhanced grain filling, resulting in higher numbers of filled grains per panicle, and an additional small effect on panicle number that jointly resulted in higher numbers of filled grains $m^{-2}$ in the secondary and micro-nutrient treated plots. Secondary and micro-nutrient effect on enhancing grain yield was thus during later crop stage at grain development and early filling, the lack of any consistent effect on grain weights implies that during late grain filling limited gains were made. It is plausible that the rice plants accumulated more secondary and micro-nutrients later in the vegetative growth stage and proximal to the onset of reproductive development, than at earlier crop stage, as observed in upland rice by Crusciol et al. (2016). Notably, the time-dependent enhanced secondary or micro-nutrient uptake could have also corresponded with enhanced N uptake, resulting in yield increase, as observed in some pot studies by Dimkpa et al. (2017).

Soil application of secondary and micro-nutrients with NPK was more effective than foliar application. This may be due to nutrient uptake through roots being easier in rice rather than through leaves. However, studies have shown contrasting effects on crop yield between foliar and soil application in different crops including rice, with some studies reporting improved grain yield with soil application, combined soil + foliar application or no difference in yield effect of the application methods (Dimkpa et al., 2017; Imran & Rehim, 2017; Khan et al., 2016; Phattarakul et al., 2012; Prakash et al., 2014; Rehman et., 2016; Saha et al., 2017; Sreedhu et al., 2015; Yin et al., 2016; Zhang et al., 2012; Zou et al., 2012). In fact the observed effectiveness of soil application of secondary and micro-nutrients with NPK presents a good opportunity for farmers in East Africa to use micro-nutrients alongside NPK fertilisation as soil application is more convenient and commonly used by farmers, and may result in positive residual effects on crop yield (Kihara et al., 2020; Nadeem & Farooq, 2019). As observed also in our 2017 trial in Doho, Uganda, a single wrongly timed foliar application may result in severe yield losses (Table 2.3). Applying secondary and micro-nutrients only either through soil or foliar without NPK resulted in lower yields, similar to unfertilised control plot. The lack of yield gain from sole application of secondary and micro-nutrients clearly shows that there are no major severe deficiencies of secondary or micro-nutrients in the studied lowlands and that NPK are the most yield limiting nutrients in these systems. This result suggests that farmers can safely use NPK fertilisation under good agronomic practices to increase yields and, when options to improve soil micro-nutrient levels become available and economical, these nutrients could further but marginally increase the efficacy of NPK application.



This study also clearly demonstrated no significant yield gains from micro-nutrient fertilisation in the lowland plinthosols and laterite soils of Uganda. This could be attributable to the fact that the soils currently contain sufficient bio-available amounts of these nutrients. Even while B was sometimes below critical values according to soil analyses (supplementary materials, Table S2.1), we observed no clear effect so no direct reasons for its application. Continued monitoring of micro-nutrient effects in these major lowland rice production areas would seem relevant still to provide an early indication of when micro-nutrients may become a real co-limitation due to micro-nutrient mining. Especially if more effort is made of making macro-nutrient fertilisers available to farmers and as farmers continue to cultivate these soils with only rice without any micro-nutrient replenishment. Most emphasis should go into B, but probably also Cu. Although we did not test Cu rigorously given estimated levels in experimental fields, we did see indications from soil analyses of fields not included in the experiment because of size limitations that it might be locally near critical values. It does thus seem relevant to include at least B and Cu in monitoring of potential emerging micro-nutrient co-limitations. The observed difference in response to secondary and micro-nutrient application in the fluvisols of Tanzania, and the plinthosols and laterite of Uganda could be attributed to difference in parent materials and geological processes from which these soils have been formed (Gabiri et al., 2018; Leemhuis et al., 2017; Tenywa et al., 2016), and cropping intensities the soils have been subjected to, the past decades, resulting to variation in soil nutrient contents.

In Tanzania, we did not have the omission of micro-nutrients from treatment combinations to provide an indication of which micro-nutrients were most yield limiting. Such omission analyses may provide further more targeted insights of relevant micro-nutrients to apply. However, soil analyses showed that B was below critical level in all the fields in both years and agro-ecologies. Boron may therefore be important to look into as it has elsewhere been shown to affect reproductive success (Atique-ur et al., 2015), and indeed we observed more filled grains that resulted to higher yields in the secondary and micro-nutrient treated plots compared to only NPK plots (Tables 2.6 and 2.7). Boron plays an essential role during rice reproductive stage, related to panicle fertility, and its deficiency is reported to result in panicle sterility due to poor development of anthers and pollen, and failure of pollen germination (Atique-ur et al., 2015). Application of B to these soils may, therefore, be essential to avert such adverse effects on rice productivity. A study by Atique-ur et al. (2014) in soils where soil B levels ranged between 0.5 – 0.6 mg/kg reported rice yield gains of up to 24% with soil B application at 1 kg B $ha^{-1}$, compared to zero B fertilisation. In our study, yield gains of up to 13 and 38%, respectively, in irrigated and rainfed lowland were observed from combination of secondary and micro-nutrients that included B and applied together with NPK through the soil, compared to only NPK application. While also nutritional quality of rice, especially in terms of grain Zn concentration, could be affected by micro-nutrient application (Cakmak et al., 2010; Imran & Rehim, 2017; Joy et al., 2015; Phattarakul et al., 2012; Ram et al., 2016; Wang et al., 2012; Yin et al., 2016; Zhang et al., 2012), the current analysis and recommendations are based on the fact that nutritional quality of rice does not affect the price farmers get for their produce. In this paper we have not made a full economic analysis but any application of micro-nutrients adds to production costs and thus has to affect yield quantity to be of interest for farmers.

## 2.5 Conclusion

This study has shown large yield gains with NPK fertilisation under good water and crop management, but with minimal yield gains under poor water management, even though good agronomic practices were followed. This indicates that for smallholder farmers to improve lowland rice productivity under rainfed condition, water is the first production input that needs to be in adequate supply during crop growth, and further yield gains can be realised with NPK fertilisation under good agronomic practices. Micro-nutrients were only effective when applied with NPK as seen in the fluvisols of Tanzania, but were not co-limiting grain yield in the plinthosols and laterite of Uganda and therefore not yet to be considered in this agro-ecology of Uganda. This indicates that NPK are the major limitation to yield, though their effect could be marginally improved by micro-nutrients. We conclude that boosting rice productivity in East Africa would require resolving the water problem for rainfed lowland farmers, following good agronomic practices, and applying NPK. There were no acute problems arising from micro-nutrients omission in our study areas, and therefore, there is need to first focus on attaining full potential for grain yield enhancement from NPK application rather than micro-nutrients. However, in some areas of the region it may be worthwhile to monitor the effects of micro-nutrient application to timely alert on the need for redressing emerging limitations.



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## References

Atique-ur-Rehman., Farooq, M., Nawaz, A., & Ahmad, R. (2014). Influence of boron nutrition on the rice productivity, kernel quality and biofortification in different production systems. Field Crops Research, 169, 123-131. DOI: 10.1016/j.fcr.2014.09.010

Atique-ur-Rehman., Farooq, M., Nawaz, A., Rehman, A., & Iqbal, S. (2015). Soil Application of Boron Improves the Tillering, Leaf Elongation, Panicle Fertility, Yield and its Grain Enrichment in Fine-Grain Aromatic Rice. Journal of Plant Nutrition, 38(3), 338-354. DOI: 10.1080/01904167.2014.963120

Banayo, N. P. M., Rahon, R. E., Sta. Cruz, P., & Kato, Y. (2020). Fertilizer responsiveness of high-yielding drought-tolerant rice in rainfed lowlands. Plant Production Science, 1-8. DOI: 10.1080/1343943X.2020.1847668

Beck, A. D. (1964). The Kilombero valley of south-central Tanganyika. East Afr. Geogr. Rev., 2, 37–43

Becker, M., & Johnson, D. E. (2001). Improved water control and crop management effects on lowland rice productivity in West Africa. Nutrient Cycling in Agroecosystems, 59(2), 119-127. DOI: 10.1023/A:1017585328904

Cai, Y., Wang, W., Zhu, Z., Zhang, Z., Lang, Y., & Zhu, Q. (2006). Effects of water stress during grain-filling period on rice grain yield and its quality under different nitrogen levels. Ying Yong Sheng Tai Xue Bao, 17(7), 1201-1206

Cakmak, I., Kalayci, M., Kaya, Y., Torun, A. A., Aydin, N., Wang, Y., & Horst, W. J. (2010). Biofortification and Localization of Zinc in Wheat Grain. Journal of Agricultural and Food Chemistry, 58(16), 9092-9102. DOI: 10.1021/jf101197h

Castillo, E. G., Tuong, T. P., Singh, U., Inubushi, K., & Padilla, J. (2006). Drought response of dry-seeded rice to water stress timing and N-fertilizer rates and sources. Soil Science and Plant Nutrition, 52(4), 496-508. DOI: 10.1111/j.1747-0765.2006.00064.x

Crusciol, C. A. C., Carmeis Filho, A. C. A., Fernandes, A. M., & Alvarez, R. C. F. (2016). Micronutrient and Silicon Uptake and Removal by Upland Rice Cultivars with Different Plant Architecture. Rev Bras Cienc Solo. 40, 1-16. DOI: 10.1590/18069657rbcs20150116

Cyamweshi, A. R., Nabahungu, L. N., Senkoro, C. J., Kibunja, C., Mukuralinda, A., Kaizzi, K. C., & Wortmann, C. S. (2018). Wheat nutrient response functions for the East Africa highlands. Nutrient Cycling in Agroecosystems, 111(1), 21-32. DOI: 10.1007/s10705-018-9912-z

Dicko, M. K., Traoré, L., Kouyaté, Z., Koné, M., Sidibé, B., Kamissoko, N., Wortmann, S. C., Dioni, L., & Diakité, C. H. (2018). Response of Rice, Maize and Millet to Fertilizers in Mali. In: Bationo A., Ngaradoum D., Youl S., Lompo F., Fening J. (eds) Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems. Springer, 139-155. DOI: 10.1007/978-3-319-58789-9_8

Dimkpa, C. O., & Bindraban, P. S. (2016). Fortification of micronutrients for efficient agronomic production: a review. Agronomy for Sustainable Development, 36(1), 7. DOI: 10.1007/s13593-015-0346-6.

Dimkpa, C. O., Bindraban, P., Fugice, J., Agyin-Birikorang, S., Singh, U. & Hellums, D. (2017). Composite micronutrient nanoparticles and salts decrease drought stress in soybean. Agronomy for Sustainable Development 37, 5. DOI: 10.1007/s13593-016-0412-8

Fairhurst, T. H., Witt, C., Buresh, R.J., & Dobermann, A. (2007). Rice: A Practical Guide to Nutrient Management (2nd edition). International Rice Research Institute, Los Baños, 146.

Fukai, S., Inthapanya, P., Blamey, F. P. C., & Khunthasuvon, S. (1999). Genotypic variation in rice grown in low fertile soils and drought-prone, rainfed lowland environments. Field Crops Research, 64(1), 121-130. DOI: 10.1016/S0378-4290(99)00055-6

Gabiri, G., Burghof, S., Diekkrüger, B., Leemhuis, C., Steinbach, S., & Näschen, K. (2018). Modeling spatial soilwater dynamics in a tropical floodplain, East Africa. Water (Switzerland), 10(2). DOI: 10.3390/w10020191

Haefele, S. M., Wopereis, M. C. S., Donovan, C., & Maubuisson, J. (2001). Improving the productivity and profitability of irrigated rice production in Mauritania. European Journal of Agronomy, 14(3), 181-196. DOI: 10.1016/S1161-0301(00)00094-0

Haefele, S. M., Wopereis, M. C. S., & Wiechmann, H. (2002). Long-term fertility experiments for irrigated rice in the West African Sahel: agronomic results. Field Crops Research, 78(2), 119-131. DOI: 10.1016/S0378-4290(02)00117-X

Haefele, S. M., Kato, Y., & Singh, S. (2016). Climate ready rice: Augmenting drought tolerance with best management practices. Field Crops Research, 190, 60-69. DOI: 10.1016/j.fcr.2016.02.001

Imran, M., & Rehim, A. (2017). Zinc fertilization approaches for agronomic biofortification and estimated human bioavailability of zinc in maize grain.

Archives of Agronomy and Soil Science, 63(1), 106-116. DOI: 10.1080/03650340.2016.1185660

Joy, E. J. M., Stein, A. J., Young, S. D., Ander, E. L., Watts, M. J., & Broadley, M. R. (2015). Zinc-enriched fertilisers as a potential public health intervention in Africa. Plant and Soil, 389(1), 1-24. DOI: 10.1007/s11104-015-2430-8

Khan, S., Rehman, H. u., Wahid, M. A., Saleem, M. F., Akhtar Cheema, M., Basra, S. M. A., & Nadeem, M. (2016). Boron fertilization improves seed yield and harvest index of Camelina sativa L. by affecting source-sink. Journal of Plant Nutrition, 39(12), 1681-1687. DOI: 10.1080/01904167.2016.1161787

Khoshgoftarmanesh, A. H., Schulin, R., Chaney, R. L., Daneshbakhsh, B., & Afyuni, M. (2010). Micronutrient-efficient genotypes for crop yield and nutritional quality in sustainable agriculture. A review. Agronomy for Sustainable Development, 30(1), 83-107. DOI: 10.1051/agro/2009017

Kihara, J., Bolo, P., Kinyua, M., Rurinda, J., & Piikki, K. (2020). Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops. Environmental Geochemistry and Health. DOI: 10.1007/s10653-019-00499-w

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., & Huising, J. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agriculture, Ecosystems & Environment, 229(Supplement C), 1-12. DOI: 10.1016/j.agee.2016.05.012

Kihara, J., Sileshi, G. W., Nziguheba, G., Kinyua, M., Zingore, S., & Sommer, R. (2017). Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. Agronomy for Sustainable Development, 37(4), 25. DOI: 10.1007/s13593-017-0431-0

Leemhuis, C., Thonfeld, F., Näschen, K., Steinbach, S., Muro, J., Strauch, A., & Diekkrüger, B. (2017). Sustainability in the food-water-ecosystem nexus: The role of land use and land cover change for water resources and ecosystems in the Kilombero Wetland, Tanzania. Sustainability (Switzerland), 9(9). DOI: 10.3390/su9091513

Nadeem, F., & Farooq, M. (2019). Application of Micronutrients in Rice-Wheat Cropping System of South Asia. Rice Science, 26(6), 356-371. DOI: 10.1016/j.rsci.2019.02.002

Ndungu-Magiroi, K. W., Kasozi, A., Kaizzi, K. C., Mwangi, T., Koech, M., Kibunja, C. N., & Wortmann, C. S. (2017). Finger millet response to nitrogen, phosphorus and potassium in Kenya and Uganda. Nutrient Cycling in Agroecosystems, 108(3), 297-308. DOI: 10.1007/s10705-017-9857-7

Nhamo, N., Rodenburg, J., Zenna, N., Makombe, G., & Luzi-Kihupi, A. (2014). Narrowing the rice yield gap in East and Southern Africa: Using and adapting existing technologies. Agricultural Systems, 131, 45-55. DOI: 10.1016/j.agsy.2014.08.003

Phattarakul, N., Rerkasem, B., Li, L. J., Wu, L. H., Zou, C. Q., Ram, H., . . . Cakmak, I. (2012). Biofortification of rice grain with zinc through zinc fertilization in different countries. Plant and Soil, 361(1), 131-141. DOI: 10.1007/s11104-012-1211-x

Prakash, C. S., Manoj, B., Satya, P. P., & Tyagi, A. K. (2014). Effect of zinc application methods on apparent utilization efficiency of zinc and phosphorus fertilizers under basmati rice–wheat rotation. Archives of Agronomy and Soil Science, 60(1), 33-48. DOI: 10.1080/03650340.2013.770145

Raes, D., Kafiriti, E. M., Wellens, J., Deckers, J., Maertens, A., Mugogo, S., & Descheemaeker, K. (2007). Can soil bunds increase the production of rain-fed lowland rice in south eastern Tanzania? Agricultural Water Management, 89(3), 229-235. DOI: 10.1016/j.agwat.2007.01.005

Ram, H., Rashid, A., Zhang, W., Duarte, A. P., Phattarakul, N., Simunji, S., & Cakmak, I. (2016). Biofortification of wheat, rice and common bean by applying foliar zinc fertilizer along with pesticides in seven countries. Plant and Soil, 403(1-2), 389-401. DOI: 10.1007/s11104-016-2815-3

Rehman, A., Farooq, M., Nawaz, A., & Ahmad, R. (2016). Improving the performance of short-duration basmati rice in water-saving production systems by boron nutrition. Annals of Applied Biology, 168(1), 19-28. DOI: 10.1111/aab.12237

Rodenburg, J., & Johnson, D. E. (2009). Weed Management in Rice-Based Cropping Systems in Africa. In D. L. Sparks (Ed.), Advances in Agronomy (Vol. 103, pp. 149-218): Academic Press.

Rodenburg, J., Johnson, J.-M., Dieng, I., Senthilkumar, K., Vandamme, E., Akakpo, C., & Saito, K. (2019). Status quo of chemical weed control in rice in sub-Saharan Africa. Food Security, 11(1), 69-92. DOI: 10.1007/s12571-018-0878-0

Saha, S., Chakraborty, M., Padhan, D., Saha, B., Murmu, S., Batabyal, K., . . . Bell, R. W. (2017). Agronomic biofortification of zinc in rice: Influence of cultivars and zinc application methods on grain yield and zinc bioavailability. Field Crops Research, 210, 52-60. DOI: 10.1016/j.fcr.2017.05.023

Saito, K., Vandamme, E., Johnson, J.-M., Tanaka, A., Senthilkumar, K., Dieng, I., & Wopereis, M. C. S. (2019). Yield-limiting macronutrients for rice in sub-Saharan Africa. Geoderma, 338, 546-554. DOI: 10.1016/j.geoderma.2018.11.036

Seck, P. A., Ali, A.T., Jeanne, Y.C., Aliou D., & Wopereis, M. C. S. (2013). Africa's Rice Economy Before and After the 2008 Rice Crisis. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., & Jalloh, A. (eds). Realizing Africa's Rice Promise. CABI, 436. DOI: 10.1079/9781845938123.0024

Senthilkumar, K., Rodenburg, J., Dieng, I., Vandamme, E., Sillo, F. S., Johnson, J-M., Rajaona, A., Ramarolahy, J. A., Gasore, R., Abera, B. B., Kajiru, G. J., Mghase, J., Rabeson, R., Lamo, J., & Saito, K. (2020). Quantifying rice yield gaps and their causes in Eastern and Southern Africa. Journal of Agronomy and Crop Science, 206, 478–490. DOI: 10.1111/jac.12417

Senthilkumar, K., Tesha, B. J., Mghase, J., & Rodenburg, J. (2018). Increasing paddy yields and improving farm management: results from participatory experiments with good agricultural practices (GAP) in Tanzania. Paddy and Water Environment, 16(4), 749-766. DOI: 10.1007/s10333-018-0666-7

Sreedhu, P. P., Mercy, G., & John, P. S. (2015). Effect of combined application of nutrients on growth and yield of irrigated rice. Journal of Tropical Agriculture, 53(2), 217-221.

Tanaka, A., Saito, K., Azoma, K., & Kobayashi, K. (2013). Factors affecting variation in farm yields of irrigated lowland rice in southern-central Benin. European Journal of Agronomy, 44, 46-53. DOI: 10.1016/j.eja.2012.08.002

Tenywa. M. M., Majaliwa, J. G. M., Yazidhi, B., Luswata, K. C., & Geofrey, G.I. (2016). The effect of Land Use Practices on Pollution Dynamics in the Highlands of Uganda. In: Management and Area-wide Evaluation of Water Conservation Zones in Agricultural Catchments for Biomass Production, Water Quality and Food Security. International Atomic Energy Agency, 79-101

Touré, A., Becker, M., Johnson, D. E., Koné, B., Kossou, D. K., & Kiepe, P. (2009). Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. Field Crops Research, 114(2), 304-310. DOI: 10.1016/j.fcr.2009.08.015

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. SOIL, 1, 491–508. DOI: 10.5194/soil-1-491-2015

Wade, L. J., Amarante, S. T., Olea, A., Harnpichitvitaya, D., Naklang, K., Wihardjaka, A., & McLaren, C. G. (1999). Nutrient requirements in rainfed lowland rice. Field Crops Research, 64(1), 91-107. DOI: 10.1016/S0378-4290(99)00053-2

Wang, J., Mao, H., Zhao, H., Huang, D. & Wang, Z. (2012). Different increases in maize and wheat grain zinc concentrations caused by soil and foliar applications of zinc in Loess Plateau, China. Field Crops Research, 135(Supplement C), 89-96. DOI: 10.1016/j.fcr.2012.07.010

Wanyama, I., Ochwoh, V. A., Nankya, E., & Van Asten. P. J. A. (2015). Optimisation of major nutrients (N, P and K) for lowland rice production in Eastern Uganda. International Journal of Agronomy and Agricultural Research, 7(2), 218-227.

Wortmann, C. S., Kaizzi, K. C., Maman, N., Cyamweshi, A., Dicko, M., Garba, M., & Serme, I. (2019). Diagnosis of crop secondary and micro-nutrient deficiencies in sub-Saharan Africa. Nutrient Cycling in Agroecosystems, 113(2), 127-140. DOI: 10.1007/s10705-018-09968-7

Yang, X., Wang, B., Chen, L., Li, P., & Cao, C. (2019). The different influences of drought stress at the flowering stage on rice physiological traits, grain yield, and quality. Scientific Reports, 9(1), 3742. DOI: 10.1038/s41598-019-40161-0

Yin, H. J, Gao, X. P, Stomph, T. J, Li, L. J, Zhang, F. S., & Zou, C. Q. (2016). Zinc concentration in rice (Oryza sativa L.) grains and allocation in plants as affected by different zinc fertilization strategies. Communications in Soil Science and Plant Analysis, 47(6), 761-768. DOI: 10.1080/00103624.2016.1146891

Zhang, Y. Q., Sun, Y. X., Ye, Y. L., Karim, M. R., Xue, Y. F., Yan, P., ... Zou, C. Q. (2012). Zinc biofortification of wheat through fertilizer applications in different locations of China. Field Crops Research, 125, 1-7. DOI: 10.1016/j.fcr.2011.08.003

Zou, C. Q., Zhang, Y. Q., Rashid, A., Ram, H., Savasli, E., Arisoy, R. Z., ... Cakmak, I. (2012). Biofortification of wheat with zinc through zinc fertilization in seven countries. Plant and Soil, 361(1), 119-130. DOI: 10.1007/s11104-012-1369-2

## Supplementary materials in Chapter 2

**Supplementary Table S2.1** Soil chemical and physical properties of sampled fields and fields selected to conduct trials in Uganda 2017

| Sampled Field | pH ($H_2$0) | EC (µS/cm) | P (ppm) | K (ppm) | Ca (ppm) | Mg (ppm) | S (ppm) | Na (ppm) | Fe (ppm) | Mn (ppm) | B (ppm) | Cu (ppm) | Zn (ppm) | C.E.C (meq/100g) | Total N (%) | Organic C (%) | C/N ratio | Texture |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Doho rice irrigation scheme 2017** | | | | | | | | | | | | | | | | | | |
| DFF1 | 4.95 | 556 | 38.3 | 385 | 3990 | 730 | 119 | 148 | 698 | 409 | 0.14 | 4.18 | 103 | 59.5 | 0.17 | 4.96 | 17.0 | Silty clay loam |
| DFF2* | 4.93 | 480 | 22.3 | 204 | 4530 | 774 | 109 | 148 | 596 | 413 | 0.09 | 4.31 | 57.9 | 65.7 | 0.20 | 5.81 | 16.9 | Silty clay loam |
| DFF3 | 5.11 | 689 | 80.5 | 204 | 3550 | 729 | 175 | 205 | 684 | 314 | 0.15 | 2.79 | 65.2 | 49.4 | 0.19 | 5.24 | 16.0 | Silty clay loam |
| DFF4 | 4.78 | 627 | 39.4 | 213 | 3880 | 708 | 161 | 155 | 652 | 304 | 0.08 | 3.96 | 83.9 | 62.0 | 0.19 | 5.30 | 16.3 | Silty clay loam |
| DFF5 | 6.57 | 190 | 51.3 | 261 | 4930 | 998 | 50.8 | 172 | 433 | 298 | 0.22 | 13.9 | 70.8 | 38.8 | 0.21 | 4.47 | 12.4 | Silty clay loam |
| DFF6 | 6.48 | 144 | 62.4 | 355 | 4430 | 959 | 38.1 | 130 | 561 | 233 | 0.23 | 5.74 | 27.5 | 36.2 | 0.18 | 4.06 | 13.1 | Silty clay loam |
| **Magoola-Bugiri 2017** | | | | | | | | | | | | | | | | | | |
| Sampled Field | pH ($H_2$0) | EC (µS/cm) | P (ppm) | K (ppm) | Ca (ppm) | Mg (ppm) | S (ppm) | Na (ppm) | Fe (ppm) | Mn (ppm) | B (ppm) | Cu (ppm) | Zn (ppm) | C.E.C (meq/100g) | Total N (%) | Organic C (%) | C/N ratio | Texture |
| BFF1* | 5.13 | 966 | 57 | 167 | 3440 | 775 | 138 | 184 | 408 | 283 | 0.30 | 1.79 | 48.6 | 48.1 | 0.14 | 4.83 | 20.1 | Silty clay loam |
| BFF2 | 5.32 | 871 | 30.4 | 133 | 2810 | 637 | 112 | 160 | 408 | 384 | 0.24 | 1.77 | 43.2 | 35.3 | 0.14 | 3.97 | 16.5 | Silty clay loam |
| BFF3 | 4.13 | 1430 | 26.3 | 153 | 2370 | 506 | 345 | 207 | 841 | 217 | 0.28 | 0.34 | 81.9 | 61.0 | 0.16 | 5.58 | 20.3 | Silty clay loam |
| BFF4 | 5.48 | 613 | 6.96 | 104 | 3500 | 1410 | 279 | 267 | 498 | 165 | 0.44 | 1.31 | 174 | 48.7 | 0.21 | 6.05 | 16.7 | Silty clay loam |

*Fields selected to conduct trials in Doho rice irrigation scheme and Magoola swamp 2017. Doho is irrigated lowland and Magoola is rainfed lowland. DFF = Doho farmer's field, BFF = Bugiri farmer's field.

**Supplementary Table S2.2** Soil chemical and physical properties for trial sites in Uganda 2016 and Tanzania 2015, 2016.

| Trial site and year | pH ($H_2O$) | EC (µS/cm) | P (ppm) | K (ppm) | Ca (ppm) | Mg (ppm) | S (ppm) | Na (ppm) | Fe (ppm) | Mn (ppm) | B (ppm) | Cu (ppm) | Zn (ppm) | C.E.C (meq/100g) | Total N (%) | Organic C (%) | Texture |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Doho 2016 | 6.8 | - | 18.8 | 156 | - | 126 | 12.8 | 13.4 | 26.6 | 1.4 | 0.8 | 1.2 | 1.8 | 32.4 | 0.08 | 4.4 | Silty clay loam |
| Kibimba 2016 | 6.5 | - | 16.6 | 148 | - | 142 | 14.5 | 6.8 | 28.3 | 1.2 | 1.2 | 1.4 | 1.8 | 32.8 | 0.09 | 4.2 | Silty clay loam |
| Msufini 2015* | 5.7 | 73.1 | 3.4 | 70.6 | 943 | 348 | 13.8 | 43.4 | 382 | 59 | 0.1 | 3.1 | 9.9 | 11.2 | 0.10 | 2.1 | Sandy clay loam |
| Msufini 2016* | 5.5 | 102 | - | 68.4 | 903 | 387 | 23.9 | 59.5 | 428 | 56.2 | 0.1 | 5.6 | 3.5 | 12.5 | 0.20 | 2.2 | Sandy clay loam |
| Idete 2015* | 5.8 | 76.4 | 5.9 | 123 | 737 | 209 | 8.3 | 30.2 | 222 | 40.8 | 0.1 | 2.4 | 7.7 | 8.2 | 0.10 | 1.5 | Sandy loam |
| Idete 2016* | 5.6 | 51.1 | - | 70.3 | 434 | 82.2 | 10.7 | 51.4 | 179 | 56.7 | 0.1 | 2.0 | 1.8 | 4.7 | 0.10 | 0.8 | Sandy loam |

*Data presented is average nutrient level for the 10 fields where trials were conducted. Doho, Kibimba and Msufini are irrigated lowlands, and Idete is rainfed lowland.

**Supplementary Table S2.3** Monthly total rainfall (mm) over the cropping season in the experimental locations in Tanzania 2015 and 2016, and Uganda 2016 and 2017.

| **Tanzania** | | | | | **Uganda** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Month** | **Idete (RL) 2015** | **Idete (RL) 2016** | **Msufini (IL) 2015** | **Msufini (IL) 2016** | **Month** | **Kibimba (IL) 2016** | **Magoola (RL) 2017** | **Doho (IL) 2016** | **Doho (IL) 2017** |
| Jan | 216 | 0 | 156 | 0 | Jun | 108 | 40 | 130 | 119 |
| Feb | 112 | 0 | 124 | 0 | Jul | 4 | 69 | 73 | 159 |
| Mar | 218 | 50 | 141 | 0 | Aug | 108 | 158 | 95 | 124 |
| Apr | 202 | 319 | 100 | 426 | Sept | 83 | 154 | 102 | 161 |
| May | 67 | 46 | 34 | 30 | Oct | 59 | 112 | 86 | 121 |
| Jun | 8 | 7 | 5 | 68 | Nov | 221 | 106 | 111 | 115 |
| Jul | 9 | 0 | 3 | 4 | Dec | 12 | 9 | 11 | 16 |
| Aug | 2 | 2 | 6 | 9 | Jan | 31 | 11 | 48 | 14 |

IL: Irrigated lowland, and RL: rainfed lowland. The cropping season for Idete and Msufini was from Jan to May for both years. Cropping season for Kibimba was Sept 2016 - Jan 2017; Magoola was Sept 2017 - Jan 2018; Doho 2016 was Aug - Dec 2016, and Doho 2017 was from Sept 2017 - Jan 2018.

# 3

# CHAPTER 3.

## Yields and yield gaps in lowland rice systems and options to improve smallholder production

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**Abstract**

Increasing productivity per unit area, hence closing the yield gap, is key to meeting cereal demand in sub-Saharan Africa. We assessed, with 114 farmers, the contribution of recommended agronomic practices (RAP) with or without NPK fertilisation on yield gaps, and options to intensify productivity. Treatments included farmers' practice (FP) as control, RAP with and without NPK, and farmer-selected best practices geared towards intensification (farmers' intensification practice, FIP). RAP without fertilisation and FIP significantly increased grain yield, each by ca. 12%, whereas RAP+NPK application produced ca. 33% extra yield, over FP. RAP gave the highest mean net income (ca. USD 220 $ha^{-1}$), fertiliser costs made RAP+NPK gave the lowest mean net income (ca. USD 50 $ha^{-1}$). Weeding and fertilisation timing contributed most to yield variation among fields. Delay in weeding and fertilisation created an average yield loss of 5.3 and 1.9 g $m^{-2}$, per day delay, respectively. Exploitable yield gap averaged 24 and 29%, respectively, across treatments and under FP. RAP, FIP, and RAP+NPK reduced the exploitable yield gap to 25, 26, and 12%, respectively. We conclude that different yield gap levels can be exploited by smallholder farmers in lowland rice systems as RAP, FIP, and RAP+NPK allow yield gap reduction, although fertilisation poses a risk to profit at current rice and fertiliser prices. To realise yield gains, farmers with good water management should combine timely weeding with other crop management practices.

**Keywords:** exploitable yield gap; attainable yield; recommended agronomic practices; intensification practice; profitability

## 3.1 Introduction

### 3.1.1 Food demand in sub-Saharan Africa

Sub-Saharan Africa (SSA) continues to grapple with the challenge of meeting the demand for staple food, where self-sufficiency in cereal production is the lowest globally (Saito et al., 2019; van Ittersum et al., 2016). In addition, SSA population continues to grow, with the projection that the population will at least double by 2050 and peak by 2100 (United Nations, 2019; Vollset et al., 2020). As a result, cereal demand is expected to triple (van Ittersum et al., 2016). Yet, cereal yields are very low, and current consumption is already dependent on considerable imports. This places the continent at the greatest risk of food insecurity, compared with other regions of the world (van Ittersum et al., 2016). Several studies indicate that meeting the projected food demand requires, at least partly, closing the gap between actual farm yields and potential yield (Foley et al., 2011; Lobell et al., 2009; Mauser et al., 2015; Mueller et al., 2012; Pradhan et al., 2015; van Wart et al., 2013).

### 3.1.2 Crop yield gap concept



A crop yield gap is defined as the difference between actual farm yield and potential yield (Lobell et al., 2009). Actual farm yield is the mean yield achieved by farmers in a given location. Potential yield is the yield obtained under ideal growth conditions with water and nutrients being non-limiting, and biotic stresses effectively controlled (Fischer, 2015; Lobell et al., 2009; Stuart et al., 2016; van Ittersum et al., 2013). From this definition, it is clear that the feasibility of attaining potential yield under farmers' field conditions is very low, due to biotic and abiotic stresses, reduction in economic gains while trying to reach maximum yield, and socio-economic factors. An alternative definition with a more practical relevance to real farming conditions is the economically attainable yield, which Fischer, (2015) and Stuart et al. (2016) defined as the optimum (i.e., profit maximising) yield attainable by farmers, given local economic conditions, and taking into account risks and existing institutions. Other studies defined the economically attainable yield as 80% of the potential yield (Laborte et al., 2012; Lobell et al., 2009; van Ittersum et al., 2013). In rice production systems, economically attainable yield has been measured as the average of the top decile of farmers' yields (Laborte et al., 2012; Senthilkumar et al., 2020; Stuart et al., 2016; Tanaka et al., 2015, 2017). In this study, we refer to economically attainable yield as the average of the top decile of farmers' yields, denoted as attainable farm yield (Fischer, 2015; Stuart et al., 2016). The difference between actual farm yield and attainable farm yield has been defined as the exploitable yield gap (Stuart et al., 2016), i.e., the yield gap which can be closed by farmers with existing technologies. Failure to close the yield gap implies that the projected cereal demand will have to be met through crop area expansion, reliance on cereal imports, or both (van Ittersum et al., 2016; van Oort et al., 2015). Yet, there will be inadequate arable cropland to support crop area expansion (Chamberlin et al., 2014). Likewise, reliance on imports is not a viable or sustainable option as most SSA countries have low incomes and weak non-agricultural exports. Hence, they lack adequate foreign currency to pay import bills. This is in addition to lack of infrastructure to store and distribute food efficiently (Arment, 2020; Manitra et al., 2012; van Ittersum et al., 2016). Thus, to meet the growing food demand associated with the growing population, there is need for increased productivity per unit land area in order to minimise land expansion for agricultural production and the subsequent negative environmental consequences, such as biodiversity loss, destruction of ecosystem services and functioning, and environmental quality deterioration from greenhouse gas emissions and nitrate leaching into water bodies (Chamberlin et al., 2014; Foley et al., 2005; Pradhan et al., 2015; Sala et al., 2000; Zabel et al., 2019). This is arguably even more important considering that wetlands where rice is produced in East Africa, constitute important reservoirs of biodiversity, and are becoming scarce (Kangalawe & Liwenga, 2005; Turyahabwe et al., 2013).

### 3.1.3 Rationale of the study

Rice is one of the major cereals in SSA, a main source of calories for households of all income groups, and the second largest source of food energy, next to maize (Nhamo et al., 2014; Seck et al., 2013; Tanaka et al., 2015). However, farm yields are very low (Balasubramanian et al., 2007; Niang et al., 2017; Tanaka et al., 2017; Tsujimoto et al., 2019), associated with poor management practices, especially related to levelling; bunding and weed management; poor nutrient management practices often leading to nutrient mining of particularly N, P, and K; use of low yielding crop varieties; and high pests and disease prevalence. Studies indicate that fertilisers are a major input to enhancing productivity (Bado et al., 2018; Hu et al., 2018; Jinsen et al., 2018; Kaizzi et al., 2012; Rurinda et al., 2014; Saito et al., 2019); nevertheless, SSA farmers on average use only ca. 5–9 kg ha$^{-1}$ of fertiliser, which is far below the 50 and 80 kg ha$^{-1}$ used in Latin America and Asia, respectively (Bado et al., 2018). In addition, on non-responsive soils, yield responses to conventional NPK fertilisers are reported to be poor (Kihara &

Njoroge, 2013; Kihara et al., 2016; Ndungu-Magiroi et al., 2017; Vanlauwe et al., 2011). Thus, fertiliser use alone may not improve farm yields. In contrast to fertilisers alone, recommended (good) agronomic practices (RAP), considered as an integrated, coherent set of crop, soil, water, weed, disease, and pest management practices may be crucial to boosting yields alongside fertiliser use as they are shown to improve rice yields, compared to farmers' practices (Nhamo et al., 2014; Senthilkumar et al., 2018; Stuart et al., 2018). Therefore, in the face of the limited accessibility to, and use of fertilisers by farmers, efforts may need to be focused first on available and feasible options for farmers to intensify their production.

Where fertiliser use remains a difficult option for farmers to improve productivity due to limited access and high cost, yield advantages from fertilisers may not be realised if farmers invest in and apply fertilisers without following recommended agronomic (crop management) practices. For instance, lower rice yield gains have been shown from N and P fertilisation compared with timely and proper weed management under farmers' practice (Haefele et al., 2000). Additionally, Tippe et al. (2020) reported marginal yield gains from NPK or di-ammonium phosphate fertilisation in weed-infested rice fields and noted that consistent yield gains cannot be attained with fertilisation at high levels of weed infestation. Similar results were reported in maize on farmers' fields with N and P fertilisation under high weed infestation (Jamil et al., 2012). Under improved water management practice by bunding, Touré et al. (2009), and Becker and Johnson (2001) observed rice yield gains due to fertilisation, but not in fields with fertilisation without bunds. These findings clearly indicate that even when farmers use fertilisers to improve their productivity, without proper crop and water management, they may not obtain substantial yield gains from fertiliser use. Hence, applying a combination of recommended agronomic practices is key to improving farm yields.



In this study, we show yields and yield gaps under different management levels, factors contributing to variation in on-farm yield, and possible options available for lowland rice farmers in Uganda to intensify their production. We demonstrate management practices that farmers need to first improve upon, in conjunction with fertilisers when used, to boost yields. Our specific objectives were to show exploitable yield gaps that farmers can bridge using recommended crop management practices, and different feasible options for farmers at different yield levels to improve productivity. This information is useful to inform policymakers on available options that can be target points of intervention to assist smallholder farmers intensify rice production in Uganda, with the potential for application in SSA.

## 3.2 Materials and methods

### 3.2.1 Study site

The study was conducted on farmers' fields in the Doho rice irrigation scheme located in Butaleja district (34°02′E, 0°56′N), Eastern Uganda, between January and December 2019. The Doho rice irrigation scheme is the largest public rice irrigation scheme in Uganda (Wanyama et al., 2017). It covers an area of 1000 ha, of which 952 ha is cultivated by over 4000 smallholder farmers. Rice is cultivated year-round, with 2–3 crops planted per year on each field, and about 6800 metric tonnes of rice harvested each year. The scheme is located in the Lake Kyoga basin agro-ecological zone and receives irrigation water from River Manafwa that originates from Mt. Elgon. It lies at an elevation of 1100 m above sea level and the annual mean temperature in the area is 22.7°C, ranging from 15.4°C to 30.7°C. The rainfall pattern is bimodal, with peaks in March–May and August–October, and a mean annual rainfall of 1186 mm (Namyenya, 2014). Soils here are plinthosols, reddish brown in colour, sandy loam, and loam textured (Tenywa et al., 2016). The scheme is divided into 11 blocks; each block sub-divided into 5–15 strips, and each strip has 20–30 farmers. Rice is the main crop grown within the irrigated lowland areas, and other crops such as maize, beans, sweet potato, banana, cabbage, tomato, and eggplant are grown in the upland.

### 3.2.2 Study description

The study was a joint experimentation involving farmers and researchers, with the aim of assessing the contribution of recommended agronomic practices, either with or without NPK fertiliser, in improving rice productivity directly on farmers' fields. The study was a follow-up of two years of researcher-managed on-farm experiments in the same location with NPK, and NPK + secondary and micro-nutrients under recommended agronomic practices, where substantial yield gains were observed with NPK fertilisation under recommended agronomic practices (Awio et al., 2021). Prior to the start of the study, discussions were held with farmers and stakeholders of the scheme on current farmers' management practices and what farmers perceived as recommended agronomic practices. Different components of such recommended agronomic practices and their advantages were discussed. At the end of the discussions, farmers were able to identify components of recommended agronomic practices they considered as feasible under their local settings, and which they could follow during and after the study. Participating farmers were selected based on their interest to participate in the joint experimentation. For each planting lot/period, interested farmers who had ready fields for planting offered their plots for use in conducting the trials. A total of 114 farmers spread across all the blocks within the scheme participated.

### 3.2.3 Experimental design

Treatment allocation within an individual farmer's field was random, and each farmer was considered a replicate. Planting was performed in four different lots: with the 1$^{st}$, 2$^{nd}$, 3$^{rd}$, and 4$^{th}$ lot planted, respectively, in January, March, April, and August 2019. Overall, three crops were evaluated across the year. The January crop was the first crop, planted in the dry season, mostly irrigated with little rainfall. March and April planting was the second crop, planted in the first rainy season of the year, fully utilising the rainfall with supplementary irrigation. August planting was the third crop planted in the second rainy season, also using rainfall with supplementary irrigation. Rice varieties K 98 and K 85, which are commonly grown by farmers within the scheme, were used. These are short-duration varieties with similar growth periods (about 120 days). Within each farmer's field, plot size for each treatment was 10 m × 10 m and a harvest area of 4 m × 4 m was marked from the centre of each treatment plot to assess grain yield.



### 3.2.4 Treatments and management

The four treatments implemented included: (1) Farmers' practice (FP, implemented by 114 farmers). This represented all the management practices that farmers currently undertake. This treatment was fully under farmers' management, where all farmers implemented their different management practices (Table 3.1) and records of such practices were taken; (2) Recommended agronomic practices without fertilisation (RAP, implemented by 114 farmers). This represented the different components of recommended agronomic practices that were demonstrated in the earlier study (Awio et al., 2021), including bunding and field levelling before transplanting; timely and line transplanting (21–28-day-old seedlings at spacing of 20 cm × 20 cm); and timely weeding (2–3 weeks after transplanting – WAT, and subsequent weeding performed when and as required) using a hand hoe. This plot was jointly managed by farmers and researchers, whereby individual farmers were instructed on what to do at a given time, and the implementation of a given management practice was performed under the researcher's supervision; (3) Recommended agronomic practices with NPK fertilisation (RAP+NPK, implemented by 19 farmers). In this treatment, in addition to management practices described in RAP, N, P, and K application at 100, 50, and 50 kg $ha^{-1}$, respectively, as urea, triple super phosphate, and muriate of potash, was included. All P was applied as basal 2 WAT. N and K were split into 50, 25, and 25%, and applied 2 WAT, at panicle initiation and at flowering, respectively. This plot was also jointly managed by the farmers and researchers; (4) Farmers' best management practices as their next feasible step to intensification (farmers' intensification practice, FIP, implemented by 96 farmers). In this treatment, individual farmers were asked to implement what they considered as their workable best practices to improve their own productivity. Thus, different farmers implemented different practices (Table 3.1). Forty-one farmers turned out to duplicate their FP; as such, only 55 farmers actually tested a novel practice. This plot was fully managed by the farmers and records of all management practices applied were taken.

For all treatment plots, field tillage was completed by the farmers following their common practice – two ploughings using either a hand hoe or an ox-plough. First and second ploughing were completed at 2–3 weeks and 1 or 2 days before transplanting, respectively. All fields were properly bunded by default because the bunds act as boundaries between farmers' fields. For practical reasons, levelling was completed in the whole farmer's field, using a hand hoe, before treatment plots were installed, making all treatments conducted on equally well levelled fields. Water supply by irrigation to treatment plots was for three days per week, based on the water release schedule for the different blocks drawn by the Scheme's management, in addition to the rainfall. For FP and FIP plots, most farmers who applied fertiliser used urea as N source and few farmers used an NPK blend (17:17:17). All farmers applied the fertiliser once, with application rate and timing varying from farmer to farmer. Weeding was completed manually using a hand hoe, the only weed management option farmers use, in addition to flooding by irrigation water when released, with timing of weeding varying among farmers. All treatment plots were weeded once during the crop growth cycle, as is common practice at the study site. Bird control was achieved by physically scaring birds away from the grain-filling stage until harvest.

**Table 3.1** Summary of treatments and associated management practices.

| Treatment | Management Practices |
|---|---|
| Farmers' practice (FP, n = 114) | Farmers implemented different management practices: transplanting time (21–39 DAS), transplanting method (random or line), weeding time (15–48 DAT), and N rate (13.8–46.0 kg $ha^{-1}$), no P and K. |
| Recommended agronomic practices without fertilisation (RAP, n = 114) | Transplanting time (21–33 DAS), line transplanting, timely weeding (14–25 DAT), and no fertilisation. |
| Recommended agronomic practices with NPK fertilisation (RAP+NPK, n = 19) | Transplanting time (25–33 DAS), line transplanting, timely weeding (15–22 DAT), and 100, 50.0 and 50.0 kg $ha^{-1}$ N, P and K. |
| Farmers' intensification practice (FIP, n = 55) | Farmers implemented different management practices: transplanting time (23–39 DAS), transplanting method (random or line), weeding time (15–40 DAT), and N (6.80–46.0 kg $ha^{-1}$), P and K (0.00–27.2 kg $ha^{-1}$)[1]. |

Field tillage, bunding, levelling and number of weeding operations (i.e. one weeding) were identical across treatments. [1]P and K were always applied in the ratio of 1:1, resulting to similar ranges of application rate. Under farmers' intensification practice, improved management practices implemented by these farmers were different from their farmers' practice. DAS = days after sowing, DAT = days after transplanting, n = number of farmers who implemented the different treatments.

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### 3.2.5 Data collection and analysis

To capture the differences among farmers in the execution of FP and FIP, data from each farmer's plot on transplanting time (days after sowing the nursery; DAS), transplanting method, weeding time (days after transplanting; DAT), and fertiliser use, rate of application (kg $ha^{-1}$) and timing of application (DAT) were collected. Data on yield components (number of panicles per hill, total number of grains per panicle, number of filled grains per panicle, 1000-grain weight), total above-ground plant dry matter and harvest index (HI) were determined by systematically selecting 12 hill samples from within 1 m outside the harvest area to avoid border rows, whereby every $6^{th}$ hill within and between rows was sampled. Number of panicles $m^{-2}$ was derived from grain yield in g $m^{-2}$, and the obtained number of grains per panicle and 1000-grain weight. Sample hills were threshed, and straw, filled, and empty grains, were separately oven-dried to a constant weight at 70°C. Total above-ground dry matter was calculated as the sum of straw yield, filled, and empty grains. HI was calculated as the ratio of filled grains over total above-ground dry matter. To obtain grain yield, all panicles from the harvest area (4 m × 4 m) were harvested using a sickle. Harvested panicles were threshed, sun-dried, and the grains winnowed to remove empty grains. Grain weight and moisture content were determined using a digital weighing scale (Mini Crane scale model MNCS-M) and moisture meter (SATAKE Moistex Model SS-7). Rice grain yield adjusted to dry weight (0% moisture content) was expressed in g $m^{-2}$. To calculate net income from grain yield (as paddy) for FIP, RAP, and RAP+NPK application over FP, grain yield adjusted to 14% moisture content was used, as that is the commercial basis for pricing rice. Fertiliser and labour costs per unit area were quantified by taking records of fertiliser price and costs of all field operations, and the selling price of paddy was fixed at USD 406 $t^{-1}$, considering 2019 average price. Land is farmer-owned under a leasehold basis, so land rental was not included in the calculations.

Data were subjected to analysis of variance (ANOVA) using an unbalanced treatment structure in Genstat ($19^{th}$ edition) at 5% probability, taking the different farmers' fields as blocks. Where differences were significant, Fisher's least significant difference test was used to separate treatment means. Homogeneity of variances and normality of data distribution were checked using Bartlett's and Shapiro–Wilk tests, respectively. During analysis, planting lot was included as a covariate; however, its effect alone or in interaction with the different treatments was not significant ($p>0.24$) so it was then dropped. To examine yield differences among farmers under different crop management practices in FP and FIP, treatment plots that received similar management practices were grouped together and analysis was performed to assess yield effects of the different management practices applied. To evaluate the contribution of FIP over FP, only farmers who tested new management practice(s) were included, so those who had similar management practices in FP and FIP were excluded from the analysis. To assess yield increase, at the individual farmer's field, due to FIP, RAP, and RAP+NPK, over FP, a paired t-test was used. Cumulative frequency diagrams constructed as number or percentage of farmers were used to show the distribution of grain yield, yield increment and net income from FIP, RAP, RAP+NPK, over FP, among the farmer population. To identify major production factors causing yield variation among fields, all treatment data on transplanting time and method, weeding time, fertiliser use, amount and application time was subjected to regression analysis using a generalised linear model to quantify the degree of influence (i.e., yield increase or decrease as a function of a given production practice) on yield variation.

### 3.2.6 Yield gap analysis

Exploitable yield gap, referred to as the difference between actual farm yield and attainable farm yield, was estimated using the top decile approach (Stuart et al., 2016; Tanaka et al., 2015, 2017). Attainable farm yield was defined as the mean yield of the top 10-percentile of treatment yields from the different farmers' plots, and mean yield for the different treatments was taken as actual farm yield. This approach is regarded as practical and robust for estimating exploitable yield gap, as it takes into consideration what is achievable under local bio-physical and socio-economic conditions (Stuart et al., 2016), and prevents errors caused by single-field yield outliers (Tanaka et al., 2017). The exploitable yield gap (EYg in g $m^{-2}$) was calculated as follows:

$$EYg = AY - Ya \quad \text{and,}$$

$$EYg\ (\%) = \left(\frac{EYg}{AY}\right) * 100$$

where AY is attainable farm yield and Ya is actual average treatment yield in g $m^{-2}$.



To assess exploitable yield gaps, under different management levels (treatments), the mean of the top 10-percentile of yields across FP, RAP and FIP was used. To estimate the different yield gap levels that can be exploited, and which farmers could close with recommended crop management practices, the mean of the top 10-percentile of yields for the individual treatments: FP, RAP, FIP, and RAP+NPK was used as attainable farm yield.

## 3.3 Results

### 3.3.1 Grain yield under different management levels

Grain yield varied significantly ($p<0.001$) among different management levels (treatments) on farmers' fields. Recommended agronomic practices (RAP) without fertilisation significantly increased grain yield by 12.2%, compared with farmers' current practice (FP, Table 3.2). Combining NPK and RAP resulted in yield gains of 18.5%, compared with RAP alone, and 32.9% compared with FP. FIP (farmers' intensification practice) led to 11.6% extra grain yield over FP. The different planting times had no significant effect ($p>0.24$) on grain yield for the different treatments (Supplementary Table S3.1). The yield differences between management levels were explained by a significantly higher number of grains per panicle and filled grains $m^{-2}$.

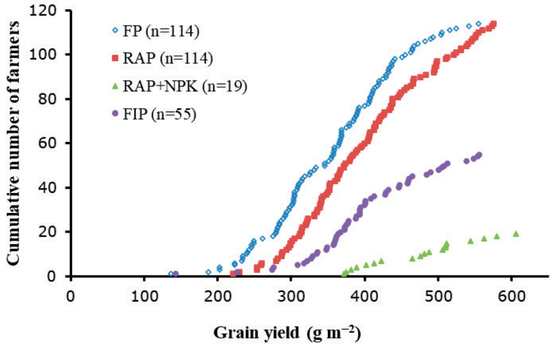
The higher number of filled grains m$^{-2}$ was due to significantly more panicles m$^{-2}$ and filled grains per panicle, where grain number was higher when the panicle number was also higher. Differences in 1000-grain weight showed a slight inverse trend as it was higher when grain yield was lower, but differences were small ranging from -0.2 to -2.2% compared with FP. HI varied significantly and was highest under RAP and lowest with RAP+NPK; here also, differences were limited, compared with yield differences, ranging from +2.0% for RAP to -4.6% for RAP+NPK compared with FP.

Yield distribution among the farmer population indicated that the median of the yields obtained by the population did increase, but not a lot (Figure 3.1). The median yield for FP was 359 g m$^{-2}$ and this shifted by 9.3% to 392 g m$^{-2}$ for RAP, which was the same as the 393 g m$^{-2}$ for FIP (9.6% over FP). The median yield shifted to 481 g m$^{-2}$ for RAP+NPK, which was 34.2% over FP (Figure 3.1). At individual farmer's level, the median yield increase from FIP, RAP, and RAP+NPK was 10.3, 12.1, and 24.7% over farmers' practice, respectively. Average yield increase was 12.7, 14.2, and 26.5% from FIP, RAP, and RAP+NPK over farmers' practice, respectively. The yield distribution also indicated larger yield differences between farmers' fields than between the management levels, with quite a number of farmers that obtained similar or even higher yields under their current practice compared with yields under RAP+NPK.

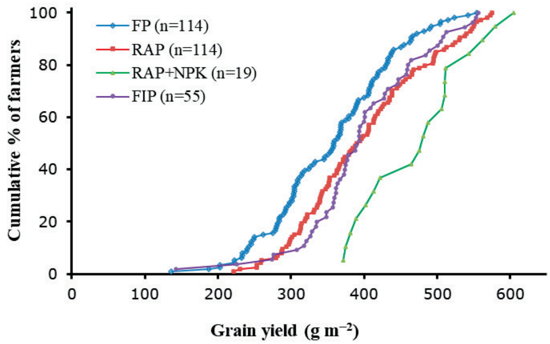
**Table 3.2** Grain yield and yield components under different management levels on farmers' fields, Doho 2019.

| Treatments[1] | Yield (g m$^{-2}$) | Panicles m$^{-2}$ | Filled grains panicle$^{-1}$ | Filled grains m$^{-2}$ (×10$^{3}$) | Filled grains (%) | 1000-grain weight (g) | HI[2] (%) |
|---|---|---|---|---|---|---|---|
| FP (n = 114) | 358$^{a}$ | 340$^{a}$ | 49.6$^{a}$ | 16.5$^{a}$ | 68.4$^{b}$ | 21.7$^{c}$ | 42.2$^{b}$ |
| FIP (n = 55) | 399$^{b}$ | 365$^{b}$ | 52.2$^{b}$ | 18.5$^{b}$ | 68.9$^{b}$ | 21.6$^{bc}$ | 42.7$^{bc}$ |
| RAP (n = 114) | 401$^{b}$ | 364$^{b}$ | 52.7$^{b}$ | 18.7$^{b}$ | 68.9$^{b}$ | 21.5$^{b}$ | 43.0$^{c}$ |
| RAP+NPK (n = 19) | 475$^{c}$ | 431$^{c}$ | 52.9$^{b}$ | 22 .5$^{c}$ | 63.1$^{a}$ | 21.2$^{a}$ | 40.2$^{a}$ |
| Mean | 408 | 375 | 51.8 | 19.1 | 67.3 | 21.5 | 42.0 |
| S.e.d. | 7.0 | 10.1 | 1.2 | 0.3 | 1.0 | 0.1 | 0.5 |
| *p*-value | **<0.001** | **<0.001** | **0.01** | **<0.001** | **0.05** | **0.02** | **0.03** |

[1]FP = farmers' practice, FIP = farmers' intensification practice; RAP = recommended agronomic practices without fertilisation; RAP+NPK = recommended agronomic practices combined with NPK fertilisation. [2]HI = harvest index. Values followed by the same letter are not statistically different according to a Fisher's post-hoc test.




**(a)**




**(b)**

**Figure 3.1** Cumulative frequency diagrams of yields obtained under different management levels: farmers' practice (FP), recommended agronomic practices without fertilisation (RAP), RAP plus NPK application (RAP+NPK) and farmers' intensification practice (FIP). (**a**) is plotted as number of farmers and (**b**) as percentage of farmer population.

### 3.3.2 Yield gaps under different management levels

Using the mean (538 g $m^{-2}$) of the top 10-percentile of yields across FP, RAP, and FIP as attainable yield, the exploitable yield gap was between 11.6 and 33.5% of this attainable yield under farmers' conditions (Figure 3.2). For the median and lower 10-percentile yields (382 and 230 g $m^{-2}$) from all treatment plots, an exploitable yield gap of 28.9 and 57.3% was observed, respectively. RAP reduced these exploitable yield gaps to 25.4% from the 57.3, 33.5, and 28.9% exploitable yield gaps observed for the lower 10-percentile yield, FP and median yield, respectively. Applying NPK under RAP reduced the exploitable yield gaps to 11.6% while FIP reduced the exploitable yield gaps to 25.8%.

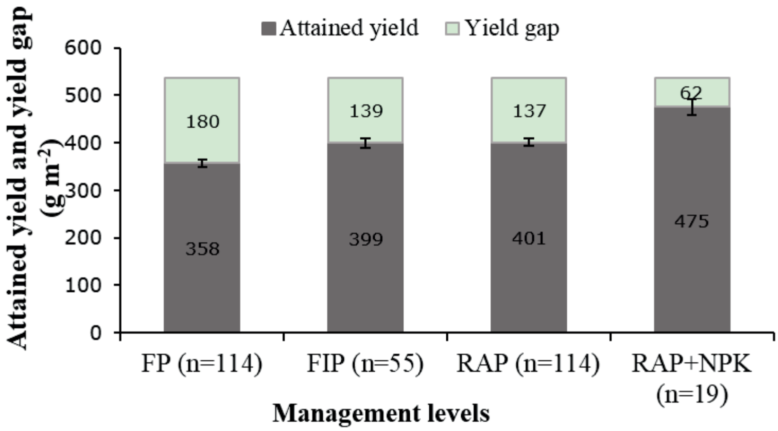



**Figure 3.2** Attained yield (g $m^{-2}$) under different management levels and the corresponding yield gaps (g $m^{-2}$) on-farmers' fields, Doho 2019. Error bars are twice standard error of means. FP = farmers' practice, FIP = farmers' intensification practice, RAP = recommended agronomic practices without fertilisation, RAP+NPK = RAP combined with NPK fertilisation.

Under current farmers' practice, the exploitable yield gap ranged from 19.9–43.7% of the attainable yield, depending on crop management practices the farmers applied (Figure 3.3). Overall, 38.6% of the farmers applied none of the components of recommended agronomic practices that were recorded (i.e., they applied poor crop management), while the remaining farmers applied one or a combination of the components of recommended agronomic practices, including line transplanting only (14.0%), fertilisation only (15.8%), timely weeding only (11.4%), timely weeding + fertilisation (7.9%), line transplanting + timely weeding + fertilisation (5.3%), line transplanting + fertilisation (3.5%), and line transplanting + timely weeding (3.5%). Farmers who applied one or a combination of the components of recommended agronomic practices reduced the yield gap substantially, with the exception of line transplanting applied alone which had no yield effect. Among the different combinations, timely weeding + fertilisation left the lowest exploitable yield gap of 19.9% (Figure 3.3).

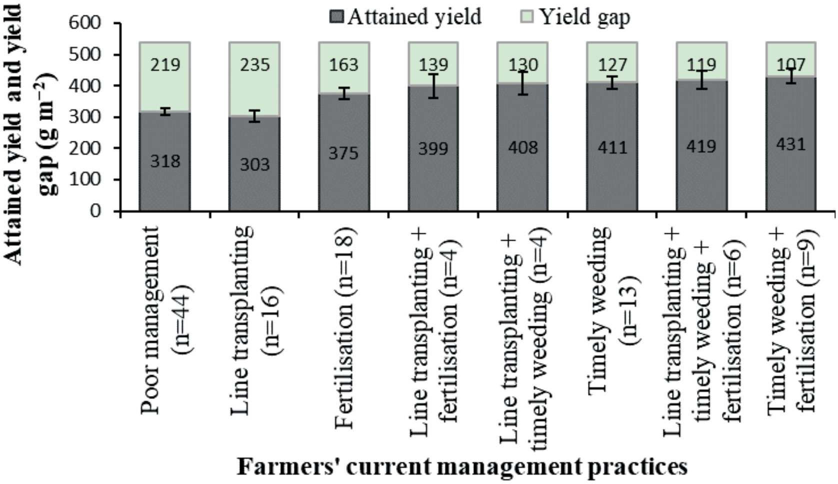



**Figure 3.3** Attained yield (g $m^{-2}$) and yield gap under different farmers' current management practices (FP), Doho 2019. Error bars are twice standard error of means. Poor management is where none of the components of recommended agronomic practices that were recorded was applied. The other management practices included one or more of the components of recommended agronomic practices applied. n is the number of farmers who applied the different management practices.

When the means of the top 10-percentile of yields under only farmers' practice, RAP, FIP, and RAP+NPK were used, different exploitable yield gap levels that farmers could partly or completely close with improved crop management practices were identified (Table 3.3). For instance, considering the mean of top 10-percentile of yields under farmers' practice (504 g $m^{-2}$) as attainable yield, an exploitable yield gap of 29.1% (147 g $m^{-2}$) existed with the average of current farmers' management practices. However, this exploitable yield gap was reduced to 20.8% (105 g $m^{-2}$) and 20.4% (103 g $m^{-2}$) with FIP and RAP, respectively, and a further reduction to only 5.7% (29 g $m^{-2}$) was made with RAP+NPK (Table 3.3). The largest yield gap was observed when the mean of the top 10-percentile of RAP+NPK yields was considered, with a yield gap of 39.6% under farmers' practice, which was reduced to 32.6% and 32.2%, respectively, with FIP and RAP. RAP+NPK reduced this yield gap to 19.7%. This analysis indicates that there are different exploitable yield gap levels under lowland rice system which, in a bid to intensify production, it seems feasible for farmers to partly close the gap by improving their crop management practices.

**Table 3.3** Yields and exploitable yield gaps under different management levels (treatments), Doho 2019.

| Treatment | Yield ($g\ m^{-2}$) | Exploitable yield gap ($g\ m^{-2}$) | | | | |
|---|---|---|---|---|---|---|
| | | FP (504) n = 11 | FIP (542) n = 5 | RAP (555) n = 11 | RAP+NPK (592) n = 2 | All treatments (543) n = 32 |
| FP | 358 | 147 | 184 | 197 | 234 | 186 |
| FIP | 399 | 105 | 142 | 156 | 193 | 144 |
| RAP | 401 | 103 | 140 | 154 | 191 | 142 |
| RAP + NPK | 475 | 29 | 66 | 80 | 117 | 68 |

Yield gap was taken as the difference between treatment mean yield and means of top 10-percentile of yields under FP, FIP, RAP, RAP+NPK, and all treatment yields. FP = farmers' practice; FIP = farmers' intensification practice; RAP = recommended agronomic practices without fertilisation; and RAP+NPK = recommended agronomic practices combined with NPK fertilisation. Values in parentheses are means of the top 10-percentile yield under respective management levels. n indicates the number of fields constituting this top 10-percentile.

### 3.3.3 Causes of yield variation among fields

Major causes of yield variation among fields in descending order of importance were weeding time, fertilisation timing, and N, P and K fertilisation, when fertilisers were applied (Table 3.4). Delayed weeding under FP and FIP decreased yield on average by 43.0 $g\ m^{-2}$ (ranging between 6.7 and 206 $g\ m^{-2}$) and 25.8 $g\ m^{-2}$ (6.0–193 $g\ m^{-2}$), respectively. The slope estimate from regression analysis showed that a delay of weeding by one day decreased grain yield on average by 5.3 $g\ m^{-2}$ (Table 3.4). Where fertiliser was applied with late weeding under farmers' practice, an average yield loss of 17.2 $g\ m^{-2}$ due to weeds was observed, with yield reduction varying between 5.1 and 155 $g\ m^{-2}$ recorded. Delay of weeding by one day when fertiliser was applied reduced grain yield by an average of 3.7 $g\ m^{-2}$, with yield loss of between 1.6 to 5.7 $g\ m^{-2}$ per day estimated ($p<0.001$, s.e. of slope estimate = 1.01). A regression analysis of the overall effect of fertilisation on yield, across all application timings, showed that fertiliser application increased yield on average by 55 $g\ m^{-2}$ per $g\ m^{-2}$ NPK applied, varying between 35 and 75 $g\ m^{-2}$ ($p<0.001$, s.e. = 10.3), while a one-day delay to apply the fertiliser reduced this yield gain by an average of 1.9 $g\ m^{-2}$. Every $g\ m^{-2}$ of N and P+K applied resulted in an average additional grain yield of 11.0 and 18.8 $g\ m^{-2}$, respectively (Table 3.4). Differences in transplanting time (DAS) had no significant effect on grain yield (p=0.39, s.e. = 1.71) across the observed time (21–39 DAS).

**Table 3.4** Effect of management practices on yield variation among treatment plots on farmers' fields, Doho 2019.

| Management practice | Slope estimate | Unit of slope estimate | Standard error | p-value | Lower 95% confidence limit | Upper 95% confidence limit | Adjusted $R^2$ |
|---|---|---|---|---|---|---|---|
| Weeding time (DAT)[1] | -5.3 | g $m^{-2}$ $day^{-1}$ | 0.54 | <0.001 | -6.4 | -4.2 | 0.22 |
| Fertilisation timing (DAT) | -1.9 | g $m^{-2}$ $day^{-1}$ | 0.48 | <0.001 | -2.8 | -0.9 | 0.13 |
| N (g $m^{-2}$) | 11.0 | $\frac{\text{g grain m}^{-2}}{\text{g N m}^{-2}}$ | 0.19 | <0.001 | 7.2 | 14.7 | 0.09 |
| P + K (g $m^{-2}$) | 18.8 | $\frac{\text{g grain m}^{-2}}{\text{g P + K m}^{-2}}$ | 0.40 | <0.001 | 11.0 | 26.7 | 0.06 |

[1]DAT – days after transplanting.

Comparing management practices in the higher (top 10-percentile), median, and lower (lower 10-percentile) yielding plots across all treatments to assess management practices at different yield levels, we found a large variation in management practices that could have resulted in the large variation in yields in the lower, median and higher yielding plots. For instance, for the higher yielding plots, ca. 77% were transplanted in line, 85% were weeded within 3 WAT, 46% received fertiliser and for 56%, fertilisation was completed within 3 WAT directly following weeding, and, for the lower yielding plots, these percentages were ca. 49, 18, 3 and 0%, respectively (Table 3.5). Average nutrient rates for the higher and lower yielding plots were 2.7 and 1.1, and 0.04 and 0 g $m^{-2}$ N and P+K, respectively. Generally, lower yielding plots were under poorer management than higher-yielding plots.

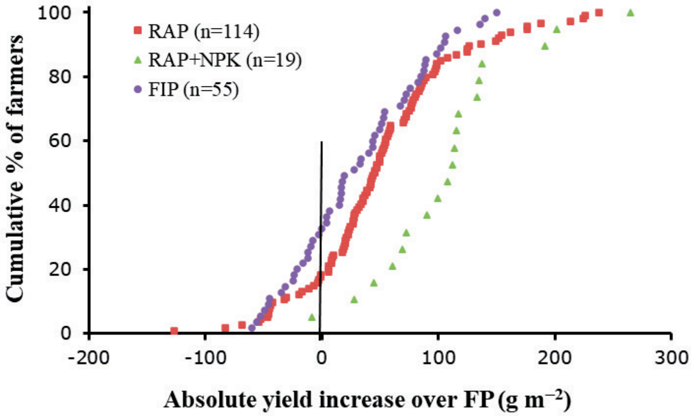
### 3.3.4 Options for intensification of lowland rice production

A paired t-test for the individual farmers indicated that yields significantly ($p$<0.001) increased on average by 25.1 g $m^{-2}$ (ranging between 10.6 and 39.6 g $m^{-2}$), 43.5 g $m^{-2}$ (33.1–54.0 g $m^{-2}$), and 85.8 g $m^{-2}$ (58.9–112.8 g $m^{-2}$) due to FIP, RAP, and RAP+NPK, respectively, over FP. The frequency distribution for absolute yield increase over FP, however, indicated there were farmers that recorded yield reductions under improved management practices, while others made large yield gains (Figure 3.4a). RAP+NPK resulted in the largest yield gains (Figure 3.4a) with mean yield gain of 109.6 g $m^{-2}$, however, with the lowest net income gains by farmers due to fertiliser costs (Figure 3.4b). RAP gave the highest mean net income (USD 222 $ha^{-1}$) followed by FIP (USD 105 $ha^{-1}$), and RAP+NPK (USD 46.3 $ha^{-1}$).

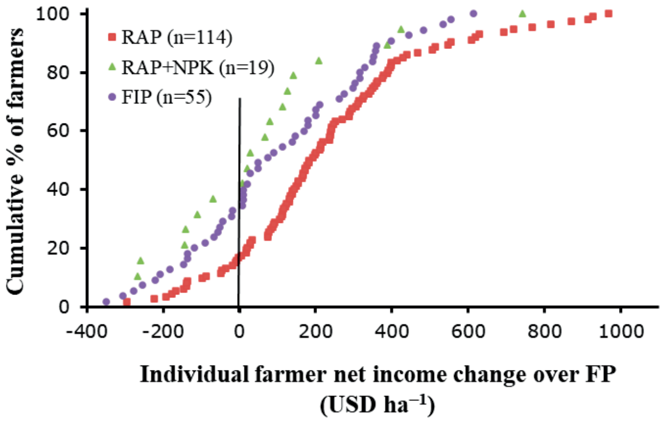
Under FIP, the different intensification options which farmers considered feasible and, thus, evaluated included line transplanting, timely weeding, fertiliser use, as single options and in all possible combinations. Pair-wise comparison of yield for individual farmers under their current practice and any tested intensification practice, showed that timely weeding alone or in combination with other improved management practices, significantly ($p \leq 0.01$) increased grain yield in the fields of those farmers who evaluated these practices as their intensification options (Figure 3.5). Timely weeding as a single intensification option, and combined with line transplanting and fertilisation, resulted in the highest yield gains of 80 and 73 g $m^{-2}$, respectively, compared with yield under current practice for farmers who implemented these management practices as their intensification options.

**Table 3.5** Percentage of farmers who applied the different management practices, amount of N, P, and K applied (g $m^{-2}$), and the number of days after transplanting (DAT) when management was applied in higher, median, and lower yielding plots on farmers' fields, Doho 2019. n refers to the number of plots, across all treatment plots, with yields that corresponded to the top and lower 10-percentile, and median yields.

| **Management practice** | | **Higher yielding plots (n=39)** | **Median yielding plots (n=39)** | **Lower yielding plots (n=39)** |
|---|---|---|---|---|
| Crop establishment method | Line transplanting (%) | 76.9 | 51.3 | 48.7 |
| | Random transplanting (%) | 23.1 | 48.7 | 51.3 |
| Weeding time (DAT) | 14-21 (%) | 84.6 | 69.2 | 17.9 |
| | 22-28 (%) | 12.8 | 10.3 | 0.0 |
| | ≥29 (%) | 2.6 | 20.5 | 82.1 |
| Average weeding time (DAT) | (p<0.001, S.e.d. = 1.5) | 19.5 | 21.9 | 32.4 |
| Fertiliser use | Yes (%) | 46.2 | 35.9 | 2.6 |
| | No (%) | 53.8 | 64.1 | 97.4 |
| Average nutrient rate (g $m^{-2}$) | N (p<0.001, S.e.d. = 0.64) | 2.69 | 1.71 | 0.04 |
| | P+K (p=0.008, S.e.d. = 0.33) | 1.06 | 0.56 | 0.0 |
| Fertilisation time (DAT) | 14-21 (%) | 55.6 | 28.6 | 0.0 |
| | 22-28 (%) | 5.6 | 14.3 | 0.0 |
| | ≥29 (%) | 38.9 | 57.1 | 100 |
| Average fertilisation time (DAT) | (p=0.24, S.e.d. = 9.7) | 25.3 | 32.0 | 61.0 |




(a)




(b)

**Figure 3.4** Cumulative frequency for absolute yield increment (**a**) and net income (**b**) over farmers' practice due to the improved management packages tested: recommended agronomic practices without fertilisation (RAP), recommended agronomic practices combined with NPK application (RAP+NPK) and farmers' intensification practice (FIP) plotted as percentage of farmer population.

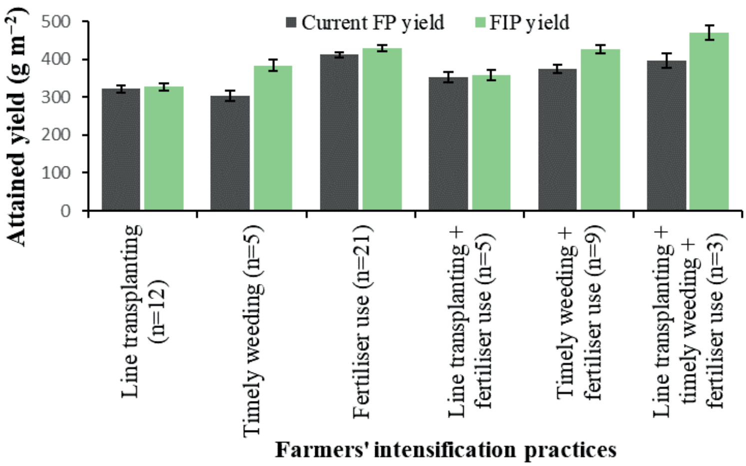



**Figure 3.5** Attained yield under current farmers' practice and different intensification practices within the fields of the same farmers who implemented the intensification practices, Doho 2019. Current farmers' practice did not include improved management practices under farmers' intensification practice. Error bars are twice standard error of means, and n is the number of farmers who implemented the different intensification practices. FP = farmers' practice and FIP = farmers' intensification practice.

At an individual farmer's field, for farmers who tested the different intensification practices, yield increment from different choices in the intensification (FIP) packages indicated that farmers who did late weeding under their current practice (FP) but timely weeded as an intensification step (FIP) had the highest yield increment, averaging 75 g $m^{-2}$ and ranging from 16 to 129 g $m^{-2}$ (Figure 3.6, yellow closed circles). Farmers who did timely weeding under both FP and FIP but increased fertiliser rate under FIP observed an average yield increment of 25 g $m^{-2}$, with the yield increment ranging from -60 to 117 g $m^{-2}$ (Figure 3.6, green closed triangles). Similarly, farmers who weeded late in both FP and FIP with late application of N(PK) or without NPK but in FIP did line transplanting only or line transplanting with higher fertiliser rate, increased fertiliser rate only or increased fertiliser rate and applied NPK blend instead of urea, had yield increments ranging from -46 to 116 g $m^{-2}$ with an average yield increment of 18 g $m^{-2}$ (Figure 3.6, blue open diamonds). However, farmers who timely weeded in FP and FIP and, in the FIP tested line transplanting only or line transplanting with application of NPK blend instead of urea or only applied NPK blend instead of urea, observed, on average, negative yield increment (-13 g $m^{-2}$) (Figure 3.6, red closed circles).

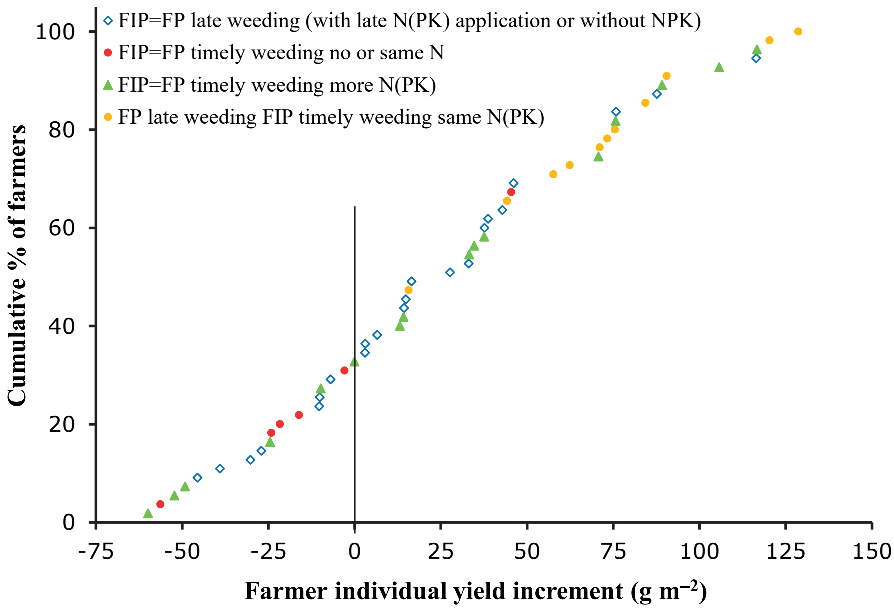



**Figure 3.6** Farmer individual yield increment from FIP over FP for four different categories of changes in management: the blue open diamond is when FIP and FP plots were weeded late with late or no fertilisation (n = 22), the red closed circle is when FIP and FP plots were timely weeded with no or the same amount of N applied (n = 6), the green closed triangle is when FIP and FP plots were timely weeded and FIP received higher N or NPK (n = 16), and the yellow closed circle is when FP was weeded late and FIP was timely weeded while the same N or NPK amount was applied between FP and FIP (n = 11).

## 3.4 Discussion

This study showed rice yields and yield gaps under different management levels and factors contributing to on-farm yield variation in a participatory on-farm study in a major public rice growing scheme in Uganda. It demonstrated management practices that farmers can improve upon to boost their lowland rice yields. The study revealed that at individual farmers' fields, grain yield can be increased by 23.1% from 3250 kg ha$^{-1}$ to 4000 kg ha$^{-1}$, by those farmers currently weeding late or by ca. 5.6% for farmers weeding timely but not using fertilisers (Figure 3.6). At the scheme level, training to use recommended agronomic practices (RAP), followed by adopting RAP plus NPK application can enhance grain yield substantially over current farmers' practice as indicated by our data (Table 3.2 and Figure 3.4a). Our findings are, therefore, in general agreement with the discussion of Pradhan et al. (2015) on the role of improved management practices in increasing crop productivity and closing yield gaps. The higher yields could be attributed to higher number of filled grains per unit area, as a result mainly of improvement in panicle number per unit area, and a supplementary positive effect on numbers of grains per panicle, but not percentage filled grains (Table 3.2). This indicates that improved crop management positively influenced tiller formation and reproductive success, resulting in the production of more panicles with more grains per panicle. At the late filling stage, there was a slight reverse effect, as evidenced by a negative correlation between 1000-grain weight and filled grains per panicle (Table 3.2). The lower proportion of filled grains and harvest index combined with high yield and high grain number observed under RAP+NPK indicates that there was a build-up towards a higher yield potential with fertilisation that was not attained, as grain filling did not take full advantage of the enhanced vegetative biomass production. This warrants further research into options for better spread of especially applied N as there are indications that more N application at later crop stage can improve grain filling hence grain yield (Banayo et al., 2018; Ju et al., 2021; Kamiji et al., 2011; Zhang et al., 2013; Zhou et al., 2017).

Cumulative distribution of net income from improved management practices showed a shift in net income to the lower side from RAP+NPK application (Figure 3.4b) due to high fertiliser costs (e.g., Urea (46% N) at USD 1.0 $kg^{-1}$; NPK (17:17:17) blend at USD 1.1 $kg^{-1}$), indicating that the nutrient rates used in this study may not be economic at current rice and fertiliser prices as there is a risk of investing in fertilisers with no or very low returns on the investment. The lower economic returns from fertiliser application at higher rates shown by this study could partly explain why farmers do not use fertilisers or use low to moderate nutrient rates. This suggests that to realise increased rice production with fertilisation at current market prices, there is a need for the government to subsidise fertilisers, in line with Koussoubé and Nauges (2017) and Sanchez (Sanchez, 2015) who showed that subsidies can increase fertiliser use and cereal yields in SSA.

Significant yield gains were realised by farmers who implemented timely weeding alone, or in combination with other improved management practices as intensification options, compared with current farmers’ practice yields (Figures 3.5 and 3.6). This demonstrates the potential for lowland rice farmers in irrigated or rainfed production systems with sufficient water supply, to improve grain yield through improved crop management practices, as previously shown (Nhamo et al., 2014; Senthilkumar et al., 2018), even without fertiliser subsidies. Farmers who weeded timely as their intensification choice (FIP) compared with late weeding under current practice (FP) had the highest individual yield increase, followed by those who timely weeded under both FP and FIP but increased fertiliser rate under FIP (Figure 3.6). Other choices in intensification did not show such consistent positive effect (Figure 3.6). This supports the need for farmers to conduct timely weeding first, and only after then apply moderate fertilisation as a next step, a position also supported by prior studies (Haefele et al., 2000; Tippe et al., 2020).

Exploitable yield gaps of 12–34% under farmers' conditions were observed for the different management levels, with yield gaps of 20–44% under current farmers' practice (Figures 3.2 and 3.3). The yield gaps observed in this study are within the range of yield gaps reported for rice in SSA (Senthilkumar et al., 2020; Tanaka et al., 2015, 2017) and in Asia (Stuart et al., 2016), using the top-decile approach. The moderately large yield gap observed shows considerable potential for farmers in the study area, and generally across lowland rice production systems in SSA, to increase rice yields. This could be achieved through improved crop management practices as also observed elsewhere (Nhamo et al., 2014; Pradhan et al., 2015). Timely weeding alone reduced the yield gap to 24% compared with 44% yield gap due to poor management under current farmers' practice (Figure 3.3).



The major factors resulting in yield variations among plots in descending order of significance were timing of weeding and fertiliser application (where applied), and level of N and P+K applied (Table 3.4). This further supports the argument that timely weeding is the first step of the package of recommended agronomic practices for farmers in the study area and in other areas with similar production systems to adopt, as yield gains from other improved management practices, such as fertilisation, are low without timely weeding (cf. also Becker et al., 2003; Nhamo et al., 2014; Niang et al., 2017; Rodenburg & Johnson, 2009; Senthilkumar et al., 2020; Waddington et al., 2010)). Although fertiliser application has been reported in many studies to boost yields (De Bauw et al., 2019; Jinsen et al., 2018; Saito et al., 2019; Vandamme et al., 2018), yield gains from fertilisation were severely reduced by late weeding in this study (Table 3.4). On the contrary, yield gains from fertiliser application were substantial where weed management was optimal (Figures 3.5 and 3.6). Several studies report rice yield gains due to N application where weeds were suppressed using good levelling and bunds, enabling proper water control within plots as part of weed management (Becker & Johnson, 2001; Rodenburg & Johnson, 2009; Senthilkumar et al., 2018; Touré et al., 2009). Consequently, better weed management which depends on time, labour and capital resources availability of smallholder farmers, could help raise grain yields and narrow the yield gaps. From a policy perspective, it would be relevant to develop, assess, and promote locally adapted simple weeding tools as demonstrated by Rodenburg et al. (2015) to improve labour efficiency of weed management. Simultaneously introducing line transplanting would be appropriate in improving the efficiency of these simple weeding tools.

Results from this study showed no significant effect of transplanting time (i.e., seedling age) on grain yield, over the range of observed transplanting times of 21–39 DAS (ca. 15- to 33-day-old seedlings). This contrasts with the literature reporting seedling age at transplanting as a major agronomic practice influencing grain yield (Kyalo et al., 2020; Liu et al., 2017), and studies reporting substantial yield reduction by transplanting rice seedlings between 20 and 35-day-old (Kyalo et al., 2020; Lampayan et al., 2015; Liu et al., 2017; Menete et al., 2008; Pasuquin et al., 2008). However, contrasting findings have also been reported (Kewat et al., 2002; Khatun et al., 2002). Whereas cultivar or varietal differences could play a role in these prior contrasting outcomes of seedling age effect on yield, the lack of effect of seedling age on grain yield in the current study seems to indicate that farmers transplant reasonably timely, and there is no need to emphasise changes to their practices.

## 3.5 Conclusions

We demonstrate that adhering to recommended agronomic practices (RAP), even without fertiliser application, significantly contributes to yield gain and income and reduces the yield gap. Additional yield gain can be realised with NPK fertiliser addition under RAP, although this reduced the net income at the rates applied. Therefore, these rates do not pay off at farmers' current rice and fertiliser prices. Based on farmer selected practices from the RAP package, the most important component was shown to be proper timing of weeding (i.e., better timing of weeding operations, depending on weed infestation levels). Therefore, further research aiming to understand differences in yield gaps between irrigated lowland rice farmers in SSA should consider bottlenecks to proper timing of weeding at farm level, including farmer knowledge and appreciation of timing, and labour constraints to this. There seems also to be a need for investigation into simple, farmer-compatible tools to facilitate timely weeding. Our findings from the farmer selected intensification practice further indicate that timely weeding applied as a single option or in combination with fertiliser use, was considered by farmers as within reach to narrow their yield gap. It remains to be tested in later seasons whether and under which conditions these farmers will apply this learning and (be able to) continue to weed their fields in a timely manner.

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**References**

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Arment, C. J. (2020). Food Dependency in Sub-Saharan Africa: Simply a Matter of ‘Vulnerability’, or Missed Development Opportunity? Development and Change, 51(2), 283-323. DOI: 10.1111/dech.12532

Awio, T., Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Kempen, B., Struik, P. C., & Stomph, T. J. (2021). Micro-nutrients in East African lowlands: Are they needed to intensify rice production? Field Crops Research, 270, 108219. DOI: 10.1016/j.fcr.2021.108219

Bado, V. B., Djaman, K., & Mel, V. C. (2018). Developing fertilizer recommendations for rice in Sub-Saharan Africa, achievements and opportunities. Paddy and Water Environment, 16(3), 571-586. DOI: 10.1007/s10333-018-0649-8

Balasubramanian, V., Sie, M., Hijmans, R. J., & Otsuka, K. (2007). Increasing Rice Production in Sub-Saharan Africa: Challenges and Opportunities. In D. L. Sparks (Ed.), Advances in Agronomy (Vol. 94, pp. 55-133): Academic Press.

Banayo, N. P. M. C., Bueno, C. S., Haefele, S. M., Desamero, N. V., & Kato, Y. (2018). Site-specific nutrient management enhances sink size, a major yield constraint in rainfed lowland rice. Field Crops Research, 224, 76-79. DOI: 10.1016/j.fcr.2018.05.006

Becker, M., & Johnson, D. E. (2001). Improved water control and crop management effects on lowland rice productivity in West Africa. Nutrient Cycling in Agroecosystems, 59(2), 119-127. DOI: 10.1023/A:1017585328904

Becker, M., Johnson, D. E., Wopereis, M. C. S., & Sow, A. (2003). Rice yield gaps in irrigated systems along an agro-ecological gradient in West Africa. Journal of Plant Nutrition and Soil Science, 166(1), 61-67. DOI: 10.1002/jpln.200390013

Chamberlin, J., Jayne, T. S., & Headey, D. (2014). Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. Food Policy, 48, 51-65. DOI: 10.1016/j.foodpol.2014.05.002

De Bauw, P., Vandamme, E., Senthilkumar, K., Lupembe, A., Smolders, E., & Merckx, R. (2019). Combining phosphorus placement and water saving technologies enhances rice production in phosphorus-deficient lowlands. Field Crops Research, 236, 177-189. DOI: 10.1016/j.fcr.2019.03.021

Fischer, R. A. (2015). Definitions and determination of crop yield, yield gaps, and of rates of change. Field Crops Research, 182, 9-18. DOI: 10.1016/j.fcr.2014.12.006

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., . . . Snyder, P. K. (2005). Global Consequences of Land Use. Science, 309(5734), 570. DOI: 10.1126/science.1111772

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., . . . Zaks, D. P. M. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337-342. DOI: 10.1038/nature10452

Haefele, S. M., Johnson, D.E., Diallo, S., Wopereis, M. C.S., Janin, I. (2000). Improved soil fertility and weed management is profitable for irrigated rice farmers in Sahelian West Africa. Field Crops Research, 66(2), 101-113. DOI: 10.1016/S0378-4290(00)00066-6

Hu, A., Tang, T., & Liu, Q. (2018). Nitrogen use efficiency in different rice-based rotations in southern China. Nutrient Cycling in Agroecosystems, 112(1), 75-86. DOI: 10.1007/s10705-018-9930-x

Jamil, M., Kanampiu, F.K., Karaya, H., Charnikhova, T., Bouwmeester, H.J. (2012). Striga hermonthica parasitism in maize in response to N and P fertilisers. Field Crops Research, 134, 1-10. DOI: 10.1016/j.fcr.2012.03.015

Jinsen., Z., N, M. W., Tomohiro, N., M, K. M., & Shinya., F. (2018). Nitrogen availability to maize as affected by fertilizer application and soil type in the

Tanzanian highlands. Nutrient Cycling in Agroecosystems, 112(2), 197-213. DOI: 10.1007/s10705-018-9939-1

Ju, C., Liu, T., & Sun, C. (2021). Panicle Nitrogen Strategies for Nitrogen-Efficient Rice Varieties at a Moderate Nitrogen Application Rate in the Lower Reaches of the Yangtze River, China. Agronomy, 11(2), 192. DOI: 10.3390/agronomy11020192

Kaizzi, K. C., Byalebeka, J., Semalulu, O., Alou, I., Zimwanguyizza, W., Nansamba, A., . . . Wortmann, C. S. (2012). Maize Response to Fertilizer and Nitrogen Use Efficiency in Uganda. Agronomy Journal, 104(1), 73-82. DOI: 10.2134/agronj2011.0181

Kamiji, Y., Yoshida, H., Palta, J. A., Sakuratani, T., & Shiraiwa, T. (2011). N applications that increase plant N during panicle development are highly effective in increasing spikelet number in rice. Field Crops Research, 122(3), 242-247. DOI: 10.1016/j.fcr.2011.03.016

Kangalawe, R. Y. M., & Liwenga, E. T. (2005). Livelihoods in the wetlands of Kilombero Valley in Tanzania: Opportunities and challenges to integrated water resource management. Physics and Chemistry of the Earth, Parts A/B/C, 30(11), 968-975. DOI: 10.1016/j.pce.2005.08.044

Kewat, M. L., Agrawal, S. B., Agrawal, K. K., & Sharma, R. S. (2002). Effect of divergent plant spacings and age of seedlings on yield and economics of hybrid rice (Oryza sativa). Indian Journal of Agronmy, 47(3), 367-371.

Khatun, A., Mollah, M. I. U., Rashid, M. H., Islam, M. S., & Khan, A. H. (2002). Seasonal Effect of Seedling Age on the Yield of Rice. Pakistan Journal of Biological Sciences, 5(1), 40-42. DOI: 10.3923/pjbs.2002.40.42

Kihara, J., & Njoroge, S. (2013). Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. Field Crops Research, 150, 1-8. DOI: 10.1016/j.fcr.2013.05.025

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., . . . Huising, J. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agriculture, Ecosystems & Environment, 229(Supplement C), 1-12. DOI: 10.1016/j.agee.2016.05.012

Koussoubé, E., & Nauges, C. (2017). Returns to fertiliser use: Does it pay enough? Some new evidence from Sub-Saharan Africa. European Review of Agricultural Economics, 44(2), 183-210. DOI: 10.1093/erae/jbw018

Kyalo, G., Chemining'wa, G., Nhamo, N., & Mussgnug, F. (2020). Effects of Improved Nursery Management, Seedling Transplanting Age and Split Nitrogen Fertilizer Application on Growth and Yield of Lowland Rice in Eastern Uganda. Journal of Agricultural Science, 12(8), 144-151. DOI: 10.5539/jas.v12n8p144

Laborte, A. G., de Bie, K., Smaling, E. M. A., Moya, P. F., Boling, A. A., & Van Ittersum, M. K. (2012). Rice yields and yield gaps in Southeast Asia: Past trends and future outlook. European Journal of Agronomy, 36(1), 9-20. DOI: 10.1016/j.eja.2011.08.005

Lampayan, R. M., Faronilo, J. E., Tuong, T. P., Espiritu, A. J., de Dios, J. L., Bayot, R. S., . . . Hosen, Y. (2015). Effects of seedbed management and delayed transplanting of rice seedlings on crop performance, grain yield, and water productivity. Field Crops Research, 183, 303-314. DOI: 10.1016/j.fcr.2015.08.014

Liu, Q., Zhou, X., Li, J., & Xin, C. (2017). Effects of seedling age and cultivation density on agronomic characteristics and grain yield of mechanically transplanted rice. Scientific Reports, 7(1), 14072. DOI: 10.1038/s41598-017-14672-7

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annual Review of Environment and Resources, 34(1), 179-204. DOI: 10.1146/annurev.environ.041008.093740

Manitra, A. R., Massimo, I., & Marianna, P. (2012). Why has Africa become a net food importer? Explaining Africa agricultural and food trade deficits. Trade and Markets Division, FAO, Rome., 89.

Mauser, W., Klepper, G., Zabel, F., Delzeit, R., Hank, T., Putzenlechner, B., & Calzadilla, A. (2015). Global biomass production potentials exceed expected future demand without the need for cropland expansion. Nature Communications, 6, 8946-8946. DOI: 10.1038/ncomms9946

Menete, M. Z. L., van Es, H. M., Brito, R. M. L., DeGloria, S. D., & Famba, S. (2008). Evaluation of system of rice intensification (SRI) component practices and their synergies on salt-affected soils. Field Crops Research, 109(1), 34-44. DOI: 10.1016/j.fcr.2008.06.003

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. Nature, 490(7419), 254-257. DOI: 10.1038/nature11420

Namyenya, A. (2014). Farmers' willingness to pay for irrigation water: the case of Doho rice irrigation scheme in eastern Uganda. MSc. Thesis, Makerere University., 90.

Ndungu-Magiroi, K. W., Kasozi, A., Kaizzi, K. C., Mwangi, T., Koech, M., Kibunja, C. N., . . . Wortmann, C. S. (2017). Finger millet response to nitrogen, phosphorus and potassium in Kenya and Uganda. Nutrient Cycling in Agroecosystems, 108(3), 297-308. DOI: 10.1007/s10705-017-9857-7

Nhamo, N., Rodenburg, J., Zenna, N., Makombe, G., & Luzi-Kihupi, A. (2014). Narrowing the rice yield gap in East and Southern Africa: Using and adapting existing technologies. Agricultural Systems, 131, 45-55. DOI: 10.1016/j.agsy.2014.08.003

Niang, A., Becker, M., Ewert, F., Dieng, I., Gaiser, T., Tanaka, A., . . . Saito, K. (2017). Variability and determinants of yields in rice production systems of West Africa. Field Crops Research, 207, 1-12. DOI: 10.1016/j.fcr.2017.02.014

Pasuquin, E., Lafarge, T., & Tubana, B. (2008). Transplanting young seedlings in irrigated rice fields: Early and high tiller production enhanced grain yield. Field Crops Research, 105(1), 141-155. DOI: 10.1016/j.fcr.2007.09.001

Pradhan, P., Fischer, G., van Velthuizen, H., Reusser, D.E., & Kropp, J.P. (2015). Closing Yield Gaps: How Sustainable Can We Be? PLoS ONE, 10(6), e0129487. DOI: 10.1371/journal.pone.0129487

Rodenburg, J., & Johnson, D. E. (2009). Weed Management in Rice-Based Cropping Systems in Africa. In D. L. Sparks (Ed.), Advances in Agronomy (Vol. 103, pp. 149-218): Academic Press.

Rodenburg, J., Saito, K., Irakiza, R., Makokha, D. W., Onyuka, E. A., & Senthilkumar, K. (2015). Labor-Saving Weed Technologies for Lowland Rice Farmers in sub-Saharan Africa. Weed Technology, 29(4), 751-757. DOI: 10.1614/WT-D-15-00016.1

Rurinda, J., Mapfumo, P., van Wijk, M. T., Mtambanengwe, F., Rufino, M. C., Chikowo, R., & Giller, K. E. (2014). Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. European Journal of Agronomy, 55, 29-41. DOI: 10.1016/j.eja.2013.12.009

Saito, K., Vandamme, E., Johnson, J.-M., Tanaka, A., Senthilkumar, K., Dieng, I., . . . Wopereis, M. C. S. (2019). Yield-limiting macronutrients for rice in sub-Saharan Africa. Geoderma, 338, 546-554. DOI: 10.1016/j.geoderma.2018.11.036

Sala, O. E., Stuart Chapin, F., Iii, Armesto, J. J., Berlow, E., Bloomfield, J., . . . Wall, D. H. (2000). Global Biodiversity Scenarios for the Year 2100. Science, 287(5459), 1770. DOI: 10.1126/science.287.5459.1770

Sanchez, P. A. (2015). En route to plentiful food production in Africa. Nature Plants, 1(1), 14014. DOI: 10.1038/nplants.2014.14

Seck, P. A., Ali, A.T., Jeanne, Y.C., Aliou D., & Wopereis, M. C.S. (2013). Africa's Rice Economy Before and After the 2008 Rice Crisis. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., & Jalloh, A. (eds). Realizing Africa's Rice Promise. CABI, 436. DOI: 10.1079/9781845938123.0024

Senthilkumar, K., Jonne, R., Ibnou, D., Elke, V., Fitta, S. S., Jean-Martial, J., . . . Kazuki, S. (2020). Quantifying rice yield gaps and their causes in Eastern and Southern Africa. In (Vol. Special Issue, pp. 13). Journal Agronomy and Crop Science: Wiley.

Senthilkumar, K., Tesha, B. J., Mghase, J., & Rodenburg, J. (2018). Increasing paddy yields and improving farm management: results from participatory experiments with good agricultural practices (GAP) in Tanzania. Paddy and Water Environment, 16(4), 749-766. DOI: 10.1007/s10333-018-0666-7

Stuart, A. M., Pame, A. R. P., Silva, J. V., Dikitanan, R. C., Rutsaert, P., Malabayabas, A. J. B., . . . Singleton, G. R. (2016). Yield gaps in rice-based farming systems: Insights from local studies and prospects for future analysis. Field Crops Research, 194, 43-56. DOI: 10.1016/j.fcr.2016.04.039

Stuart, A. M., Pame, A. R. P., Vithoonjit, D., Viriyangkura, L., Pithuncharurnlap, J., Meesang, N., . . . Lampayan, R. M. (2018). The application of best management practices increases the profitability and sustainability of rice farming in the central plains of Thailand. Field Crops Research, 220, 78-87. DOI: 10.1016/j.fcr.2017.02.005

Tanaka, A., Diagne, M., & Saito, K. (2015). Causes of yield stagnation in irrigated lowland rice systems in the Senegal River Valley: Application of dichotomous decision tree analysis. Field Crops Research, 176, 99-107. DOI: 10.1016/j.fcr.2015.02.020

Tanaka, A., Johnson, J.-M., Senthilkumar, K., Akakpo, C., Segda, Z., Yameogo, L. P., . . . Saito, K. (2017). On-farm rice yield and its association with biophysical factors in sub-Saharan Africa. European Journal of Agronomy, 85, 1-11. DOI: 10.1016/j.eja.2016.12.010

Tenywa. M.M., M., J.G.M., Yazidhi, B., Luswata, K.C., Geofrey, G.I. (2016). The effect of Land Use Practices on Pollution Dynamics in the Highlands of Uganda. In: Management and Area-wide Evaluation of Water Conservation Zones in

Agricultural Catchments for Biomass Production, Water Quality and Food Security. International Atomic Energy Agency, 79-101.

Tippe, D. E., Bastiaans, L., van Ast, A., Dieng, I., Cissoko, M., Kayeke, J., . . . Rodenburg, J. (2020). Fertilisers differentially affect facultative and obligate parasitic weeds of rice and only occasionally improve yields in infested fields. Field Crops Research, 254, 107845. DOI: 10.1016/j.fcr.2020.107845

Touré, A., Becker, M., Johnson, D. E., Koné, B., Kossou, D. K., & Kiepe, P. (2009). Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. Field Crops Research, 114(2), 304-310. DOI: 10.1016/j.fcr.2009.08.015

Tsujimoto, Y., Rakotoson, Tovohery., Tanaka, Atsuko., & Saito, Kazuki. (2019). Challenges and opportunities for improving N use efficiency for rice production in sub-Saharan Africa. Plant Production Science, 22(4), 413-427. DOI: 10.1080/1343943X.2019.1617638

Turyahabwe, N., Kakuru, W., Tweheyo, M., & Tumusiime, D. M. (2013). Contribution of wetland resources to household food security in Uganda. Agriculture & Food Security, 2(1), 5. DOI: 10.1186/2048-7010-2-5

United Nations, D. o. E. a. S. A., Population Division. (2019). World Population Prospects 2019: Highlights (ST/ESA/SER.A/423). 46.

van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. Field Crops Research, 143, 4-17. DOI: 10.1016/j.fcr.2012.09.009

van Ittersum, M. K., van Bussel, L. G. J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., . . . Cassman, K. G. (2016). Can sub-Saharan Africa feed itself? Proceedings of the National Academy of Sciences, 113(52), 14964. DOI: 10.1073/pnas.1610359113

van Oort, P. A. J., Saito, K., Tanaka, A., Amovin-Assagba, E., Van Bussel, L. G. J., van Wart, J., . . . Wopereis, M. C. S. (2015). Assessment of rice self-sufficiency in 2025 in eight African countries. Global Food Security, 5, 39-49. DOI: 10.1016/j.gfs.2015.01.002

van Wart, J., Kersebaum, K.C., Peng, S., Milner, M. & Cassman, K.G. (2013). Estimating crop yield potential at regional to national scales. Field Crops Research, 143, 34-43. DOI: 10.1016/j.fcr.2012.11.018

Vandamme, E., Ahouanton, K., Mwakasege, L., Mujuni, S., Mujawamariya, G., Kamanda, J., . . . Saito, K. (2018). Phosphorus micro-dosing as an entry point to sustainable intensification of rice systems in sub-Saharan Africa. Field Crops Research, 222, 39-49. DOI: 10.1016/j.fcr.2018.02.016

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., & Six, J. (2011). Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant and Soil, 339(1), 35-50. DOI: 10.1007/s11104-010-0462-7

Vollset, S. E., Goren, E., Yuan, C.-W., Cao, J., Smith, A. E., Hsiao, T., . . . Murray, C. J. L. (2020). Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. The Lancet, 1285–1306. DOI: 10.1016/S0140-6736(20)30677-2

Waddington, S. R., Li, X., Dixon, J., Hyman, G., & de Vicente, M. C. (2010). Getting the focus right: production constraints for six major food crops in Asian and African farming systems. Food Security, 2(1), 27-48. DOI: 10.1007/s12571-010-0053-8

Wanyama, J., Ssegane, H., Kisekka, I., Komakech, A. J., Banadda, N., Zziwa, A., . . . Lubwama, K. F. (2017). Irrigation Development in Uganda: Constraints, Lessons Learned, and Future Perspectives. J. Irrig. Drain Eng., 143(5), 10.

Zabel, F., Delzeit, R., Schneider, J. M., Seppelt, R., Mauser, W., & Václavík, T. (2019). Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. Nature Communications, 10(1), 2844. DOI: 10.1038/s41467-019-10775-z

Zhang, Z., Chu, G., Liu, L., Wang, Z., Wang, X., Zhang, H., . . . Zhang, J. (2013). Mid-season nitrogen application strategies for rice varieties differing in panicle size. Field Crops Research, 150, 9-18. DOI: 10.1016/j.fcr.2013.06.002

Zhou, W., Tengfei, L., Yong, C., Hu, J., Zhang, Q., Ren, W. (2017). Late nitrogen application enhances spikelet number in indica hybrid rice (Oryza sativa L.). Scientia Agricola, 74(2), 127-133. DOI: 10.1590/1678-992X-2016-0094

## Supplementary materials in Chapter 3

**Supplementary Table S3.1** On-farm grain yield (g $m^{-2}$) for four treatments and four different planting lots, Doho, 2019. Planting lot 1 corresponds to the dry season, planting lots 2 and 3 were planted during the first rainy season and planting lot 4 during the second rainy season.

| Treatment | Planting lot | | | |
|---|---|---|---|---|
| | 1 (January) | 2 (March) | 3 (April) | 4 (August) |
| FP | 324 (se=8.7, n=21 ) | 327 (se=14.2, n=8) | 385 (se=6.0, n=45) | 351 (se=6.3, n=40) |
| FIP | 359 (se=10.5, n=14) | 466 (se=27.9, n=2) | 430 (se=8.4, n=22) | 383 (se=9.5, n=17) |
| RAP | 364 (se=8.7, n=21 ) | 397 (se=14.2, n=8) | 433 (se=6.0, n=45) | 385 (se=6.3, n=40) |
| RAP+NPK | 445 (se=22.7, n=3) | 422 (se=39.3, n=1) | 501 (se=12.4, n=10) | 451 (se=17.6, n=5) |

The different planting lots had no significant effect ($p>0.24$) on grain yield for the different treatments. FP = farmers' practice, FIP = farmers' intensification practice; RAP = recommended agronomic practices without fertilisation; RAP+NPK = recommended agronomic practices combined with NPK fertilisation; se = standard error of means; n = number of fields planted for each treatment in a planting lot. Month in parentheses is the planting time for the lot.

# 4

# CHAPTER 4.

## Indigenous nutrient supply, weeding and fertilisation strategies influence on-farm N, P and K use efficiency in lowland rice

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**Abstract**

Enhancing use efficiency of applied fertiliser increases farmers' returns on fertiliser investment through reducing nutrient inputs and improving yields. We investigated on-farm how indigenous nutrient supply and management practices affected N, P, and K uptake, agronomic efficiency and recovery efficiency of fertiliser, and physiological efficiency of nutrients taken up, under irrigated lowland rice conditions in Uganda. Treatments included recommended agronomic practices (RAP) without fertilisation, farmers' practice (FP), farmers' selected intensification practice (FIP), and RAP with NPK fertilisation (RAP+NPK). Indigenous N, P, and K supply varied greatly among farmers' fields. N, P, and K uptake were significantly higher under RAP+NPK than RAP, FP, and FIP; however, physiological efficiency (PE; kg grain $kg^{-1}$ nutrient uptake) was significantly lower under RAP+NPK by 19% (N), and 12% (P/K), due to a larger effect of NPK application on uptake than on yield, leading to higher tissue concentrations. Indigenous available N reduced apparent N recovery, and agronomic and physiological N efficiencies independent of treatment. Also, P and K PEs decreased with increasing indigenous supply. Delaying weeding beyond recommended time, in interaction with indigenous N supply, decreased agronomic N efficiency; but increased PE of N. Interaction between P rate and timing reduced its PE; K rate and weeding time interaction reduced its PE. The decrease in efficiencies at high indigenous supply and delayed weeding indicates a need for site-specific fertilisation strategies based on naturally available nutrient levels and proper weeding. Weeding and fertilisation timing directly affect nutrient use efficiency, and therefore, fertiliser use efficiency in rice production systems.

**Keywords:** Apparent recovery, agronomic efficiency, recovery efficiency, physiological efficiency, *Oryza sativa*

## 4.1 Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops in sub-Saharan Africa (SSA), the most rapidly growing food commodity, and the second largest source of caloric intake after maize (Bado et al., 2018; Tsujimoto et al., 2019). Rice is mostly grown by smallholder farmers, and yields are generally low. Yet, demand is projected to continue to rise due to high population growth rate, rapid urbanisation, and increasing consumer preference for rice (Balasubramanian et al., 2007; Tanaka et al., 2017; Tsujimoto et al., 2019). Because of the low yields, current local production does not meet the growing demand, and consumption is satisfied through imports. However, import dependence to meet the demand could worsen food insecurity and poverty (Tanaka et al., 2017). Moreover, improving rice production is not only important for improving country-level food security, but is also vital for enhancing household income, alleviating poverty, and promoting socio-economic growth of rice farmers (Seck et al., 2013; Tanaka et al., 2015).

Fertilisers are reported as a yield enhancing input (Awio et al., 2021; Bado et al., 2018; Kwesiga et al., 2019; Niang et al., 2017; Saito et al., 2019). While rice yields can be augmented through fertilisation, large variation in yield responses to fertiliser application has been observed among farmers' fields within the same growing environment. For instance, in a participatory study under irrigated lowland condition on farmers' fields in Uganda, grain yields ranged from 4.3 to 7.0 t $ha^{-1}$ under researcher-supervised management practices including 100, 50 and 50 kg $ha^{-1}$ N, P and K applications, respectively (Awio et al., 2022). Under farmers' N rates ranging from 6.8 to 46 kg N $ha^{-1}$, grain yield varied between 3.2 to 6.5 t $ha^{-1}$. Likewise, Saito et al. (2019) reported grain yields between 0.8 and 2.3 t $ha^{-1}$ on-farm with 160, 25 and 70 kg $ha^{-1}$ N, P and K, respectively, at the same location in Uganda. In several other rice growing environments in SSA, this large yield variation among fields has been observed under the same growing conditions, when the same amounts of N, P and K were applied; with the highest variation of 0.1 to 7.2 t $ha^{-1}$ grain yield with 110, 20 and 50 kg $ha^{-1}$ N, P and K, respectively, observed in Benin under rainfed lowland condition (Saito et al., 2019). These differences in yield response to fertilisation among fields under similar growing conditions could reflect differences in soil indigenous nutrient supply (Haefele & Wopereis, 2005; Kihara & Njoroge, 2013; Vanlauwe et al., 2006). Indigenous nutrient supply is "*the total amount of a particular nutrient that is available to crops from the soil during a cropping cycle*", as "estimated by measuring plant nutrient uptake in a nutrient omission plot" (Witt & Dobermann, 2002). It can originate from incorporated crop residues, residual organic and inorganic nutrients from previous nutrient

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applications, biological fixation, irrigation or flood water, atmospheric deposition, and soil weathering (Cui et al., 2008; Dobermann et al., 2003a; Witt & Dobermann, 2002).

Indigenous nutrient supply determines yield response to fertilisation, where yield response to applied nutrients has been observed to be low when indigenous nutrient supply is high (Kihara et al., 2016; Kihara & Njoroge, 2013; Saito et al., 2015; Saito et al., 2019; Vanlauwe et al., 2011). Likewise, use efficiency of fertiliser nutrients is observed to be low at higher soil nutrient supply (Haefele & Wopereis, 2005; Haefele et al., 2003; Kihara & Njoroge, 2013; Vanlauwe et al., 2011). Fertiliser application rate and timing, weeding time and the associated weed infestation levels, other crop management practices, and climatic conditions also influence fertiliser nutrient use efficiency (Davies et al., 2020; Tippe et al., 2020; Xu et al., 2016; Zemichael et al., 2017). While indigenous nutrient supply is shown to determine fertiliser nutrient use efficiency, its interaction with crop management practices, for instance timing of weeding – the most important component of management practices (Awio et al., 2022), could further influence use efficiency of fertiliser nutrients. However, there is no clear evidence of the effect of interaction between indigenous nutrient supply and crop management practices on fertiliser nutrient use efficiency. Current fertiliser recommendations for site-specific nutrient management are based on indigenous nutrient supply (Chivenge et al., 2021; Dobermann et al., 2002) without consideration for proper weed management, which may make such recommendations inefficient when fertilisers are applied, and weeding is not done timely. Some of the agronomic indices used to describe nutrient use efficiency include agronomic efficiency (AE) – kg grain yield increase $kg^{-1}$ nutrient applied; recovery efficiency (RE) – kg increase in nutrient uptake $kg^{-1}$ nutrient applied; and physiological efficiency (PE) – kg grain $kg^{-1}$ nutrient uptake (Cassman et al., 1998; Dobermann, 2007; Li et al., 2014).

In SSA, fertilisers remain an expensive crop production input for most rice farmers, resulting in farmers' actual application rates being lower than recommended rates. Ensuring good nutrient use efficiency of the applied fertiliser is important for increasing both fertiliser use and rice yield (Tsujimoto et al., 2019; Vanlauwe et al., 2011). This could ensure that farmers achieve positive returns from fertiliser investments, while avoiding negative environmental effects, including contribution to greenhouse gas emissions, and loss of excess nutrients to surface and underground water. The objective of the present study was, therefore, to understand the effect of the interaction between indigenous nutrient supply and management practices in shaping nutrient uptake and use efficiency on-farm, under irrigated lowland rice conditions. Previous studies indicate that an increase in indigenous nutrient supply reduces agronomic and recovery efficiency of applied nutrients, and physiological efficiency of nutrients taken-up. The latter implies nutrient concentrations in biomass increase. We hypothesise an interaction between indigenous nutrient supply with timing of weeding and of fertilisation, which are a challenge to rice farmers in Uganda in particular, and SSA at large. Agronomic and recovery efficiency of applied nutrients, and the physiological efficiency of nutrients taken-up are expected to decline as indigenous nutrient supply increases, due to a reduction in uptake of applied nutrients and an increase in biomass nutrient concentrations. The reduction in agronomic and recovery efficiencies will be stronger with delayed weeding and fertilisation, while delayed weeding and fertilisation will also reduce the physiological efficiency due to a reduction in uptake of applied nutrients.

## 4.2 Materials and methods

### 4.2.1 Trial site, design and treatments

The trials used for the current analysis were participatory trials involving farmers and researchers, conducted on farmers' fields between January and December 2019, in the Doho rice irrigation scheme in Butaleja district (34°02' E, 0°56' N), Eastern Uganda. The Doho rice irrigation scheme is the largest public rice irrigation scheme in Uganda (Wanyama et al., 2017), covering an area of 1000 ha, of which 952 ha is cultivated by over 4000 smallholder farmers. The scheme lies at an elevation of 1100 m above sea level and the annual mean temperature in the area is 22.7°C, ranging from 15.4°C to 30.7°C. It is characterised by a bimodal rainfall pattern, with peaks in March–May and August–October, with a mean annual rainfall of 1186 mm. The soils are plinthosols, reddish brown in colour, sandy loam, and loam textured (Awio et al., 2022). Currently, the scheme is divided into 11 blocks; each block is sub-divided into 5–15 strips, and each strip has 20–30 farmers.



The scheme has been under lowland rice growing by smallholder farmers for about four decades (Sserunkuuma et al., 2003), where rice is cultivated in a monoculture system, with 2–3 crops planted per year in the same field. Irrigation management is similar across fields based on water release schedules for the different blocks drawn by the scheme's management, in addition to rainfall. Farmers incorporate rice straw from the previous crop during land preparation; no external sources of organic input are applied. Varied amounts of inorganic fertilisers, especially N, are used by farmers, ranging from 0 to about 50 kg N ha$^{-1}$ and almost no P and K (Awio et al., 2022). Farmers from all blocks were invited to participate in the trials. The fields used for the participatory trials were from farmers that decided to participate, while participation from all blocks was guaranteed. For each planting period, interested farmers who had fields ready for planting offered their plots for use in conducting the trials. A total of 47 farmers' fields spread across all the 11 blocks within the scheme were used.

In the trials, farmers differed in nutrient application rates, and on plots with researcher proposed rates, 100, 50 and 50 kg ha$^{-1}$ N, P and K, were applied, respectively. Treatments included: (i) recommended agronomic practices without fertilisation (RAP) as a control, which represented optimal management practices (Awio et al., 2022). This treatment was jointly managed by farmers and researchers, whereby individual farmers executed a given management practice under the researcher's supervision (Table 4.1). (ii) Farmers' practice (FP), which represented all the management practices currently undertaken by farmers. The treatment was fully under farmers' management, where all farmers implemented their individual management practices, and records of such management practices were taken. (iii) Recommended agronomic practices with NPK fertilisation (RAP+NPK), where in addition to optimal management practices, N, P, and K were applied at 100, 50 and 50 kg ha$^{-1}$, respectively, as urea, triple superphosphate, and muriate of potash. All P was applied as basal, 2 weeks after transplanting (WAT). N and K were split into 50, 25 and 25%, and applied 2 WAT, at panicle initiation and at flowering, respectively. This plot was also jointly managed by the farmers and researchers. (iv) Farmers' best selected management practices as their next feasible step to intensification (farmers' intensification practice, FIP). Here individual farmers implemented what they considered as their best set of practices to improve their own yield. Hence, different farmers implemented different practices (Table 4.1). This plot was fully managed by the farmers and records of all management practices were taken.

For all treatment plots, ploughing was done by the farmers following their common practice: two ploughings using either a hand hoe or an ox-plough. First and second ploughing were done at 2–3 weeks and 1 or 2 days before transplanting, respectively. All fields were properly bunded by default because the bunds act as boundaries between farmers' fields. For practical reasons, levelling was completed in the whole farmer's field, using a hand hoe, before treatment plots were installed, making all treatments conducted on equally well levelled fields. In addition to rainfall, water was supplied three days per week by irrigation to all treatment plots in a field, based on the water release schedule for the different blocks. For FP and FIP plots, all the farmers applied the fertiliser once, with application timing varying from farmer to farmer. All treatment plots were weeded manually using a hand hoe, once during the crop growth cycle, as is common practice at the study site, with timing of weeding varying among farmers. Bird control was by physical scaring of birds from the grain-filling stage until harvest.

Different farmers implemented different number of treatments, with all farmers having the recommended agronomic practices (RAP) as control plot. An individual farmer's field was divided into plots and these plots were randomly allocated to the treatments selected and implemented by the farmer, and each farmer was considered a replicate. Planting was done in January, March, April, and August 2019, with overall three crops evaluated across the year. The January crop was the first crop, planted in the dry season, and depended mostly on irrigation water with little rainfall. March and April, and August plantings were the second and third crops, planted in the first and second rainy seasons of the year, respectively, and fully utilised the rainfall with supplementary irrigation. Short-duration rice varieties K 98 and K 85, commonly cultivated by farmers within the study site, were used. Within each farmer's field, each treatment had a plot size of 10 m × 10 m, and a harvest area of 4 m × 4 m marked from the centre of each treatment plot was used for grain yield assessment.

**Table 4.1** Summary of treatments evaluated and associated management practices.

| Treatment | Management practices |
|---|---|
| Recommended agronomic practices without fertilisation (RAP, n = 47) | Transplanting time (23 – 33 DAS), line transplanting, timely weeding (14 – 25 DAT), and no fertilisation. |
| Farmers' practice (FP, n = 37) | Farmers implemented different management practices: transplanting time (23 – 39 DAS), transplanting method (line or random), weeding time (15 – 39 DAT), and N rate (13.8 – 46 kg $ha^{-1}$) as urea, applied once 20 – 65 DAT, no P and K. |
| Recommended agronomic practices with NPK fertilisation (RAP+NPK, n = 19) | Transplanting time (25 – 33 DAS), line transplanting, timely weeding (15 – 22 DAT), and 100, 50 and 50 kg $ha^{-1}$ N, P and K. |
| Farmers' intensification practice (FIP, n = 43) | Farmers implemented different management practices: transplanting time (23 – 39 DAS), transplanting method (line or random), weeding time (15 – 39 DAT), and N (6.8 – 46 kg $ha^{-1}$), P and K (0 – 27.2 kg $ha^{-1}$) as urea or NPK blend all applied once 15 – 71 DAT. |

Field tillage, bunding, levelling and number of weeding operations were identical across treatments for all farmers. Under farmers' intensification practice, improved management practices implemented by these farmers were different from their farmers' practice. DAS = days after sowing, DAT = days after transplanting, n = number of farmers' fields where the different treatments were implemented.

### 4.2.2 Estimating effects of indigenous nutrient supply and weeding time delay

To estimate the effect of the indigenous supply of N, P and K of individual farmers' fields, an estimate of such supply under RAP is needed. Two methods have been used in the literature, one is the amount of N, P or K taken up by a crop species under zero fertilisation, but otherwise good management (Haefele et al., 2003). The alternative method is to measure the amount of N, P or K taken up by a crop while other nutrients are made unlimited through the so-called omission plot technique (Dobermann et al., 2003b; Haefele & Wopereis, 2005; Witt & Dobermann, 2002). The latter is a better estimate to establish recommendations for optimal fertilisation or a potential supply capacity. The former, though, provides a better estimate of indigenous supply under (good) farmer practice and conditions. As the current paper aims to analyse how the apparent nutrient uptake from fertilisation is affected by the indigenous supply when no nutrients are provided, the uptake under no fertilisation suits best and is thus used as an estimate for indigenous nutrient supply (for N, P and K denominated, respectively, as INS, IPS and IKS).

Weeding time is defined as the time of weeding (in days) after transplanting. Recommended weeding time was considered as weeding time in RAP plots after transplanting, which was between 14 and 25 days after transplanting. Weeding time delay for a given FP or FIP plot was taken as the number of days weeding was done in FP or FIP plot after weeding in RAP plot, .i.e., the difference in weeding time between RAP and FP or FIP plots. Weeding time delay was 0 if weeding in RAP and FP/FIP plots was done on the same day, and greater than 0 if weeding in FP/FIP plot was done after weeding in RAP plot. Weeding time delay varied between 0-20 days.

### 4.2.3 Plant analysis

At harvest, 12 sample hills were systematically selected from within 1 m outside the 4 m × 4 m harvest area (Awio et al., 2022), and plants cut at soil surface level. Sample hills were threshed, and straw, filled, and empty grains, were separately oven-dried at 70°C to a constant weight. Dry matter harvest index (HI) was calculated as the ratio of filled grains over total above-ground biomass of the sample hills. For each treatment plot, a sub-sample of the straw, filled, and empty grains was reconstituted to make a single sample. Each sample was ground into a fine powder using a high-speed vibrating sample mill (Model CT 293 Cyclotec™, Foss Analytical A/S, Denmark) for analysis of N, P, and K tissue concentrations. Total tissue N concentration was analysed by the Dumas combustion method using a TruMac® CN (LECO Corporation, USA) elemental analyser. Total P and K tissue concentrations were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) with a Thermo-Fisher Scientific iCAP-Q (Thermo Fisher Scientific, Germany) analyser. Chemical analyses were done at the School of Biosciences laboratory, University of Nottingham, UK.

Plant N, P and K uptake was calculated from concentrations in total above-ground dry matter. Total above-ground dry matter was derived from HI of the 12 sample hills and grain yield (from the 4 m × 4 m harvest area) at 14% moisture content. Indigenous N, P and K supply of each farmer's field was estimated by measuring N, P and K uptake in total above-ground dry matter of recommended agronomic practices (RAP) plots where no nutrients were applied but otherwise management was optimal. Apparent recovery of N, P and K from applied fertiliser was calculated as the difference between total uptake in the fertilised plot and uptake in the unfertilised plot under RAP.

### 4.2.4 Statistics



Data were subjected to analysis of variance (ANOVA) using an unbalanced treatment structure in Genstat ($19^{th}$ edition) at 5% probability, where the different farmers' fields were taken as blocks. Where differences among treatments were significant, Fisher's unprotected least significant difference test was used to separate treatment means. Homogeneity of variances and normality of data distribution were checked using Bartlett's and Shapiro–Wilk tests, respectively. During analysis, planting period was included as a covariate; however, its effect alone or in interaction with the different treatments was not significant ($p>0.18$) so it was then dropped. To quantify the effect of soil indigenous nutrient supply and management practices on apparent recovery, agronomic and recovery efficiency of applied nutrients, and physiological efficiency of nutrients taken up, all treatment data on indigenous N, P, and K supply, weeding time, fertiliser amount and application time were subjected to multiple regression analysis using a generalised linear model following a stepwise regression procedure.

## 4.3 Results

### 4.3.1 Agronomic and recovery efficiencies of applied nutrients

Agronomic efficiency (AE) and recovery efficiency (RE) of N, P and K were not significantly different among treatments ($p \geq 0.06$, Table 4.2). However, apparent recovery of fertiliser nutrients differed significantly ($p < 0.001$) among treatments. AE of N varied from -100 to 68.8, -85.9 to 75.7 and -0.5 to 22.2 kg grain $kg^{-1}$ N applied, under FP, FIP and RAP+NPK, respectively. RE of N ranged between -2.2 and 1.8, -1.8 and 2.1, and –0.04 and 0.9 kg N in plant tissue per kg N applied, respectively, under FP, FIP and RAP+NPK. N, P and K apparent recoveries were higher in the RAP+NPK treatment, averaging 43.1, 7.5 and 55.8 kg N, P and K $ha^{-1}$, respectively. Average N apparent recovery was -2.2 kg $ha^{-1}$ under FP, which was not statistically different from 3.5 kg $ha^{-1}$ in FIP plot. P and K apparent recoveries were on average 0.03 and 0.98 kg $ha^{-1}$, respectively, under FIP.

AE of P or K ranged from -18.1 to 62.0 and -1.1 to 44.4 kg grains $kg^{-1}$ nutrient applied, respectively, under FIP and RAP+NPK. RE of P was between -0.4 and 0.4 and between 0.01 and 0.4, and for K between -2.2 and 5.1 and between -0.3 and 2.9 kg nutrient in plant tissue $kg^{-1}$ nutrient applied, respectively, under FIP and RAP+NPK. Negative agronomic and recovery efficiency values indicate poor utilisation of the applied nutrients by crops, whereby their uptake and subsequent use in grain production were lower than when no fertiliser was applied but practices were as recommended (RAP).

**Table 4.2** Agronomic and recovery efficiencies of N, P and K for different treatments on-farm under irrigated lowland condition, Doho – Uganda, 2019

| **Treatment** [a] | **RE (kg nutrient in plant tissue $kg^{-1}$ nutrient applied)**[b] | | | **AE (kg grain $kg^{-1}$ nutrient applied)**[c] | |
|---|---|---|---|---|---|
| | N | P | K | N | P or K [d] |
| FP | -0.14 | -[e] | -[e] | -7.42 | -[e] |
| FIP | 0.25 | 0.00 | 0.22 | 6.32 | 18.2 |
| RAP+NPK | 0.41 | 0.15 | 1.12 | 8.41 | 17.9 |
| **S.e.d.** | 0.16 | 0.05 | 0.35 | 5.39 | 6.33 |
| **p-value** | 0.08 | 0.06 | 0.11 | 0.06 | 0.93 |

[a] FP = farmers' practice, FIP = farmers' intensification practice, RAP+NPK = recommended agronomic practices with NPK fertilisation. [b] Recovery efficiency, [c] agronomic efficiency, [d] P and K were always applied in the ratio of 1:1, resulting in identical AE values. [e] P or K were not applied under FP.

### 4.3.2 Nutrient uptake and physiological efficiency

Uptake of N, P and K was significantly ($p<0.001$) different among treatments. RAP+NPK had the highest N, P and K uptake, while N, P and K uptake was similar under RAP, FP and FIP (Table 4.3). There was a large variation in uptake among plots of the same treatment with and without fertilisation, ranging from 52.9 – 176, 12.7 – 46.4, and 81.9 – 324 kg $ha^{-1}$ N, P and K, respectively (Supplementary Figure 4.1), indicating differences in indigenous nutrient supply capacity among farmers' fields. The different planting periods had no significant effect ($p>0.18$) on nutrient uptake under the different treatments (Supplementary Table S4.1). Physiological efficiency (PE) of N, P and K differed significantly ($p<0.05$) among treatments, where RAP, FP and FIP had higher PE of N, P and K compared with RAP+NPK (Table 4.3). N, P and K PE values were on average 18.9, 12.1 and 11.5%, respectively, lower under RAP+NPK compared with RAP, FP and FIP. There was no statistical difference in PE of N, P and K between RAP, FP and FIP. Likewise, across treatments PE varied two- to three-fold among plots with the same treatment, for N, P and K, respectively, from 30.7 – 73.7, 116 – 305, and 18.9 – 49.4 kg grains $kg^{-1}$ uptake (Supplementary Figure 4.2). The significantly lower PE of N, P and K observed under RAP+NPK was mainly due to a larger positive effect of RAP+NPK on N, P and K uptake, compared with a smaller positive effect on grain yield, whereby the increase in uptake was on average twice as much as the increase in yield. This increase in N, P and K uptake resulted in a higher total biomass production with a higher nutrient concentration and a lower dry matter HI for RAP+NPK, compared with RAP, FP and FIP. Lower PE of N could be explained by the large increase (16.1%) in N concentration with a decrease (6.3%) in dry matter HI compared with RAP. For P and K PE, dry matter HI and P and K concentration could explain roughly to a similar extent the decrease in PE under RAP+NPK, with P and K concentration in biomass increasing by 5.5 and 7.4%, respectively, compared with RAP (Table 4.3). The lack of significant differences in PE of N, P and K between RAP, FP and FIP could be attributed to the fact that changes in N, P and K uptake under FP and FIP compared with RAP were roughly the same, while also the magnitude of change in dry matter HI, and N, P and K tissue concentrations were comparable.

**Table 4.3** Nutrient use efficiency indices, grain yield, dry matter harvest index, and biomass nutrient concentration for different treatments on-farm under irrigated lowland condition, Doho – Uganda, 2019.

| **Treatment** [a] | **Uptake (kg nutrient ha$^{-1}$)** | | | **PE (kg grain/kg uptake)**$^{b}$ | | | **Grain yield (× 10$^{1}$ kg ha$^{-1}$)** | **Total biomass (× 10$^{2}$ kg ha$^{-1}$)** | **Dry matter HI (%)**$^{c}$ | **Nutrient concentration (g kg$^{-1}$)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | N | P | K | | | | N | P | K |
| RAP | 89.6$^{a}$ | 24.5$^{a}$ | 161$^{a}$ | 53.5$^{b}$ | 197$^{b}$ | 31.0$^{b}$ | 476$^{ab}$ | 112$^{a}$ | 42.9$^{b}$ | 8.06$^{a}$ | 2.19$^{b}$ | 14.3$^{a}$ |
| FP | 86.8$^{a}$ | 23.1$^{a}$ | 153$^{a}$ | 53.4$^{b}$ | 202$^{b}$ | 30.7$^{b}$ | 456$^{a}$ | 109$^{a}$ | 42.2$^{b}$ | 7.98$^{a}$ | 2.13$^{a}$ | 14.0$^{a}$ |
| FIP | 93.5$^{a}$ | 24.4$^{a}$ | 162$^{a}$ | 53.1$^{b}$ | 204$^{b}$ | 31.1$^{b}$ | 489$^{b}$ | 115$^{a}$ | 42.9$^{b}$ | 8.15$^{a}$ | 2.12$^{ab}$ | 14.1$^{a}$ |
| RAP+NPK | 130$^{b}$ | 32.2$^{b}$ | 215$^{b}$ | 43.3$^{a}$ | 177$^{a}$ | 27.4$^{a}$ | 553$^{c}$ | 139$^{b}$ | 40.2$^{a}$ | 9.36$^{b}$ | 2.31$^{c}$ | 15.3$^{b}$ |
| **S.e.d.** | 3.38 | 0.82 | 6.14 | 1.15 | 4.64 | 1.00 | 11.8 | 3.09 | 0.67 | 0.16 | 0.04 | 0.35 |
| **p-value** | <0.001 | <0.001 | <0.001 | <0.001 | <0.010 | 0.03 | <0.001 | <0.001 | <0.010 | <0.001 | <0.001 | 0.02 |

[a] RAP = recommended agronomic practices without fertilisation, FP = farmers' practice, FIP = farmers' selected intensification practices, RAP+NPK = recommended agronomic practices with NPK fertilisation. [b] Physiological efficiency and [c] Harvest index (ratio of grain yield and total above-ground dry matter of 12 sample hills given as %). Values followed by the same letters are not different according to Fisher's unprotected LSD test.

### 4.3.3 Factors driving on-farm use efficiency of applied nutrients

#### 4.3.3.1 Agronomic efficiency of applied nutrients

Multiple linear regression analyses were made, first with the combined data from plots under farmers' management practices (combining farmers' practice and farmers' intensification practice plots). Agronomic efficiency (AE) of applied N was influenced by soil indigenous N supply (INS), and an interaction between INS and the delay in weeding, compared with recommended weeding time. Indigenous N supply had a negative effect on AE, whereby one kg ha$^{-1}$ increase in indigenous N uptake resulted in a reduction of AE by 0.8 kg grain kg$^{-1}$ N applied. The interaction of weeding time delay and INS reduced AE by 0.02 kg kg$^{-1}$ (Model 1A, Table 4.4). Agronomic efficiency predictions from the model indicated that an increase in INS with an increase in delayed weeding would result in a reduction in AE, with a larger reduction at higher levels of INS (Figure 4.1A).

A second multiple linear regression was made on data combining plots under farmers' practice (FP), farmers' intensification practice (FIP) and recommended agronomic practices plus an application of 100 kg N and 50 kg P and K ha$^{-1}$ (RAP+NPK). Likewise, INS, and an interaction between INS and the delay in weeding compared with recommended weeding time were the main determinants of N AE. In contrast, the AEs of P and K were unaffected by any of these factors. An increase in INS by a kg ha$^{-1}$ reduced AE of N by 0.7 kg kg$^{-1}$ (Model 1B). The interaction between INS and weeding time delay reduced AE by 0.02 kg kg$^{-1}$. AE predictions from the model showed that AE would be reduced with increasing INS and delayed weeding, with larger reductions at higher levels of INS and delayed weeding (Figure 4.1B).

#### 4.3.3.2 Apparent recovery and recovery efficiency of applied nutrients

Multiple linear regression analysis of the combined data from plots under farmers' management practices (farmers' practice and farmers' intensification practice plots) showed that apparent N recovery from applied fertiliser was influenced by soil INS, and an interaction between fertilisation timing and the delay in weeding, compared with recommended weeding time. Apparent N recovery by the rice crop decreased with increasing soil INS, indicating a negative effect of high indigenous N supply on the apparent recovery of applied N (Model 2A, Table 4.4). Both a delay in weeding time and late fertilisation had a negative effect on apparent recovery of applied N and these effects strengthened each other (Model 2A, Table 4.4); together they affected the intercept with the x-axis of the relation between apparent N recovery and indigenous N supply, where the intercept shifted to the right with timely weeding (Figure 4.2A).

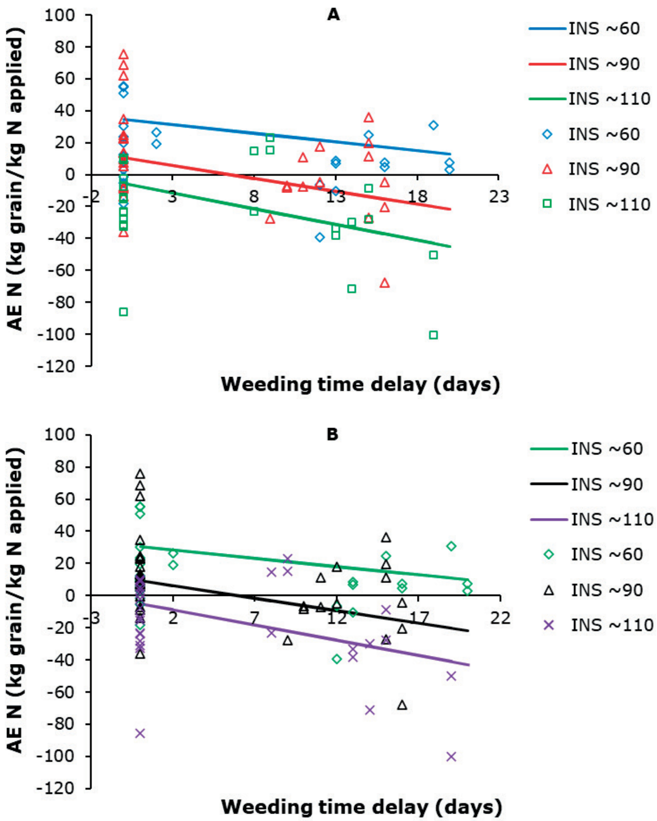


**Figure 4.1** Agronomic efficiency (AE) of N under FP and FIP (**A**) and across FP, FIP and RAP+NPK (**B**) as affected by indigenous N supply (INS; kg ha$^{-1}$), and the interaction between INS and weeding time delay (days after weeding in recommended agronomic practices, RAP, plot), Doho, 2019. Regression lines are fitted for predicted AE values from Models 1A and 1B, respectively. Data points are observed AE values from FP and FIP; and FP, FIP and RAP+NPK plots, respectively. FP = farmers' practice; FIP = farmers' intensification practice; and RAP+NPK = recommended agronomic practices combined with 100, 50 and 50 kg ha$^{-1}$, respectively, N, P and K application.

Combining data from plots under farmers' practice (FP), farmers' intensification practice (FIP) and recommended agronomic practices plus NPK application (RAP+NPK), the multiple linear regression showed that application of N shifted the intercept with the y-axis of the relation between apparent N recovery and indigenous N supply upwards, but this recovery was reduced by both delay in weeding and indigenous N supply (Model 2B, Table 4.4 and Figure 4.2B). There was an indication that lower N applications (for instance, up to 35 kg $ha^{-1}$) under timely weeding and in fields with indigenous N supply of around 60 kg $ha^{-1}$ would still have decent apparent N recovery. However, a fortnight delay in weeding would bring apparent N recovery to almost zero, while even at timely weeding such N application rate would make no sense at indigenous N supply levels of around 100 kg $ha^{-1}$ or higher (Figure 4.2B).

Recovery efficiency (RE) of applied nitrogen under farmers' management practices (FP and FIP), and across FP, FIP and RAP+NPK was only significantly ($p<0.001$) influenced by a delay in weeding time compared with recommended weeding time. A delay in weeding by one day reduced RE of N by 0.04 kg N in plant tissue kg−1 N applied (Model 5, Table 4.4). There was a large variation in RE across weeding time delays, where a 14 day delay in weeding compared to recommended weeding time had most of the lowest RE values (Supplementary Figure 4.3).



Apparent recovery of P across FIP and RAP+NPK plots was affected by P application rate, whereby recovery of applied P increased with amount of P applied (Model 3, Table 4.4). Estimation from the regression model showed that P application at rates below 15 kg $ha^{-1}$ in these fields would not be useful as apparent recovery of the applied P would be negative (Figure 4.3A). Apparent P recovery was, however, not affected by soil indigenous P supply (IPS), weeding or fertilisation time (Supplementary Figure 4.4). Similarly, apparent recovery of fertiliser K was influenced by amount of K applied, in which apparent recovery increased with increasing K application rate (Model 4, Table 4.4). Like P, K applications below ca. 15 kg $ha^{-1}$ would make no sense, as the apparent K recovery would be negative (Figure 4.3B). Also, apparent K recovery was not affected by indigenous K supply (IKS), weeding or fertilisation time (Supplementary Figure 4.5). Recovery efficiencies of applied P and K were not affected by any of the management factors.

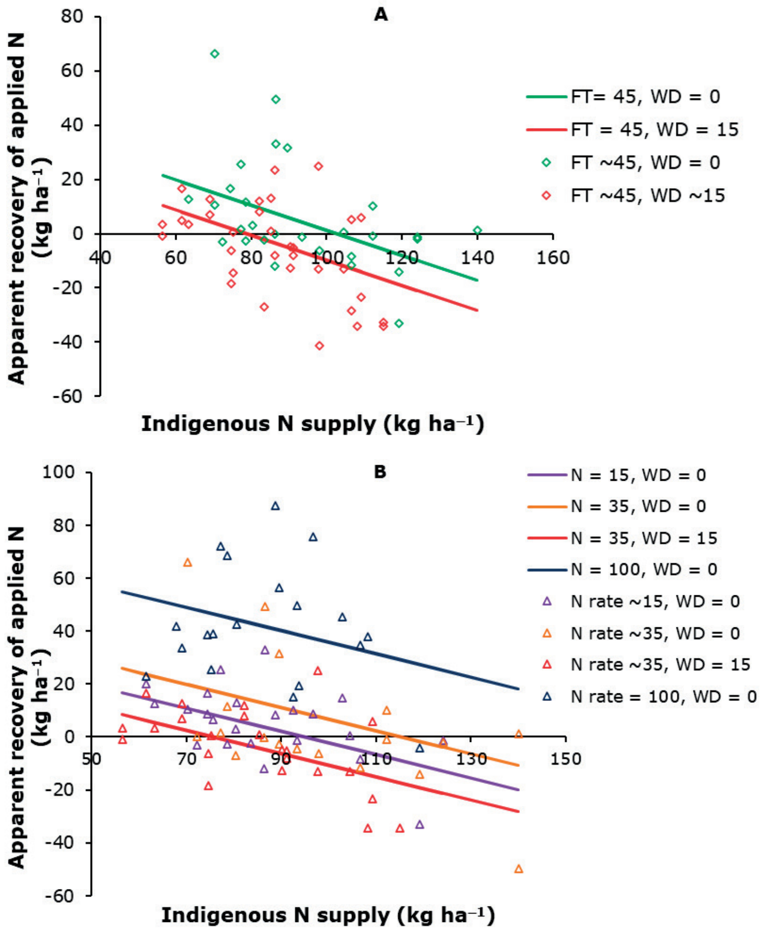


**Figure 4.2** Apparent N recovery under FP and FIP (**A**) and across FP, FIP and RAP+NPK (**B**) as influenced by indigenous N supply; and the additional interactive effect of fertilisation time (FT) and weeding time delay (WD), and weeding time delay and N rate. Apparent N recovery was calculated as the difference between total uptake in the N fertilised plots and N uptake in unfertilised plots under recommended agronomic practices (RAP). Regression lines are fitted for predicted apparent recovery values from Models 2A and 2B, respectively. Data points are observed apparent recovery data from FP and FIP; and from FP, FIP and RAP+NPK plots, respectively. FT in days after transplanting, WD in days after weeding in RAP plot, ~ means approximately. FP = farmers' practice, FIP = farmers' intensification practice and RAP+NPK = recommended agronomic practices combined with NPK application.

**Table 4.4** Multiple linear regression models for the different factors driving on-farm use efficiency of applied nutrients, Doho – Uganda, 2019.

| Model | Model description and parameter values | $R^2$ |
|---|---|---|
| 1A | Agronomic Efficiency N = a + b × INS + c × INS × weeding time delay + error<br>a = 82.6; b = -0.80; c = -0.02; s.e. = 13.7<br>b, c (<0.001) | 0.38 |
| 1B | Agronomic Efficiency N = a + b × INS + c × INS × weeding time delay + error<br>a = 72.8; b = -0.71; c = -0.02; s.e. = 11.5<br>b, c (<0.001) | 0.36 |
| 2A | Apparent N recovery = a + b × INS + c × weeding time delay × fertilisation time + error<br>a = 47.4; b = -0.46; c = -0.02; s.e. = 9.34<br>b (<0.001); c (0.002) | 0.25 |
| 2B | Apparent N recovery = a + b × N rate + c × INS + d × weeding time delay × N rate + error<br>a = 35.0; b = 0.45; c = -0.44; d = -0.03; s.e. = 9.74<br>b, c, d (<0.001) | 0.52 |
| 3 | Apparent P recovery = a + b × P rate + error<br>a = -2.88; b = 0.20; s.e. = 1.73<br>b (<0.001) | 0.38 |
| 4 | Apparent K recovery = a + b × K rate + error<br>a = -21.9; b = 1.55; s.e. = 16.0<br>b (<0.001) | 0.30 |
| 5 | Recovery Efficiency N = a + b × weeding time delay + error<br>a = 0.33; b = -0.04; s.e. = 0.09<br>b (<0.001) | 0.11 |
| 6A | Physiological Efficiency N = a + b × INS + error<br>a = 61.3; b = -0.09; s.e. = 3.94<br>b (0.04) | 0.04 |
| 6B | Physiological Efficiency N = a + b × weeding time delay + c × N rate × INS + error<br>a = 55.6; b = 0.13; c = -0.001; s.e. = 1.43<br>b (0.002); c (<0.001) | 0.27 |
| 7 | Physiological Efficiency P = a + b × IPS + c × P rate × P fertilisation time + error<br>a = 307; b = -3.38; c = -0.05; s.e. = 28.1<br>b (0.01); c (<0.01) | 0.36 |
| 8 | Physiological Efficiency K = a + b × IKS + c × K rate × weeding time + error<br>a = 48.8; b = -0.09; c = -0.01; s.e. = 4.17<br>b (<0.001); c (0.01) | 0.40 |

INS = Indigenous N supply, IPS = Indigenous P supply, IKS = Indigenous K supply. Weeding and fertilisation time (days after transplanting, DAT), weeding time delay – delay in weeding compared with weeding in recommended agronomic practice plot (RAP, days after weeding in RAP). Values in parentheses are corresponding p-values for effect of model parameter, s.e. is standard error of estimate of constant a.

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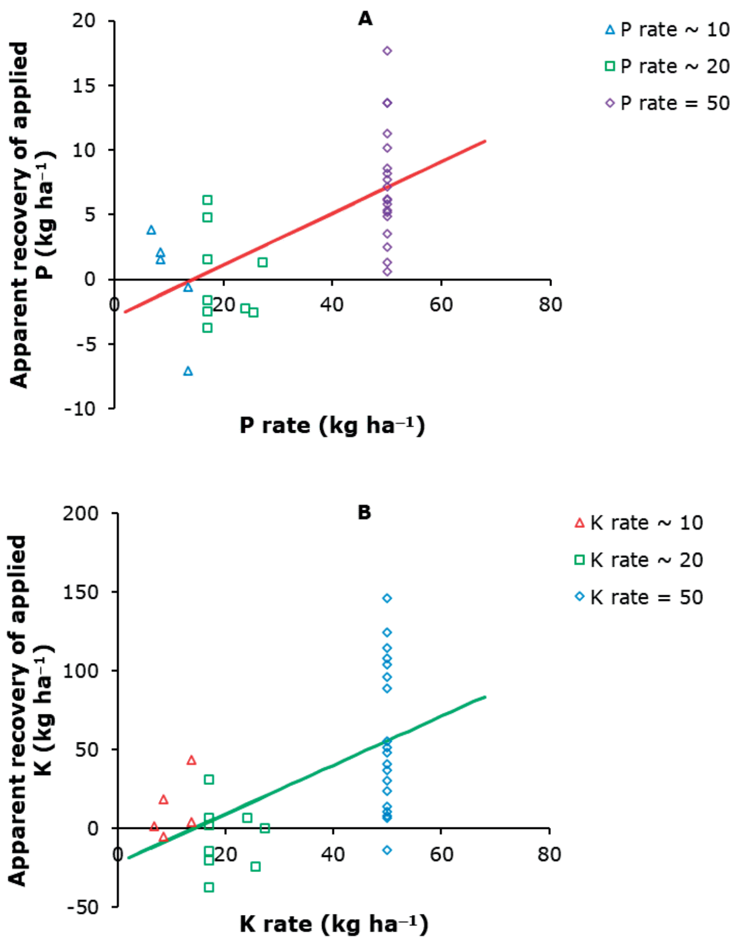



**Figure 4.3** Apparent recovery of fertiliser P (**A**) and K (**B**) across FIP and RAP+NPK as influenced by P and K rate, respectively, on-farm, Doho, 2019. Apparent recovery was calculated as the difference between total uptake in fertilised plots and uptake in unfertilised plots under recommended agronomic practices (RAP). The regression line is fitted for predicted apparent recovery values from Models 3 and 4, respectively. Data points are observed apparent recovery values from FIP and RAP+NPK plots. FIP = farmers' intensification practice and RAP+NPK = recommended agronomic practices plus NPK application.

#### 4.3.3.3 Physiological efficiency of nutrients taken up

Multiple linear regression of the combined data from plots under farmers' management practices across FP and FIP showed that physiological efficiency (PE) of N was significantly (p=0.04) influenced by INS, where PE decreased by 0.1 kg grain $kg^{-1}$ N uptake (kg $kg^{-1}$) for every kg $ha^{-1}$ increase in N uptake from the soil (Model 6A, Table 4.4). Across FP, FIP and RAP+NPK, weeding time delay, and interaction between INS and N rate were the drivers of N physiological efficiency. One day delay in weeding increased PE of N by 0.1 kg $kg^{-1}$. Interaction between INS and amount of N applied reduced PE by 0.001 kg $kg^{-1}$ for every additional kg $ha^{-1}$ N uptake from combined soil and fertiliser sources (Model 6B). Estimated PE values from Model 6B showed that increasing N rate with increasing INS reduced PE of N (Figure 4.4). Indeed, PE of N on-farm was generally lower at higher N amounts (100 kg $ha^{-1}$) compared with lower N rates (Figure 4.4). This could indicate that the increase in N availability to crops, from N application and soil supply, resulted in more N uptake by crops which was to a greater extent used to produce additional vegetative biomass rather than extra grain. The increase in the PE of N with delayed weeding could be explained by a larger negative effect of delayed weeding on N uptake, compared with the effect on grain yield, where reduction in N uptake was 16.3%, compared with 11.1% grain yield reduction (Supplementary Table S4.2). There was also a positive effect of delayed weeding on dry matter HI, in that HI was 3.3% higher under late weeding compared with timely weeding. This could imply that with delayed weeding the crops adjusted their sink size in relation to the source, since uptake and overall tissue concentration decreased, so the plants became more efficient in utilising the available nutrients taken up to produce more grains.

The physiological efficiency of P across FIP and RAP+NPK was influenced by IPS and the interaction of P rate and P fertilisation time. Increase in IPS by one kg $ha^{-1}$ led to a reduction in PE of P by 3.4 kg $kg^{-1}$. The interaction between P rate and fertilisation time also reduced PE of P by 0.05 kg $kg^{-1}$ for every additional kg $ha^{-1}$ of P applied combined with a day delay in P fertiliser application. Predictions from regression Model 7 (Table 4.4) indicated a larger drop in PE of P at high P rate, compared with lower rates (Figure 4.5A), which could imply luxury uptake of P at high rate which was inefficiently utilised by the crops for grain production. The PE of K was determined by IKS and interaction between K applied and weeding time. Similarly for K, an increase in IKS by one kg $ha^{-1}$ resulted in a reduction in the PE by 0.1 kg $kg^{-1}$. Interaction of K rate and weeding time likewise reduced the PE of K by 0.01 kg kg$^{-1}$ for every kg ha$^{-1}$ increase in K rate with a day delay in weeding (Model 8, Table 4.4). Predictions of K PE by Model 8 showed that at lower or higher K rates, PE reduced with delayed weeding, however, with larger reductions at higher K rate (Figure 4.5B). This could indicate that at lower K rates, timing of weeding was a major factor affecting PE of K, while the interaction effect of K amount and weeding time on PE was more negative at higher K applications.

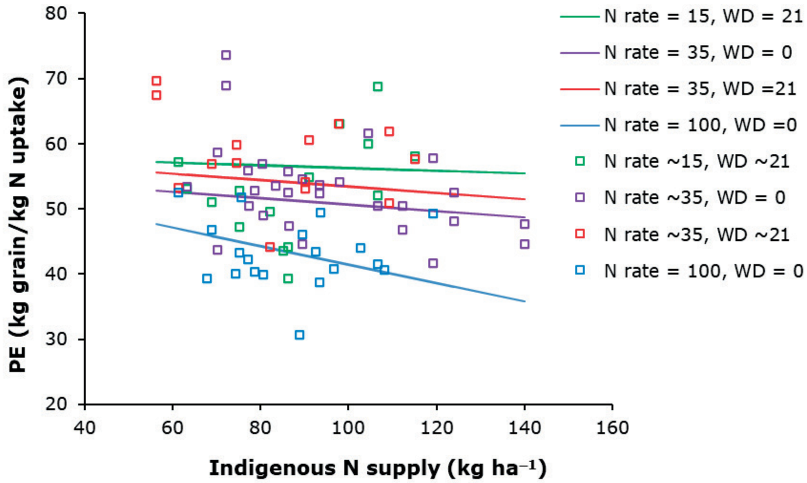
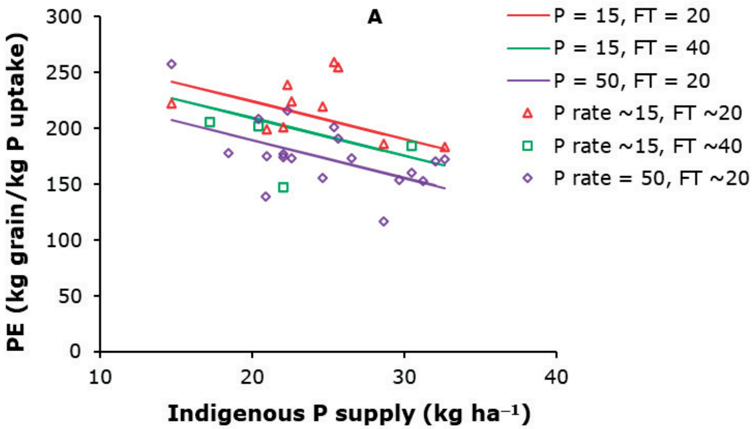



**Figure 4.4** Physiological efficiency of N across FP, FIP and RAP+NPK as affected by weeding time delay (WD; days after weeding in RAP plot) and interaction between indigenous N supply and N application rate on-farm, Doho, 2019. Regression lines are fitted for predicted PE values from Model 4B. Data points are observed PE values from FP, FIP and RAP+NPK plots. FP = farmers' practice, FIP = farmers' intensification practice and RAP+NPK = recommended agronomic practices combined with NPK application.



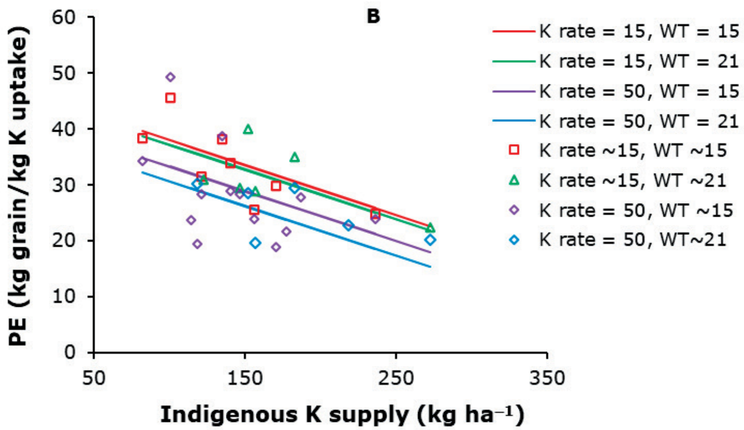




**Figure 4.5** Physiological efficiency (PE) of P (**A**) and K (**B**) across FIP and RAP+NPK as determined by indigenous supply; and interaction between P rate and P fertilisation time (FT; days after transplanting), and K rate and weeding time (WT; days after transplanting), respectively, on-farm, Doho, 2019. Regression lines are fitted for predicted PE values from Model 7 and 8, respectively. Data points are observed PE values from FIP and RAP+NPK plots. FIP = farmers' intensification practice and RAP+NPK = recommended agronomic practices plus NPK application.

## 4.4 Discussion

We observed a large variation in indigenous N, P and K supply at zero fertilisation among rice farmers' fields in the Doho rice irrigation scheme, Uganda. N and P varied about 2.5-fold among fields while K varied about 3.6-fold (Supplementary Figure 4.1). Earlier studies reported similar variations in indigenous nutrient supply among famers' fields. For instance, Haefele et al. (2003) and Haefele and Wopereis (2005) reported large variations in indigenous N, P and K supply among rice fields under similar growing conditions in SSA. Large field-to-field variations in indigenous P supply (IPS) of rice fields have also been reported for soils with various geological backgrounds, as well as in soils from adjacent fields (Nishigaki et al., 2019). Similar variations in indigenous supply among fields was reported in maize (Fofana et al., 2005; Tabi et al., 2008) and millet (Fofana et al., 2008) fields in SSA. Likewise, in Asia, where fertilisers have been used over a long time at higher rates than in SSA, Cassman et al. (1996) observed huge variations in indigenous N supply (INS) among rice fields in the tropics under comparable growing conditions, noting that the variation was not only among fields but also in the same field over time. Comparable variations in INS, IPS and indigenous K supply (IKS) have also been reported among rice (Dobermann et al., 2003b; Xu et al., 2017), maize and wheat fields (Chuan et al., 2013; Cui et al., 2008; Xu et al., 2014). Dobermann et al. (2003b) identified soil type, climate, and crop management practices as the causes of the large variation in indigenous supply. The differences in indigenous supply among farmers' fields in the studied irrigation scheme could not be explained by climate or soil type, as these did not really vary. The large variation in indigenous nutrient supply observed among farmers' fields in this study is an indication that past crop management must have differed, and hence field-specific nutrient management is essential for individual farmers in this production system, where application rates could be based on farmers' insights of indigenous nutrient supply under zero fertilisation. This is generally relevant across SSA (Chivenge et al., 2022).

The findings of reduced agronomic efficiency (AE); apparent recovery, hence recovery efficiency (RE); and physiological efficiency (PE) with increasing soil indigenous nutrient supply (Figures 4.1, 4.2, 4,4 and 4.5) confirm previous studies on the relationship between indigenous nutrient supply and use efficiency of applied nutrients. In rice fields of SSA, Haefele et al. (2003) and Haefele and Wopereis (2005) reported reduction in fertiliser N, P and K recovery fractions with the increase in indigenous nutrient supply. Relatedly, lower fertiliser N recovery was observed in maize fields in non-degraded soils with higher INS than in degraded soils with lower INS (Fofana et al., 2005). However, in millet grown in infields and outfields (i.e., fields close to and away from the homestead, respectively), fertiliser N and P recovery was higher in infields with higher indigenous supply than in outfields (Fofana et al., 2008). Samaké et al. (2005) observed that in very degraded soils in outfields, fertilisation may not enhance nutrient uptake hence recovery, as there are too many limiting factors, including biotic stresses like striga for millet. Agronomic efficiency of N and P was also reported to reduce in fields where indigenous supply of these nutrients was high (Kihara & Njoroge, 2013; Vanlauwe et al., 2011). Equally, Xu et al. (2017) reported reduction in AE of N, P and K in Asian rice fields with increasing indigenous N, P and K supply. Comparable observations were also reported in maize and wheat (Chuan et al., 2013; Xu et al., 2014). The reduction in fertiliser nutrient use efficiency observed in our study, when soil indigenous nutrient supplies were high, further underscores the need for site-specific nutrient application based on individual field capacity to supply nutrients from indigenous sources. While nutrient use efficiencies decreased with increasing soil indigenous supply, the current study further showed an interaction between indigenous nutrient supply and timing of weeding in influencing use efficiencies of applied nutrients (Figures 4.1 – 4.2, 4.4 and 4.5B). For instance, the interaction between indigenous N supply and weeding time delay significantly reduced AE of N (Figure 4.1), compared with recommended weeding time. Similarly, delaying weeding affected the intercept of the relation between apparent N recovery and indigenous N supply (Figure 4.2), strongly reducing N recovery efficiency. This effect of delayed weeding combined with indigenous nutrient supply on fertiliser nutrient use efficiencies suggests that site-specific nutrient application must be combined with timely weeding as site-specific recommendations may be inefficient when farmers apply fertilisers and don't weed timely. Present recommendation for site-specific nutrient application is based on indigenous soil supply but not on weed management (Chivenge et al., 2021; Dobermann et al., 2002), indicating that site-specific nutrient management approaches for SSA farmers should take into consideration proper crop management practices, especially timely weeding, which is critical for crop response to fertiliser application (Awio et al., 2022). This will ensure that farmers apply the right amounts of fertilisers under appropriate management practices and make economic returns on fertiliser investments through enhanced fertiliser nutrient use efficiency. Also, the possibility of within-field variation as observed by previous studies (for instance Cassman et al., 1996) should be considered to demonstrate the importance of adopting precise and variable nutrient rates combined with good agronomic practices to maximise production within a single field, thereby also saving money for the farmers. This requires that farmers are empowered to make judicious management decisions based on the actual status of their fields.

In this study, indigenous N, P and K supply were estimated by measuring N, P and K uptake in RAP plots where no nutrients were applied but management was optimal with the aim to estimate the role of indigenous nutrient supply of the fields under farmer management in the agronomic efficiency of fertiliser applications. An alternative approach to estimate indigenous nutrient supply is using nutrient omission plots. While the method applied here might under-estimate the indigenous nutrient supply, also noted by Haefele et al. (2003) using the same approach, the alternative method would potentially lead to an over-estimation of indigenous supply capacity for nutrients that are least deficient in the system. Considering the above reasoning, we opted for the approach that takes the observed uptake of non-fertilised plots as estimates of uptake under farmer conditions. We consider this as the indigenous nutrient supply, but not supply capacity. In fact the trend that at higher indigenous nutrient supply fertiliser use efficiency is reduced was also observed by previous studies that used nutrient omission trials in rice and maize fields in SSA (e.g., Haefele & Wopereis, 2005; Vanlauwe et al., 2006) and Asia (Dobermann et al., 2003b). Likewise, indigenous nutrient supply values estimated by our approach are comparable to values from omission trials (Dobermann et al., 2003b; Haefele & Wopereis, 2005). From a practical perspective, indigenous supply estimated using our approach is the most appropriate and much more relevant in explaining the problem of fertiliser use efficiency that farmers encounter, than using the indigenous supply capacity estimation from an omission plot.

Delayed weeding reduced the apparent recovery, RE and AE of N, and the PE of K, while PE of N increased with delayed weeding. Touré et al. (2009) observed lower fertiliser N AE in unbunded rice plots, which had higher weed biomass, than in bunded plots. Similarly, fertiliser N AE was reported to be three-fold lower in open rice fields where weed pressure was high, than in bunded fields (Becker & Johnson, 2001). While all our fields were bunded, late weeding showed similar impact. The reduction in use efficiency due to delayed weeding could be attributed to competition among rice plants and weeds for nutrients from both soil and fertiliser sources. This indicates that appropriate weeding time is necessary to allow plants to efficiently utilise nutrients from indigenous sources, and from fertilisers when farmers decide to apply. The increase in PE of N with delayed weeding could imply that, with reduced N uptake, crops became more efficient in utilising the available N taken up to produce more grains by adjusting their sink size in relation to the source. Delayed application of the fertiliser reduced the apparent recovery of fertiliser N under farmers' management practices across farmers' practice (FP) and farmers' intensification practice (FIP), and PE of P. This could imply that, under farmers' current N rates, N application needs to be synchronised with the correct crop stage for optimal uptake, probably N application at maximum tillering or panicle initiation stage in fields where indigenous supply is low or at grain filling stage where indigenous supply is moderate or high; this point was also observed by Becker and Johnson (2001) and Becker et al. (2003).

Low PE of N, P and K, and low dry matter harvest index were observed at high application rates under recommended agronomic practices (Table 4.3). This could indicate increased uptake by crops, which was used to enhance vegetative biomass production rather than grain yield. This may require that fertiliser nutrients, especially N, be more spread at this high rate to include split application at later crop stage as previous studies indicate that late application can enhance grain filling and grain yield (Banayo et al., 2018; Becker & Johnson, 2001; Zhou, 2017).

## 4.5 Conclusions

Indigenous nutrient supply at zero fertilisation varied largely among farmers' fields within the same irrigation scheme. Use efficiency of applied nutrients decreased with increasing indigenous nutrient supply, indicating that site-specific fertiliser recommendation is required based on indigenous nutrient supply levels of individual farmer's fields. Delayed weeding and nutrient application timing also reduced use efficiency of fertiliser nutrients. Moreover, an interaction between indigenous nutrient supply and timing of weeding was observed. Therefore, at current farmers' fertiliser application rates, appropriate weeding and indigenous soil supply-based fertilisation strategies appear to be the major management practices that need to be developed with farmers to enable improving the use efficiency of applied nutrients, and hence, grain yield.



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## References

Awio, T., Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Kempen, B., Struik, P. C., & Stomph, T. J. (2021). Micro-nutrients in East African lowlands: Are they needed to intensify rice production? *Field Crops Research, 270*, 108219. DOI: 10.1016/j.fcr.2021.108219

Awio, T., Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Struik, P. C., & Stomph, T. J. (2022). Yields and Yield Gaps in Lowland Rice Systems and Options to Improve Smallholder Production. *Agronomy, 12*(3), 552. DOI: 10.3390/agronomy12030552

Bado, V. B., Djaman, K., & Valère, M. C. (2018). Managing Fertilizer Recommendations in Rice-Based Cropping Systems Challenges and Strategic Approaches. In A. Bationo, D. Ngaradoum, S. Youl, F. Lompo, & J. O. Fening (Eds.), *Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems: Volume 1* (pp. 25-50). Cham: Springer International Publishing.

Balasubramanian, V., Sie, M., Hijmans, R. J., Otsuka, K. (2007). Increasing Rice Production in sub-Saharan Africa: Challenges and Opportunities. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 94, pp. 55-133): Academic Press.

Banayo, N. P. M. C., Bueno, C. S., Haefele, S. M., Desamero, N. V., & Kato, Y. (2018). Site-specific nutrient management enhances sink size, a major yield constraint in rainfed lowland rice. *Field Crops Research, 224*, 76-79. DOI: 10.1016/j.fcr.2018.05.006

Becker, M., & Johnson, D. E. (2001). Improved water control and crop management effects on lowland rice productivity in West Africa. *Nutrient Cycling in Agroecosystems, 59*(2), 119-127. DOI: 10.1023/A:1017585328904

Becker, M., Johnson, D. E., Wopereis, M. C. S., & Sow, A. (2003). Rice yield gaps in irrigated systems along an agro-ecological gradient in West Africa. *Journal of Plant Nutrition and Soil Science, 166*(1), 61-67. DOI: 10.1002/jpln.200390013

Cassman, K. G., Gines, G. C., Dizon, M. A., Samson, M. I., & Alcantara, J. M. (1996). Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. *Field Crops Research, 47*(1), 1-12. DOI: 10.1016/0378-4290(95)00101-8

Cassman, K. G., Peng, S., Olk, D. C., Ladha, J. K., Reichardt, W., Dobermann, A., & Singh, U. (1998). Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Research, 56*(1), 7-39. DOI: 10.1016/S0378-4290(97)00140-8

Chivenge, P., Saito, K., Bunquin, M. A., Sharma, S., & Dobermann, A. (2021). Co-benefits of nutrient management tailored to smallholder agriculture. *Global Food Security, 30*, 100570. DOI: 10.1016/j.gfs.2021.100570

Chivenge, P., Zingore, S., Ezui, K. S., Njoroge, S., Bunquin, M. A., Dobermann, A., & Saito, K. (2022). Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa. *Field Crops Research, 281*, 108503. DOI: 10.1016/j.fcr.2022.108503

Chuan, L., He, P., Pampolino, M. F., Johnston, A. M., Jin, J., Xu, X., . . . Zhou, W. (2013). Establishing a scientific basis for fertilizer recommendations for wheat in China: Yield response and agronomic efficiency. *Field Crops Research, 140*, 1-8. DOI: 10.1016/j.fcr.2012.09.020

Cui, Z., Zhang, F., Chen, X., Miao, Y., Li, J., Shi, L., . . . Bao, D. (2008). On-farm estimation of indigenous nitrogen supply for site-specific nitrogen management in the North China plain. *Nutrient Cycling in Agroecosystems, 81*(1), 37-47. DOI: 10.1007/s10705-007-9149-8

Davies, B., Coulter, J. A., & Pagliari, P. H. (2020). Timing and rate of nitrogen fertilization influence maize yield and nitrogen use efficiency. *PLoS ONE, 15*(5), e0233674. DOI: 10.1371/journal.pone.0233674

Dobermann, A. (2007). Nutrient use efficiency – measurement and management. *International Fertilizer Industry Association, Paris, France*, 30.

Dobermann, A., Witt, C., Abdulrachman, S., Gines, H. C., Nagarajan, R., Son, T. T., . . . Adviento, M. A. A. (2003b). Soil Fertility and Indigenous Nutrient Supply in Irrigated Rice Domains of Asia. *Agronomy Journal, 95*(4), 913-923. DOI: 10.2134/agronj2003.9130

Dobermann, A., Witt, C., Abdulrachman, S., Gines, H. C., Nagarajan, R., Son, T. T., . . . Bartolome, V. (2003a). Estimating Indigenous Nutrient Supplies for Site-Specific Nutrient Management in Irrigated Rice. *Agronomy Journal, 95*(4), 924-935. DOI: 10.2134/agronj2003.9240

Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H. C., Nagarajan, R., . . . Adviento, M. A. A. (2002). Site-specific nutrient management for intensive rice cropping system in Asia. *Field Crops Research, 108*(1), 115. DOI: 10.1016/j.fcr.2008.04.002

Fofana, B., Tamélokpo, A., Wopereis, M. C. S., Breman, H., Dzotsi, K., & Carsky, R. J. (2005). Nitrogen use efficiency by maize as affected by a mucuna short fallow and P application in the coastal savanna of West Africa. *Nutrient Cycling in Agroecosystems, 71*(3), 227-237. DOI: 10.1007/s10705-004-5084-0

Fofana, B., Wopereis, M. C. S., Bationo, A., Breman, H., & Mando, A. (2008). Millet nutrient use efficiency as affected by natural soil fertility, mineral fertilizer use and rainfall in the West African Sahel. *Nutrient Cycling in Agroecosystems, 81*(1), 25-36. DOI: 10.1007/s10705-007-9146-y

Haefele, S. M., & Wopereis, M. C. S. (2005). Spatial variability of indigenous supplies for N, P and K and its impact on fertilizer strategies for irrigated rice in West Africa. *Plant and Soil, 270*(1), 57-72. DOI: 10.1007/s11104-004-1131-5

Haefele, S. M., Wopereis, M. C. S., Ndiaye, M. K., Barro, S. E., & Ould Isselmou, M. (2003). Internal nutrient efficiencies, fertilizer recovery rates and indigenous nutrient supply of irrigated lowland rice in Sahelian West Africa. *Field Crops Research, 80*(1), 19-32. DOI: 10.1016/S0378-4290(02)00152-1

Kihara, J., Huising, J., Nziguheba, G., Waswa, B. S., Njoroge, S., Kabambe, V., . . . Coulibaly, A. (2016). Maize response to macronutrients and potential for profitability in sub-Saharan Africa. *Nutrient Cycling in Agroecosystems, 105*(3), 171-181. DOI: 10.1007/s10705-015-9717-2

Kihara, J., & Njoroge, S. (2013). Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. *Field Crops Research, 150*, 1-8. DOI: 10.1016/j.fcr.2013.05.025

Kwesiga, J., Grotelüschen, K., Neuhoff, D., Senthilkumar, K., Döring, T. F., & Becker, M. (2019). Site and Management Effects on Grain Yield and Yield Variability of Rainfed Lowland Rice in the Kilombero Floodplain of Tanzania. *Agronomy, 9*(10). DOI: 10.3390/agronomy9100632

Li, M., Zhang, H., Yang, X., Ge, M., Ma, Q., Wei, H., . . . Luo, D. (2014). Accumulation and utilization of nitrogen, phosphorus and potassium of irrigated rice cultivars with high productivities and high N use efficiencies. *Field Crops Research, 161*, 55-63. DOI: 10.1016/j.fcr.2014.02.007

Niang, A., Becker, M., Ewert, F., Dieng, I., Gaiser, T., Tanaka, A., . . . Saito, K. (2017). Variability and determinants of yields in rice production systems of West Africa. *Field Crops Research, 207*, 1-12. DOI: 10.1016/j.fcr.2017.02.014

Nishigaki, T., Tsujimoto, Y., Rinasoa, S., Rakotoson, T., Andriamananjara, A., & Razafimbelo, T. (2019). Phosphorus uptake of rice plants is affected by phosphorus forms and physicochemical properties of tropical weathered soils. *Plant and Soil, 435*(1-2), 27-38. DOI: 10.1007/s11104-018-3869-1

Saito, K., Diack, S., Dieng, I., & N'Diaye, M. K. (2015). On-farm testing of a nutrient management decision-support tool for rice in the Senegal River valley. *Computers and Electronics in Agriculture, 116*, 36-44. DOI: 10.1016/j.compag.2015.06.008

Saito, K., Vandamme, E., Johnson, J.-M., Tanaka, A., Senthilkumar, K., Dieng, I., . . . Wopereis, M. C. S. (2019). Yield-limiting macronutrients for rice in sub-Saharan Africa. *Geoderma, 338*, 546-554. DOI: 10.1016/j.geoderma.2018.11.036

Samaké, O., Smaling, E. M. A., Kropff, M. J., Stomph, T. J., & Kodio, A. (2005). Effects of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. *Agriculture, Ecosystems & Environment, 109*(3), 335-345. DOI: 10.1016/j.agee.2005.02.024

Seck, P. A., Ali, A.T., Jeanne, Y.C., Aliou D., & Wopereis, M. C.S. (2013). Africa's Rice Economy Before and After the 2008 Rice Crisis. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., & Jalloh, A. (eds). Realizing Africa's Rice Promise. *CABI*, 436. DOI: 10.1079/9781845938123.0024

Sserunkuuma, D., Ochom, N., Ainembabazi, H. (2003). Collective Action in Canal Irrigation Systems Management: The Case of Doho Rice Scheme in Uganda. *Department of Agricultural Economics and Agribusiness, Makerere University*, 22.

Tabi, F. O., Diels, J., Ogunkunle, A. O., Iwuafor, E. N. O., Vanlauwe, B., & Sanginga, N. (2008). Potential nutrient supply, nutrient utilization efficiencies, fertilizer recovery rates and maize yield in northern Nigeria. *Nutrient Cycling in Agroecosystems, 80*(2), 161-172. DOI: 10.1007/s10705-007-9129-z

Tanaka, A., Diagne, M., & Saito, K. (2015). Causes of yield stagnation in irrigated lowland rice systems in the Senegal River Valley: Application of dichotomous decision tree analysis. *Field Crops Research, 176*, 99-107. DOI: 10.1016/j.fcr.2015.02.020

Tanaka, A., Johnson, J.-M., Senthilkumar, K., Akakpo, C., Segda, Z., Yameogo, L. P., . . . Saito, K. (2017). On-farm rice yield and its association with biophysical factors in sub-Saharan Africa. *European Journal of Agronomy, 85*, 1-11. DOI: 10.1016/j.eja.2016.12.010

Tippe, D. E., Bastiaans, L., van Ast, A., Dieng, I., Cissoko, M., Kayeke, J., . . . Rodenburg, J. (2020). Fertilisers differentially affect facultative and obligate

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parasitic weeds of rice and only occasionally improve yields in infested fields. *Field Crops Research, 254*, 107845. DOI: 10.1016/j.fcr.2020.107845

Touré, A., Becker, M., Johnson, D. E., Koné, B., Kossou, D. K., & Kiepe, P. (2009). Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. *Field Crops Research, 114*(2), 304-310. DOI: 10.1016/j.fcr.2009.08.015

Tsujimoto, Y., Rakotoson, Tovohery., Tanaka, Atsuko., & Saito, Kazuki. (2019). Challenges and opportunities for improving N use efficiency for rice production in sub-Saharan Africa. *Plant Production Science, 22*(4), 413-427. DOI: 10.1080/1343943X.2019.1617638

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., & Six, J. (2011). Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant and Soil, 339*(1), 35-50. DOI: 10.1007/s11104-010-0462-7

Vanlauwe, B., Tittonell, P., & Mukalama, J. (2006). Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. *Nutrient Cycling in Agroecosystems, 76*(2), 171-182. DOI: 10.1007/s10705-005-8314-1

Wanyama, J., Ssegane, H., Kisekka, I., Komakech, A. J., Banadda, N., Zziwa, A., Lubwama, K. F. (2017). Irrigation Development in Uganda: Constraints, Lessons Learned, and Future Perspectives. *J. Irrig. Drain Eng., 143*(5), 10.

Witt, C., & Dobermann, A. (2002). A site-specific nutrient management approach for irrigated, lowland rice in Asia. *Better Crops Int, 16*(1), 20-24.

Xu, X., He, P., Pampolino, M. F., Johnston, A. M., Qiu, S., Zhao, S., . . . Zhou, W. (2014). Fertilizer recommendation for maize in China based on yield response and agronomic efficiency. *Field Crops Research, 157*, 27-34. DOI: 10.1016/j.fcr.2013.12.013

Xu, X., He, P., Yang, F., Ma, J., Pampolino, M. F., Johnston, A. M., & Zhou, W. (2017). Methodology of fertilizer recommendation based on yield response and agronomic efficiency for rice in China. *Field Crops Research, 206*, 33-42. DOI: 10.1016/j.fcr.2017.02.011

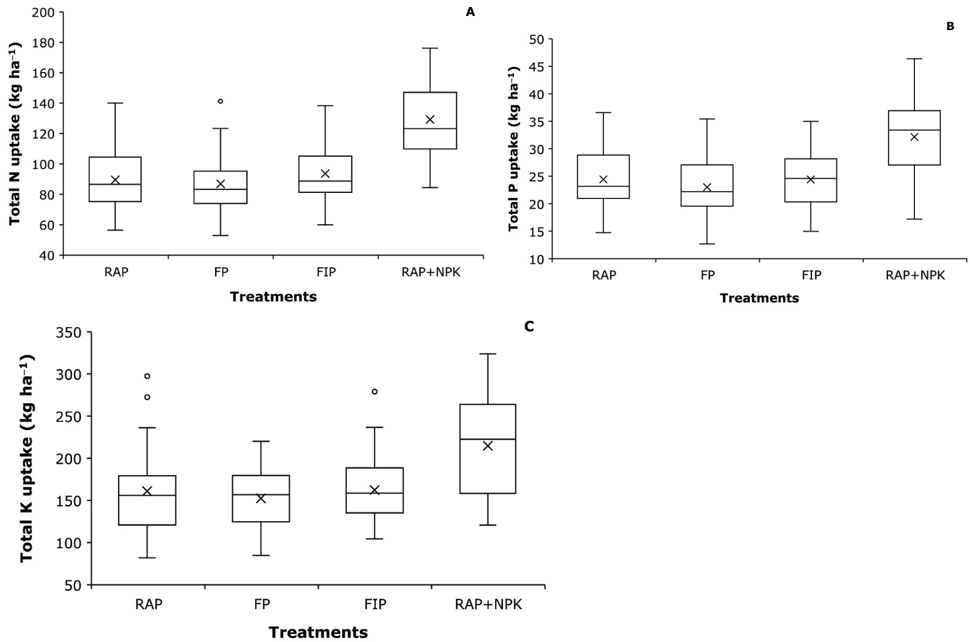
Xu, X., He, P., Zhao, S., Qiu, S., Johnston, A. M., & Zhou, W. (2016). Quantification of yield gap and nutrient use efficiency of irrigated rice in China. *Field Crops Research, 186*, 58-65. DOI: 10.1016/j.fcr.2015.11.011

Zemichael, B., Dechassa, N., & Abay, F. (2017). Yield and Nutrient Use Efficiency of Bread Wheat (Triticum Aestivum L.) as Influenced by Time and Rate of Nitrogen

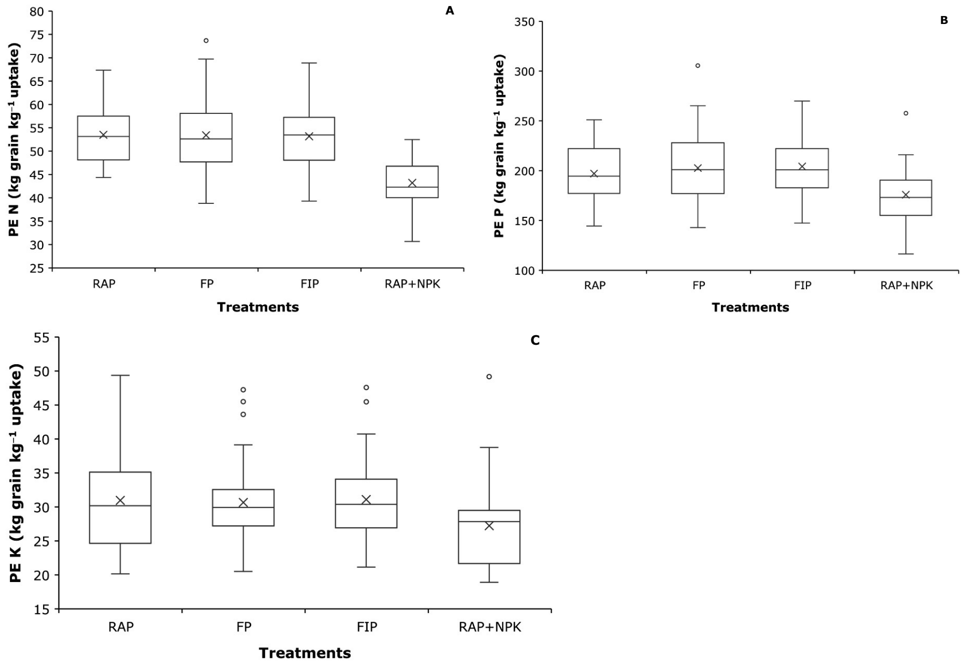
Application in Enderta, Tigray, Northern Ethiopia. *Open Agriculture, 2*(1), 611-624. DOI: 10.1515/opag-2017-0065

Zhou, W., Tengfei, L., Yong, C., Hu, J., Zhang, Q., Ren, W. (2017). Late nitrogen application enhances spikelet number in indica hybrid rice (Oryza sativa L.). *Scientia Agricola, 74*(2), 127-133. DOI: 10.1590/1678-992X-2016-0094

## Supplementary materials in Chapter 4




**Supplementary Figure 4.1** Total N (**A**), P (**B**) and K (**C**) uptake under different management practices on-farm, Doho rice irrigation scheme, eastern Uganda, 2019. RAP = recommended agronomic practices without fertilisation (n = 47), FP = farmers' practice (n = 37), FIP = farmers' intensification practice (n = 43), RAP+NPK = recommended agronomic practices with NPK fertilisation (n = 19). No P and K was applied by farmers under FP.




**Supplementary Figure 4.2** Physiological efficiency of N (**A**), P (**B**) and K (**C**) under different management practices on-farm, Doho rice irrigation scheme, eastern Uganda, 2019. RAP = recommended agronomic practices without fertilisation (n = 47), FP = farmers' practice (n = 37), FIP = farmers' intensification practice (n = 43), RAP+NPK = recommended agronomic practices with NPK fertilisation (n = 19). No P and K was applied by farmers under FP.

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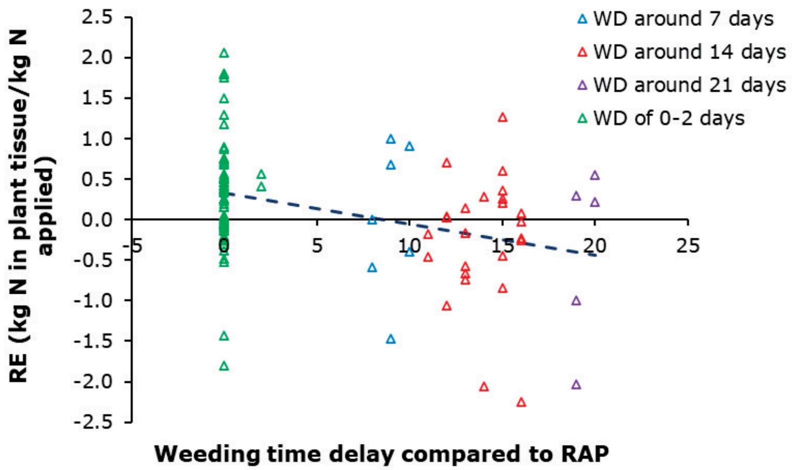
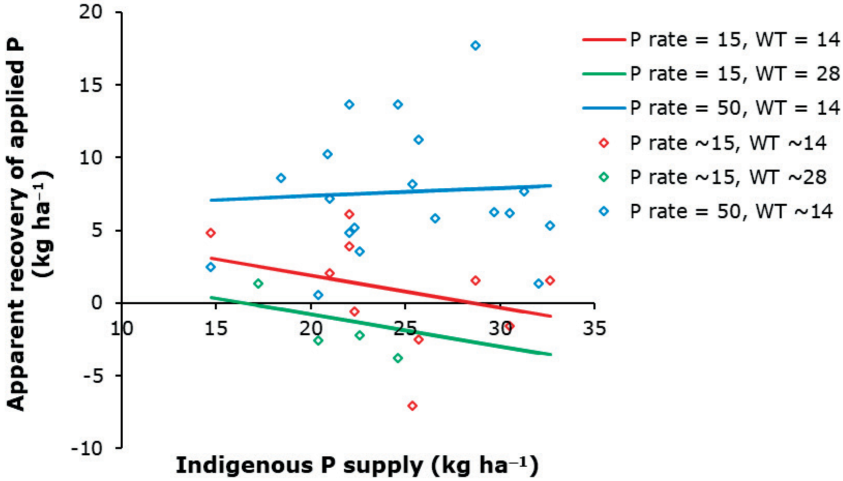



**Supplementary Figure 4.3** Recovery efficiency of N as influenced by weeding time delay compared with recommended weeding time, on-farm, Doho – Uganda, 2019. The regression line is fitted for predicted N recovery values from the model: *N recovery efficiency = a + b × weeding time delay + error*; where a = 0.33, b = -0.04, s.e. = 0.09 ($R^2$ = 0.11); and b (<0.001). Data points are observed N recovery efficiency data from FP, FIP and RAP+NPK plots. FP = farmers' practice, FIP = farmers' intensification practice, and RAP+NPK = recommended agronomic practices with NPK application.




**Supplementary Figure 4.4** Apparent P recovery across FIP and RAP+NPK as influenced by indigenous P supply, weeding time (WT – days after transplanting), and interaction between indigenous P supply and P rate on-farm, Doho, 2019. Apparent P recovery was calculated as the difference between total P uptake in P applied plot and non-applied plot under recommended agronomic practices (RAP). Regression lines are fitted for predicted apparent recovery model: *apparent recovery of P = a + b × weeding time + c × IPS + d × IPS × P rate + error*; where a = 8.99, b = -0.19, c = -0.34, d = 0.01, s.e. = 6.08 ($R^2 = 0.37$); and b, c (>0.05), d (<0.001). Data points are observed P apparent recovery from FIP and RAP+NPK plots. FIP = farmers' intensification practice and RAP+NPK = recommended agronomic practices combined with NPK application.

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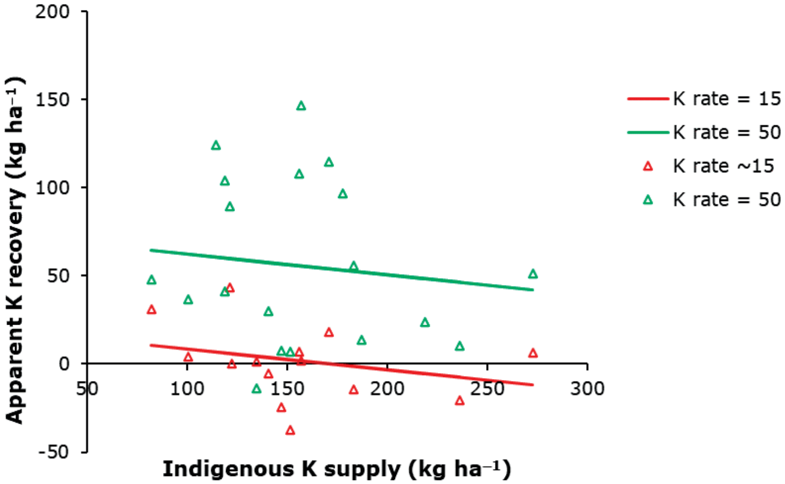


**Supplementary Figure 4.5** Apparent recovery of applied K across FIP and RAP+NPK influenced by indigenous K supply and K amount on-farm, Doho, 2019. Apparent K recovery was calculated as the difference between total uptake in K applied plot and non K applied recommended agronomic practices (RAP) plot. Regression lines are fitted for predicted apparent K recovery values from the model: *apparent K recovery* = *a* + *b* × *IKS* + *c* × *K rate* + *error*; where a = -3.0, b = -0.12, c = 1.54, s.e. = 28.5 ($R^2$ = 0.29); and b (>0.05), c (<0.001). Data points are observed apparent K recovery data from FIP and RAP+NPK plots. FIP = farmers' intensification practice and RAP+NPK = recommended agronomic practices with NPK application.

**Supplementary Table S4.1** On-farm N, P and K uptake (kg $ha^{-1}$) and grain yield (kg $ha^{-1}$) for four treatments and four different planting periods, Doho rice irrigation scheme, Uganda, 2019. Planting period 1 corresponds to the dry season, planting periods 2 and 3 were planted during the first rainy season and planting period 4 during the second rainy season.

| Treatment | Planting period | | | | |
|---|---|---|---|---|---|
| | 1 (January) | 2 (March) | 3 (April) | 4 (August) | Mean |
| | **N uptake** | | | | |
| RAP | 81.9 (se=3.98, n=12 ) | 81.3 (se=9.76, n=2) | 95.7 (se=3.09, n=20) | 87.5 (se=3.82, n=13) | 97.2[bc] |
| FP | 79.8 (se=3.98, n=11 ) | 93.1 (se=9.76, n=1) | 91.9 (se=3.09, n=15) | 83.6 (se=3.82, n=10) | 82.0[a] |
| FIP | 80.5 (se=3.98, n=12) | 112 (se=9.76, n=2) | 101 (se=3.17, n=19) | 89.2 (se=4.36, n=10) | 88.4[b] |
| RAP+NPK | 110 (se=7.94, n=3) | 123 (se=13.8, n=1) | 142 (se=4.35, n=10) | 118 (se=6.17, n=5) | 99.5[c] |
| | **P uptake** | | | | |
| RAP | 21.2 (se=0.97, n=12 ) | 20.1 (se=2.38, n=2) | 26.7 (se=0.76, n=20) | 24.6 (se=0.94, n=13) | 23.4[b] |
| FP | 19.4 (se=0.97, n=11 ) | 23.5 (se=2.38, n=1) | 24.3 (se=0.76, n=15) | 24.2 (se=0.94, n=10) | 20.3[a] |
| FIP | 19.7 (se=0.97, n=12) | 25.8 (se=2.38, n=2) | 26.6 (se=0.77, n=19) | 25.4 (se=1.07, n=10) | 25.1[b] |
| RAP+NPK | 23.9 (se=1.94, n=3) | 28.1 (se=3.36, n=1) | 35.1 (se=1.07, n=10) | 32.4 (se=1.51, n=5) | 26.5[c] |
| | **K uptake** | | | | |
| RAP | 133 (se=7.38, n=12 ) | 142 (se=18.1, n=2) | 184 (se=5.72, n=13) | 154 (se=7.08, n=20) | 149[ab] |
| FP | 130 (se=7.38, n=11 ) | 139 (se=18.1, n=1) | 166 (se=5.72, n=10) | 155 (se=7.08, n=15) | 133[a] |
| FIP | 136 (se=7.38, n=12) | 160 (se=18.1, n=2) | 174 (se=5.86, n=10) | 171 (se=8.08, n=19) | 162[b] |
| RAP+NPK | 140 (se=14.7, n=3) | 171 (se=25.5, n=1) | 242 (se=8.06, n=5) | 216 (se=11.4, n=10) | 180[c] |
| | **Grain yield** | | | | |
| RAP | 4530 (se=142, n=12 ) | 4195 (se=348, n=2) | 5153 (se=110, n=20) | 4417 (se=136, n=13) | 4692[a] |
| FP | 4270 (se=142, n=11 ) | 4478 (se=348, n=1) | 4798 (se=110, n=15) | 4435 (se=136, n=10) | 4469[a] |
| FIP | 4522 (se=142, n=12) | 5415 (se=348, n=2) | 5195 (se=113, n=19) | 4620 (se=156, n=10) | 4521[a] |
| RAP+NPK | 5176 (se=283, n=3) | 4911 (se=491, n=1) | 5830 (se=155, n=10) | 5240 (se=220, n=5) | 5100[b] |

The different planting periods had no significant effect ($p>0.18$) on nutrient uptake and grain yield for the different treatments. RAP = recommended agronomic practices without fertilisation; FP = farmers' practice; FIP = farmers' intensification practice; RAP+NPK = recommended agronomic practices combined with NPK fertilisation; se = standard error of means; n = number of fields planted for each treatment in a planting period. Month in parentheses is the planting time. Treatment mean values followed by the same letters are not different according to Fisher's unprotected LSD test.

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**Supplementary Table S4.2** Simple linear regression analysis of the effect of weeding and fertilisation timing on nutrient use efficiency across treatments on-farm, Doho rice irrigation scheme, eastern Uganda, 2019

| Index | Slope estimate | Unit of slope estimate | p-value | Standard error | Lower 95% CL | Upper 95% CL | Adjusted $R^2$ |
|---|---|---|---|---|---|---|---|
| **Weeding timing** | | | | | | | |
| Uptake (kg N $ha^{-1}$) | -1.52 | kg $ha^{-1}$ $day^{-1}$ | <0.001 | 0.34 | -2.19 | -0.85 | 0.16 |
| Uptake (kg P $ha^{-1}$) | -0.66 | kg $ha^{-1}$ $day^{-1}$ | 0.04 | 0.31 | -1.28 | -0.03 | 0.10 |
| Uptake (kg K $ha^{-1}$) | -3.31 | kg $ha^{-1}$ $day^{-1}$ | 0.23 | 2.68 | -8.77 | 2.16 | 0.02 |
| AE (kg grain/kg N applied) | -1.16 | kg $kg^{-1}$ $day^{-1}$ | <0.01 | 0.40 | -1.94 | -0.38 | 0.07 |
| AE (kg grain/kg P or K applied) | -0.12 | kg $kg^{-1}$ $day^{-1}$ | 0.88 | 0.79 | -1.72 | 1.49 | 0.00 |
| RE (kg uptake/kg N applied) | -0.03 | kg $kg^{-1}$ $day^{-1}$ | <0.01 | 0.01 | -0.06 | -0.01 | 0.09 |
| RE (kg uptake/kg P applied) | -0.01 | kg $kg^{-1}$ $day^{-1}$ | 0.26 | 0.01 | -0.02 | 0.01 | 0.01 |
| RE (kg uptake/kg K applied) | -0.08 | kg $kg^{-1}$ $day^{-1}$ | 0.19 | 0.06 | -0.21 | 0.04 | 0.02 |
| PE (kg grain/kg N uptake) | 0.32 | kg $kg^{-1}$ $day^{-1}$ | <0.01 | 0.11 | 0.10 | 0.54 | 0.07 |
| PE (kg grain/kg P uptake) | 1.10 | kg $kg^{-1}$ $day^{-1}$ | 0.47 | 1.49 | -1.94 | 4.14 | 0.00 |
| PE (kg grain/kg K uptake) | -0.06 | kg $kg^{-1}$ $day^{-1}$ | 0.87 | 0.33 | -0.72 | 0.61 | 0.00 |
| Grain yield (kg $ha^{-1}$) | -42.9 | kg $ha^{-1}$ $day^{-1}$ | <0.001 | 11.8 | -66.3 | -19.5 | 0.11 |
| Total biomass (kg $ha^{-1}$) | -142 | kg $ha^{-1}$ $day^{-1}$ | <0.001 | 30.6 | -203 | -80.9 | 0.17 |
| Dry matter HI (%) | 0.12 | % $day^{-1}$ | 0.05 | 0.06 | 0.00 | 0.23 | 0.03 |
| Dry matter N concentration (g $kg^{-1}$) | -0.03 | g $kg^{-1}$ $day^{-1}$ | 0.03 | 0.01 | -0.06 | 0.00 | 0.04 |
| **Fertilisation timing** | | | | | | | |
| Uptake (kg N $ha^{-1}$) | -0.77 | kg $ha^{-1}$ $day^{-1}$ | <0.001 | 0.16 | -1.09 | -0.46 | 0.19 |
| Uptake (kg P $ha^{-1}$) | -0.19 | kg $ha^{-1}$ $day^{-1}$ | 0.05 | 0.09 | -0.39 | 0.00 | 0.09 |
| AE (kg grain/kg N applied) | -0.39 | kg $kg^{-1}$ $day^{-1}$ | 0.05 | 0.19 | -0.77 | -0.01 | 0.03 |
| AE (kg grain/kg P or K applied) | -0.19 | kg $kg^{-1}$ $day^{-1}$ | 0.43 | 0.24 | -0.67 | 0.29 | 0.00 |
| RE (kg uptake/kg N applied) | -0.01 | kg $kg^{-1}$ $day^{-1}$ | 0.02 | 0.01 | -0.02 | 0.00 | 0.04 |
| RE (kg uptake/kg P applied) | <0.01 | kg $kg^{-1}$ $day^{-1}$ | 0.72 | <0.01 | -0.01 | 0.004 | 0.00 |
| RE (kg uptake/kg K applied) | -0.03 | kg $kg^{-1}$ $day^{-1}$ | 0.09 | 0.02 | -0.07 | 0.01 | 0.06 |
| PE (kg grain/kg N uptake) | 0.15 | kg $kg^{-1}$ $day^{-1}$ | <0.01 | 0.05 | 0.05 | 0.26 | 0.07 |
| PE (kg grain/kg P uptake) | -0.02 | kg $kg^{-1}$ $day^{-1}$ | 0.98 | 0.46 | -0.95 | 0.92 | 0.00 |
| PE (kg grain/kg K uptake) | -0.03 | kg $kg^{-1}$ $day^{-1}$ | 0.78 | 0.10 | -0.23 | 0.18 | 0.00 |
| Grain yield (kg $ha^{-1}$) | -21.7 | kg $ha^{-1}$ $day^{-1}$ | <0.001 | 5.60 | -32.8 | -10.6 | 0.13 |
| Total biomass (kg $ha^{-1}$) | -66.9 | kg $ha^{-1}$ $day^{-1}$ | <0.001 | 14.7 | -96.1 | -37.7 | 0.17 |
| Dry matter HI (%) | 0.04 | % $day^{-1}$ | 0.14 | 0.03 | -0.01 | 0.10 | 0.01 |
| Dry matter N concentration (g $kg^{-1}$) | -0.02 | g $kg^{-1}$ $day^{-1}$ | 0.01 | 0.01 | -0.03 | -0.01 | 0.06 |

PE = physiological efficiency, AE = agronomic efficiency, RE = recovery efficiency, HI = harvest index, taken as ratio of grain yield and total above-ground dry matter of 12 sample hills, and CL = confidence limit.

# 5

# CHAPTER 5.

## Management practices and rice grain yield of farmers after participation in a joint experimentation

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**Abstract**

Low productivity of rice in Uganda is attributed to sub-optimal production practices related to soil nutrient, crop and weed management. Application of improved management practices could enhance productivity. Returning one year after a joint experimentation in which different components of recommended agronomic practices (RAP) for rice were tested, we assessed change in management practices and grain yield of participating farmers (participated in joint experimentation) and non-participating farmers (did not participate) with plots in the same irrigation scheme. Participating farmers belonging to the lower-yielding farmers under farmers' practice (FP) during joint experimentation improved their management practices, compared with the middle- and top-yielding farmers. Sixty-one, 24 and 7% of lower-, middle- and top-yielding farmers, respectively, weeded earlier after experimentation compared with weeding time under FP during joint experimentation. Seventy-nine percent of lower-yielding farmers used fertiliser after experimentation compared with 18% during experimentation, with a higher N rate increase than middle- and top-yielding farmers. Overall, participating farmers transplanted and weeded earlier, and applied slightly higher N rates compared with non-participating farmers. Top-yielding farmers had significantly ($p=0.03$) higher grain yield, followed by middle- and lower-yielding farmers. However, lower-yielding farmers made significantly ($p<0.001$) higher yield gain than middle- and top-yielding farmers. A paired t-test showed that average yield gain was 1358 (1027 – 1689), 473 (252 – 695) and -91.7 (-397 – 213) kg ha−1, respectively, for lower-, middle- and top-yielding farmers. Participating farmers had higher grain yield (4125 kg ha−1) than non-participating farmers (3893 kg ha−1). Three farm types were identified that differed in application of RAP, however, with small differences in household characteristics. The farm type with higher fertiliser use in nursery and field, line transplanting, timely weeding and higher N rate had the highest grain yield. We conclude that joint experimentation had a larger effect on raising yield of lower-yielding farmers, bringing farmers closer in their management and outputs. Lack of differences among farm households could indicate that wealth is not crucial in innovation adoption in this production system.

**Keywords:** Joint experimentation, participating farmers, non-participating farmers, recommended agronomic practices, *Oryza sativa*.

## 5.1 Introduction

Rice (*Oryza sativa*) in Uganda has become an important food staple and cash crop, especially among the rural smallholder farmers, making it the second most important cereal after maize (KilimoTrust, 2014; Uganda Bureau of Statistics, UBOS, 2021). Yet, rice yield in Uganda averages only 2800 kg ha$^{-1}$ for both irrigated and rainfed rice compared with the global average yield of 4700 kg ha$^{-1}$ [Food and Agriculture Organisation of the United Nations (FAO), 2021], and a yield potential in sub-Saharan Africa of 9200 and 7000 kg ha$^{-1}$ for irrigated and rainfed rice, respectively (Global Yield Gap Atlas, 2022). As a result, demand for rice surpasses production, which has resulted in an average net annual milled rice import of around 62000 tonnes between 2015 and 2020, costing the country about USD 23.2 million each year (FAO, 2022). The low yield is attributed to, among other factors, soil-related constraints, poor management of rice fields, and use of low-yielding varieties.

Application of modern agricultural production technologies, such as improved weed management practices, appropriate use of inorganic fertilisers, and modern, high-yielding varieties could enhance rice crop productivity, hence reducing shortage and saving money spent on imports. This is in addition to increasing household food security, reducing poverty directly through increased household incomes and welfare, and indirectly through lower food prices and higher wages (Kassie et al., 2011, 2018; Manda et al., 2019; Wossen et al., 2019). Yet, even with the evident benefits of many of the new agricultural technologies, smallholder farmers either do not adopt them or it takes a long time for such technologies to start being adopted (Mottaleb, 2018). The lack of or slow adoption of improved agricultural technologies is attributed to high costs, uncertainties about proper application and success under local farmers' environmental conditions, and farmers' perceptions and expectations (Mottaleb, 2018; Sinyolo, 2020). Further studies show that variation in adoption of improved management practices that enhance crop yields is related to differences in socio-economic characteristics of farm households, including, for instance, family size, farm size and income, farmers' age and education, labour availability, availability of cash for investment, and risk perception (Danlami et al., 2016; Fosso and Nanfosso, 2016; Hassan et al., 2016; Tadesse et al., 2017; Takahashi et al., 2020; Urfels et al., 2021). Moreover, past participation in on-farm trials, training and awareness about the technology, and contact with extension agents are shown to influence adoption (Danlami et al., 2016, 2019; Hassan et al., 2016; Takahashi et al., 2020). Due to such constraints, improved agricultural technologies may not necessarily result in poverty reduction as some of these constraints make improved technologies inaccessible and less profitable for the poorer farmers (Wossen et al., 2019).

Increasing rice production for enhanced food and income security requires understanding the intricacy of smallholder rice farms in Uganda and their use of improved management practices (Giller et al., 2011; Priegnitz et al., 2019). Getting insights into the diverse and specific farm types necessitates evaluating the uptake of improved management practices in the rice production system together with the socio-economic characteristics and the associated variation in yield among rice farmers. Developing farm typologies i.e., collections of farms that are homogeneous in uptake of improved management practices (Priegnitz et al., 2019) is thus the first and crucial step in examining the adoption of improved management practices in smallholder farms. These typologies could help support more strong policy interventions as well as advisory programmes to improve the adoption of production technologies to increase rice yields (Banerjee et al., 2014). Typologies can also be used to help support the development, implementation and monitoring of agricultural development projects; and to develop more suitable agricultural technologies and policies for less-favoured regions and households. This is in addition to being a practical framework for designing differentiated approaches to addressing rural challenges (Kuivanen et al., 2016; Priegnitz et al., 2019).

This study assessed the change in management practices and grain yield of rice farmers one year after the end of a one-year joint experimentation, conducted between January and December 2019 on-farm together with farmers, where different components of recommended agronomic practices (RAP) for lowland rice production were tested (Awio et al., 2022). Farm types were identified and characterised based on packages of RAP applied on-farm. Components of RAP that were used to form clusters of farms based on how these improved management practices were taken up by the farmers included field levelling, use of certified seed, use of fertiliser in the nursery bed, timely transplanting, line transplanting, gap-filling, use of fertiliser in the field, and timely weeding. For these farm clusters, differences in their socio-economic characteristics and additional rice farming practices were evaluated. The overall objective of the study was to evaluate how the joint experimentation with farmers translated one year later in changes in farmers' management practices and, hence, grain yield, and to identify factors that were related to uptake of improved management practices. Specific objectives of the study were (i) to assess change in management practices and the related change in grain yield of farmers one year after participation in joint experimentation, (ii) to compare management practices, grain yield and yield gap of farmers who participated and those who did not participate in the joint experimentation, and (iii) to identify and characterise farm types based on packages of RAP which farmers have adopted. Examining the impact of farmers' participation in a joint experimentation may be crucial in informing decisions on how yield enhancing related technologies for rice could be delivered to farmers to ensure adoption and realisation of expected results.

## 5.2 Materials and Methods

### 5.2.1 Study area

The study was conducted in the Doho rice irrigation scheme, where components of recommended agronomic practices (RAP) for rice had been previously tested in researcher led on-farm field trials designed and managed together with farmers (Awio et al., 2022). The Doho rice irrigation scheme is located in Eastern Uganda in the Butaleja district[1] (34°02'E, 0°56'N). It is the largest public rice irrigation scheme in Uganda (Wanyama et al., 2017), covering an area of 1000 ha, of which 952 ha is cultivated by over 4000 smallholder farmers. It lies at an altitude of 1100 m a.s.l. and belongs to the Lake Kyoga basin agro-ecological zone. It receives irrigation water from River Manafwa that originates from Mt. Elgon. The annual average rainfall in the area is 1186 mm, distributed over two rainy seasons, from March to May and from August to October. The annual average temperature here is 22.7°C, with daily mean temperatures ranging from 15.4°C to 30.7°C (Namyenya, 2014). The scheme is divided into 11 blocks, where each block is sub-divided into 5–15 strips, and each strip has 20–30 farmers. Rice varieties commonly grown by farmers within the scheme are K 98 and K 85.



[1] A district in Uganda is the local government administrative unit, divided into counties, sub-counties, parishes and villages.

### 5.2.2 Data types and data collection

A semi-structured questionnaire was used to collect comprehensive information from smallholder rice farmers in the study area. Field observations were made at the time of field visits after individual farmer interviews to collect information on farmers' crop management practices and grain yield. Pre-testing of the semi-structured questionnaire was done at the beginning of January 2021 with 7 farmers within the scheme. The questionnaire was then refined and revised with closed and open-end questions to improve further discussion with respondents. In total, 146 rice farmers distributed across 6 sub-counties, 20 parishes and 41 villages of the Butaleja district were interviewed face-to-face in the local language (and only for the literate farmers upon indicating preference, English was used) by specifically trained enumerators from mid-January to the start of May 2021. Of these 146 farmers, 86 were part of the 114 farmers who participated in the joint experimentation of 2019 (herein referred to as participating farmers) and 60 had not taken part in the joint experimentation (herein denoted as non-participating farmers). These latter 60 farmers were purposively selected, as a control group to compare with the participating farmers, based on records from block leaders and willingness to take part in the study, to include farmers considered to be from poor, medium and rich socio-economic backgrounds. All farmers who participated in this study were those who were in production and were to harvest their rice within the time frame of the study to make assessment of crop management practices and grain yield in farmers' fields possible. The study was conducted with informed oral consent by all respondents. Confidentiality of all information collected was guaranteed and research protocols ensured that it was impossible to link published, aggregated data to individual respondents. Applicable guidelines and regulations for survey ethics were diligently followed. No ethical approval prior to the study was obtained as this was not required in Uganda.

The collected information (Table 5.1) included characteristics of the farm household head and farmer (name, gender, age, education), household size, farm size (total household land area, total land area under rice production), herd size (total herd size, number of cattle, small ruminants and poultry), farmer's participation in the joint experimentation, information on family and hired labour for rice production, duration in rice growing, and on rice management practices including adoption of all specified RAP (cf. Table 5.1), seed source, grain yield, and market price for paddy and milled rice. Cropping area was recorded in acres and converted to hectares for reporting (1 ha being equal to 2.47 acres). All costs were recorded in Ugandan Shillings (UGX) and where it is converted to US Dollar for reporting the exchange rate of May 2021 was used (1 USD = 3530 UGX). For grain yield estimation, a survey plot of 10 m × 10 m within each farmer's field was marked from the centre of the field during field observations and a net plot of 4 m × 4 m from within the 10 m × 10 m plot was defined for final yield assessment. At harvest all panicles from the net plot were cut using a sickle, threshed, sun-dried, and the grains winnowed to remove empty grains. Grain weight and moisture content were measured using a digital weighing scale (Mini Crane scale model MNCS-M) and moisture meter (SATAKE Moistex Model SS-7). Rice grain yield adjusted to 0% moisture content (dry weight) was expressed in kg $ha^{-1}$.

### 5.2.3 Data analysis

To assess differences in management practices and grain yield among all farmers, data were subjected to analysis of variance (ANOVA) using an unbalanced treatment structure in Genstat ($19^{th}$ edition) at 5% probability, taking the different farmers' fields as blocks. Where differences were significant, treatment means were separated using Fisher's least significant difference (LSD) test. A paired t-test was done for participating farmers to assess individual farmer's yield gain after participation in the joint experimentation. To quantify the effect of change in management practices of participating farmers after joint experimentation on grain yield, regression analysis using Generalised Linear Model was used. The exploitable yield gap (i.e., the difference between attainable farm yield and actual farm yield) was estimated using the top decile approach (Stuart et al., 2016). Attainable farm yield was defined as the mean yield of the top 10-percentile of yields from all farmers' fields after joint experimentation, and actual farm yield was taken as the mean yield of participating and non-participating farmers. To evaluate the differences in management practices and grain yield of participating farmers, these farmers were grouped based on grain yield in (i) farmers' practice (FP) plot and (ii) recommended agronomic practice (RAP) plot during the joint experimentation. Based on FP plot yield, farmers were categorised as lower-yielding (with grain yields between 1364 and 3037 kg $ha^{-1}$ dry weight, n = 28), middle-yielding (with grain yields varying from 3048 – 4050 kg $ha^{-1}$ dry weight, n = 29) and top-yielding (with grain yields ranging from 4065 – 5545 kg $ha^{-1}$ dry weight, n = 29) third during the joint experimentation. Based on RAP plot yield, farmers were grouped as those who had higher yield in RAP plot compared with FP plot (i.e., RAP yield>FP yield: RAP and FP yield ranged from 2210 – 5753 and 1364 – 5545 kg $ha^{-1}$ dry weight, respectively, n =

69) and those who had higher FP plot yield compared with RAP plot yield (i.e., FP yield>RAP yield: FP and RAP yield ranged from 3048 – 4825 and 2875 – 4255 kg $ha^{-1}$ dry weight, respectively, n = 17) during the joint experimentation.

To construct farm typologies, where combined data for participating and non-participating farm households were used, SPSS (Statistical Package for the Social Sciences), version 25.0 was used to analyse the data following a multivariate method. A principal component analysis (PCA) was first used to reduce the number of variables into a new set of components. Eight variables related to components of RAP (i.e., field levelling, use of certified seed, use of fertiliser in the nursery bed, timely transplanting, line transplanting, gap-filling, use of fertiliser in the field, and timely weeding) were chosen for the PCA. Three principal components exceeding an eigenvalue of 1.00, according to Kaiser's criterion, were retained accounting together for 50.1% of the total variance (Supplementary Table S5.1). Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy indicated the sample was adequate (value of 0.56) and Bartlett's test of sphericity ($p=0.008$) showed that the analysis would be valid. Evaluating the correlations between the variables and the three components, a loading of >0.50 was considered. With the identified components, a hierarchical, agglomerative cluster analysis (CA) was done using Ward's method to minimise the variance within a cluster and squared Euclidean distance to measure the distances. The clustering procedure resulted in the agglomeration schedule in a dendrogram (Supplementary Figure 5.1). After clustering farms based on the components of RAP applied, one-way ANOVA was used to test for significant differences between clusters for variables in the categories: RAP components adopted, socio-economic characteristics, rice production and farming knowledge, and other sources of income (Table 5.1). Differences in means between the clusters were separated using Fisher's LSD test. The proportion of participating and non-participating farm households in each identified cluster or farm type was determined. Analysis of household characteristics for participating and non-participating farmers in each cluster was done where results indicated households under a given cluster, whether participating or non-participating farm households, were identical (Supplementary Table S5.2).

## 5.3 Results

### 5.3.1 Grain yield and management practices of participating farmers

Participating farmers that had lower (lower-yielding third), moderate (middle-yielding third) and higher (top-yielding third) yields under FP during joint experimentation likewise observed significantly different yields after experimentation ($p=0.03$, S.e.d = 169). Top-yielding farmers during joint experimentation also had the highest mean yield one year later (4379 kg $ha^{-1}$), followed by middle (4039 kg $ha^{-1}$) and lower (3951 kg $ha^{-1}$) yielding farmers who had similar yields (Figure 5.1A). Average yields during experimentation had been 4471, 3566 and 2593 kg $ha^{-1}$, respectively, for the top-, middle- and lower-yielding farmers ($p<0.001$, S.e.d = 98.5). Median yields after experimentation were 4458, 4161 and 3895 kg $ha^{-1}$, against 4323, 3589 and 2772 kg $ha^{-1}$ during experimentation, respectively, for the top-, middle- and lower-yielding farmers (Figure 5.1A). Despite having lower grain yield, lower-yielding farmers observed a significantly ($p<0.001$, S.e.d = 199) higher yield gain compared with the middle- and top-yielding farmers (Figure 5.1B, Supplementary Table S5.3). A paired t-test indicated that at individual farmer's field, average yield gain was 1358 kg $ha^{-1}$, ranging between 1027 and 1689 kg $ha^{-1}$ for the lower-yielding farmers ($p<0.001$). This gain was on average 473 kg $ha^{-1}$ for the middle-yielding farmers, ranging between 252 and 695 kg $ha^{-1}$ ($p<0.001$). Top-yielding farmers had on average -91.7 kg $ha^{-1}$ yield gain, ranging from -397 to 213 kg $ha^{-1}$ ($p=0.54$) (Supplementary Table S5.3).

A multiple linear regression showed that change in grain yield after joint experimentation was influenced by change in weeding time and combined effect of change in fertilisation timing and N rate, accounting for overall 41% of the yield gain observed (Table 5.2). Weeding and fertilisation by one day earlier on average increased grain yield by 40.9 and 11.6 kg $ha^{-1}$ $day^{-1}$, respectively. Increasing N amount by 1 kg $ha^{-1}$ resulted to 16.6 kg $ha^{-1}$ increase in grain yield (Table 5.2). There was a significant difference ($p<0.001$, S.e.d = 3.20) in change of weeding time among the farmers, explaining the observed differences in yield gain. Lower-yielding farmers improved their weeding time by weeding on average 2 days earlier (ranging from 2 days later to 6 days earlier) after experimentation compared with weeding time in the FP plot during experimentation. Middle- and top-yielding farmers weeded on average 8 (range: 3 – 12) and 14 (range: 9 - 19) days later, respectively, after experimentation compared with weeding time in the FP plot during experimentation (Table 5.3). Overall, the majority

(61%) of lower-yielding farmers weeded earlier than their weeding time in the FP plot during joint experimentation, compared with 24 and 7% of middle- and top-yielding farmers, respectively (Figure 5.2). In all, weeding time delay compared with recommended weeding time, after experimentation, was not different among farmers ($p>0.05$, S.e.d = 2.76), with average weeding delay of 14, 15 and 15 days, respectively, for the lower-, middle- and top-yielding farmers (Figure 5.3). During experimentation, this weeding delay was significant among farmers ($p<0.001$, S.e.d = 1.76), where lower-, middle- and top-yielding farmers had an average weeding delay of 16, 8 and 3 days, respectively. Lower-yielding farmers also had a slightly larger N rate increase of 19.7 kg $ha^{-1}$ compared with 16.0 and 12.2 kg $ha^{-1}$ increase in N rate for the middle- and top-yielding farmers, after experimentation, respectively (Table 5.3).

**Table 5.1** Description of variables, units, number of respondents (n), and minimum and maximum values of variables used in the principal component analysis (PCA) and cluster analysis (CA), and the subsequent characterisation of farm types.

| Name of variable | Description and units | Minimum | Maximum |
|---|---|---|---|
| **Field levelling** | = 1 if yes, 0 if no | 0 | 1 |
| **Use of certified seed** | = 1 if certified seed, 0 if farmer-saved seed | 0 | 1 |
| **Use of fertiliser in the nursery bed** | = 1 if yes, 0 if no | 0 | 1 |
| Transplanting time | = days of transplanting rice seedlings after sowing the nursery (DAS) | 21 | 46 |
| **Timely transplanting** | = 1 if transplanting is done up to 28 DAS, 0 if transplanting is done after 28 DAS | 0 | 1 |
| **Line transplanting** | = 1 if line transplanting, 0 if random transplanting | 0 | 1 |
| **Gap-filling** | = 1 if yes, 0 if no | 0 | 1 |
| **Use of fertiliser in the field** | = 1 if yes, 0 if no | 0 | 1 |
| Weeding time | = days of weeding after transplanting (DAT) | 15 | 70 |
| **Timely weeding** | = 1 if weeding is done up to 21 DAT, 0 if weeding done after 21 DAT | 0 | 1 |
| N rate | = amount of N applied in kg ha$^{-1}$ | 0 | 68.2 |
| Timely fertilisation | = 1 if fertilisation is done up to 30 DAT, 0 if fertilisation is done after 30 DAT | 0 | 1 |
| Fertilisation time | = days fertiliser is applied after transplanting (DAT) | 7 | 60 |
| Organic (rice straw) input | = 1 if rice straw is incorporated in the soil during ploughing, 0 if not | 0 | 1 |
| Age of household head | = household head's age in years | 22 | 82 |
| Gender of household head | = 1 if male, 0 if female | 0 | 1 |
| Household head's education | = 1 if higher than primary school, 0 if no education or primary education | 0 | 1 |
| Age of farmer | = farmer's age in years | 20 | 80 |
| Gender of farmer | = 1 if male, 0 if female | 0 | 1 |
| Farmer's education | = 1 if higher than primary school, 0 if no education or only primary education | 0 | 1 |
| Farmer participated in joint experiment | = 1 if yes, 0 if no | 0 | 1 |
| Household size | = total number of household members | 2 | 35 |
| Family labour | = average number of household members ha$^{-1}$ season$^{-1}$ | 1 | 128 |
| Hired labour | = average number of people hired ha$^{-1}$ season$^{-1}$ | 0 | 124 |
| Cost of hired labour | = average amount of money spent on hired labour ha$^{-1}$ season$^{-1}$ in UGX × $10^6$ | 0 | 2.5 |
| Herd size[1] | = total number of livestock in tropical livestock unit (TLU) | 0 | 8.9 |

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| | | | |
|---|---|---|---|
| Small ruminant ratio | = share of small ruminants (goats and sheep) in total herd size | 0 | 1 |
| Poultry ratio | = share of poultry (chicken) in total herd size | 0 | 1 |
| Total value of livestock | = value of cattle, goats, chicken, sheep and pigs combined in UGX × $10^6$ | 0 | 16.8 |
| Total household land area | = hectares of land owned by household | 0 | 6.48 |
| Total value of land | = value of land owned by household in UGX × $10^6$ | 0 | 64.0 |
| Total land area for rice growing | = hectares of land used for rice growing | 0.1 | 3.24 |
| Land tenure for rice growing | = 1 if owned, 0 if rented or borrowed | 0 | 1 |
| Grain yield[2] | = rice grain yield in kg $ha^{-1}$ dry weight | 1930 | 5905 |
| Price of paddy | = selling price of paddy in UGX $kg^{-1}$ | 600 | 1100 |
| Price of milled rice | = selling price of milled rice in UGX $kg^{-1}$ | 1200 | 2500 |
| Total income from rice per year per farm [3] | = total cash income from selling all rice harvest in UGX $year^{-1}$ $ha^{-1}$ × $10^6$ | 2.96 | 25.7 |
| Duration in rice growing | = number of years the farmer has been engaged in rice growing | 2 | 38 |
| Attended training/advise on rice farming | = 1 if yes, 0 if no | 0 | 1 |
| Other crops | = total annual household income from other crops in UGX × $10^6$ | 0 | 7.0 |
| Livestock | = total annual household income from livestock in UGX × $10^6$ | 0 | 8.6 |
| Employment | = total annual household income from formal employment in UGX × $10^6$ | 0 | 7.0 |
| Causal labourer | = total annual household income from informal employment (UGX × $10^6$) | 0 | 1.4 |
| Business | = total annual household income from business (UGX × $10^6$) | 0 | 5.87 |
| Crop sale ratio | = share of income from sale of crops | 0.36 | 1.00 |
| Livestock sale ratio | = share of income from sale of livestock | 0 | 0.33 |
| Off-farm income ratio | = share of combined income from formal employment, casual labourer and business | 0 | 0.64 |

Variables in bold are the ones used in the PCA and clustering. RAP = recommended agronomic practices. [1]Tropical livestock unit (TLU) is taken to be an animal of 250 kg live weight (Jahnke et al., 1987), [2]Estimated from the 4 m × 4 m net plot, [3]Income estimate reported by the farmer, not calculated from estimated grain yield, number of observations (n) = 146.

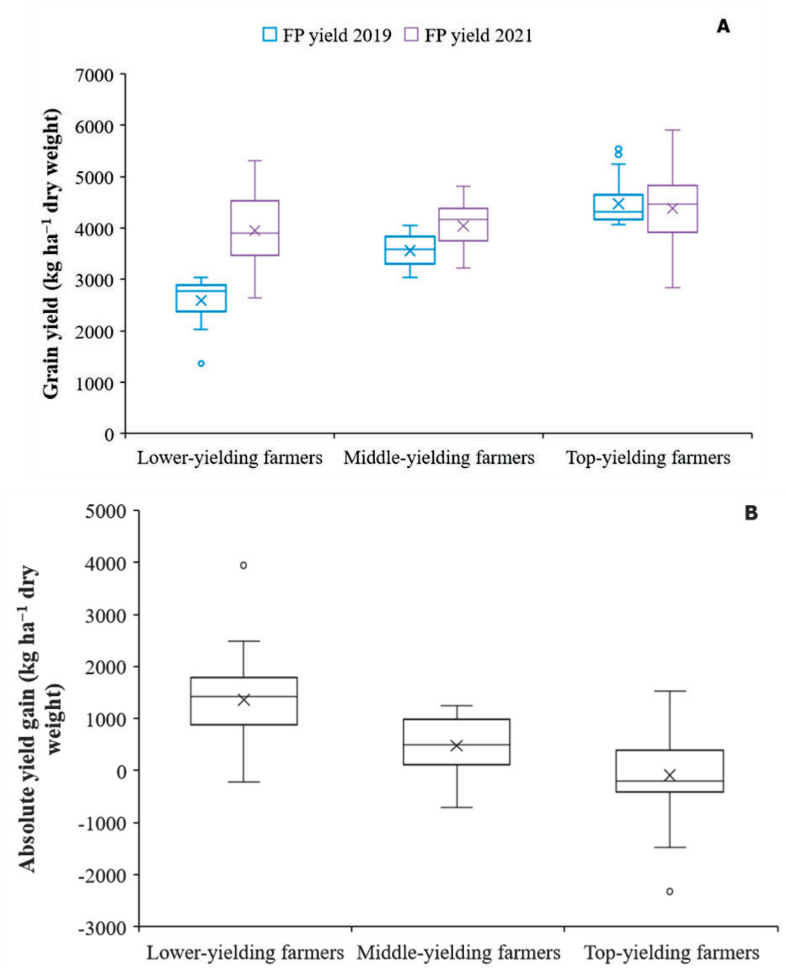


**Figure 5.1** Distribution of grain yield during and after joint experimentation (**A**), and yield gain of farmers one year after participation in joint experimentation (**B**). Absolute yield gain was calculated as the difference between grain yield under FP (farmers' practice) one year after and during joint experimentation. FP yield 2019 = FP yield during joint experimentation in 2019; FP yield 2021 = FP yield in 2021, one year after joint experimentation; Lower- (n = 28), middle- (n = 29) and top- (n = 29) yielding farmers are grouped based on yield obtained under FP during joint experimentation.

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Analysis of household socio-economic characteristics of lower-, middle- and top-yielding farmers showed no major difference among households that could explain differences in yield or yield gain among farmers. Even though lower-yielding farm households had significantly smaller household size, fewer small ruminants and less income from other crops compared with middle- and top-yielding farm households (Table 5.4), these differences were small and populations overlapped. Likewise lower-yielding farm households had smaller herd size, land size, area under rice production and a larger income from off-farm activities, however, these differences were not significant among groups. The lack of clear differences among farm households could indicate that all these farmers have the potential to achieve the higher yield levels attained by top producers under their current production system.

**Table 5.2** Slopes of linear regression lines relating change in grain yield on farmers' fields and change in management practices of farmers after participation in joint experimentation, Doho 2021.

| Management practice | Slope estimate | Unit of slope estimate | Standard error | p-value | Lower 95% confidence limit | Upper 95% confidence limit | Adjusted $R^2$ |
|---|---|---|---|---|---|---|---|
| Weeding time (DAT) | 40.9 | kg $ha^{-1}$ $day^{-1}$ | 6.23 | <0.001 | 28.6 | 53.3 | 0.33 |
| N (kg $ha^{-1}$) | 16.6 | $\frac{kg\ grain\ ha^{-1}}{kg\ N\ ha^{-1}}$ | 5.83 | 0.01 | 5.03 | 28.2 | 0.08 |
| Fertilisation timing (DAT) | 11.6 | kg $ha^{-1}$ $day^{-1}$ | 5.51 | 0.04 | 0.63 | 22.5 | 0.04 |
| Transplanting time (DAS) | 8.7 | kg $ha^{-1}$ $day^{-1}$ | 20.3 | 0.67 | -31.7 | 49.1 | 0.00 |
| + Weeding time (DAT) | 39.6 | kg $ha^{-1}$ $day^{-1}$ | 5.86 | <0.001 | 27.9 | 51.3 | |
| + Fertilisation timing × N rate | 0.51 | $\frac{kg\ ha^{-1}\ day^{-1}}{kg\ N\ ha^{-1}}$ | 0.15 | <0.001 | 0.22 | 0.80 | 0.41 |

DAT – days after transplanting; DAS – days after sowing; number of observations (n) = 86

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**Table 5.3** Grain yield and management practices during (2019) and after (2021) joint experimentation separately for the same farmers with lower, middle and higher yields during joint experimentation in 2019.

| Parameter | | During experimentation | | | After experimentation | | |
|---|---|---|---|---|---|---|---|
| | | Lower | Middle | Top | Lower | Middle | Top |
| Grain yield (kg ha$^{-1}$) | | 2593$^{a}$ | 3566$^{b}$ | 4471$^{c}$ | 3951$^{a}$ | 4039$^{a}$ | 4379$^{b}$ |
| Weeding time | 14-21 DAT (%) | 3.6 | 17.2 | 65.5 | 3.6 | 13.8 | 13.8 |
| | 22-28 DAT (%) | 0 | 24.2 | 20.7 | 25.0 | 13.8 | 24.1 |
| | ≥29 DAT (%) | 96.4 | 58.6 | 13.8 | 71.4 | 72.4 | 62.1 |
| Average weeding time (DAT) | | 36.5$^{c}$ | 28.4$^{b}$ | 22.0$^{a}$ | 34.6 | 36.1 | 35.8 |
| Fertiliser use | Yes (%) | 17.9$^{a}$ | 27.6$^{a}$ | 55.2$^{b}$ | 78.6 | 75.9 | 79.3 |
| | No (%) | 82.1 | 72.4 | 44.8 | 21.4 | 24.1 | 20.7 |
| Average N amount (kg ha$^{-1}$) | | 4.44$^{a}$ | 6.84$^{a}$ | 14.7$^{b}$ | 24.1 | 22.9 | 26.9 |
| Fertilisation time | 14-21 DAT (%) | 0 | 0 | 6.2 | 9.1 | 27.3 | 21.7 |
| | 22-28 DAT (%) | 0 | 12.5 | 25.0 | 27.3 | 9.1 | 17.4 |
| | ≥29 DAT (%) | 100 | 87.5 | 68.8 | 63.6 | 63.6 | 60.9 |
| Average fertilisation time (DAT) | | 40.2$^{ab}$ | 44.6$^{b}$ | 32.9$^{a}$ | 30.0 | 33.6 | 32.4 |
| Crop establishment method | Line transplanting (%) | 21.4 | 20.7 | 34.5 | 39.3 | 44.8 | 41.4 |
| | Random transplanting (%) | 78.6 | 79.3 | 65.5 | 60.7 | 55.2 | 58.6 |
| Transplanting time | 21-28 DAS (%) | 25 | 27.6 | 20.7 | 25 | 20.7 | 41.4 |
| | 29-35 DAS (%) | 75 | 69.0 | 72.4 | 50 | 62.1 | 44.8 |
| | ≥36 DAS (%) | 0 | 3.4 | 6.9 | 25 | 17.2 | 13.8 |
| Average transplanting time (DAS) | | 29.6 | 29.7 | 30.7 | 31.9 | 31.8 | 30.9 |

DAT – days after transplanting; DAS – days after sowing. Values followed by a same letter are statistically the same according to Fisher's post-hoc test. For the lower-, middle- and top-yielding farmers, number of observations (n) are 28, 29 and 29, respectively, during and after joint experimentation.

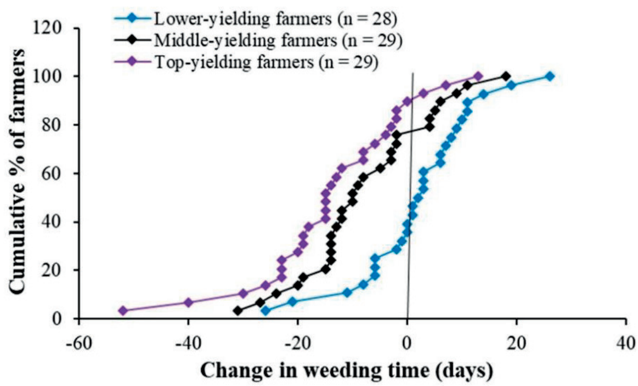


**Figure 5.2** Change in weeding time by farmers after joint experimentation, Doho 2021. Change in weeding time was calculated as the difference between weeding time in FP plot during (2019) and after (2021) joint experimentation, days after transplanting (DAT). Minus (-) value implies that weeding time after experimentation was later compared with weeding time in FP plot during experimentation.

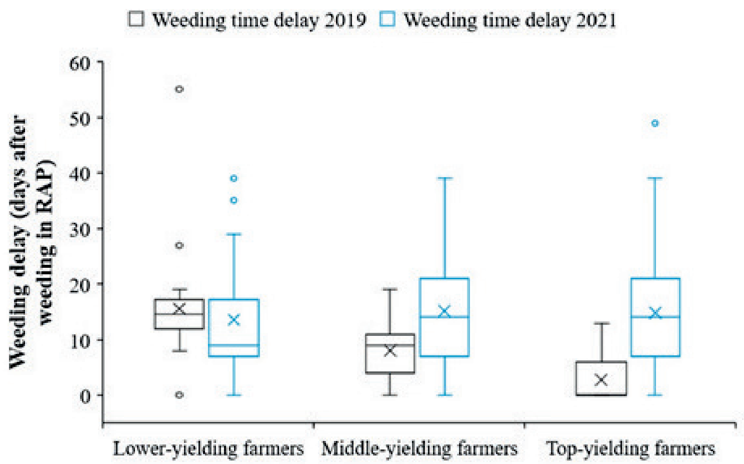


**Figure 5.3** Weeding time delay compared to weeding time under recommended agronomic practices (RAP) during (2019) and after (2021) joint experimentation. Weeding time delay was calculated as the difference in weeding time under FP and RAP. Weeding time delay 2019 = weeding delay during joint experimentation in 2019; Weeding time delay 2021 = weeding delay after joint experimentation in 2021; Lower- (n = 28), middle- (n = 29) and top- (n = 29) yielding farmers are grouped based on yield obtained under FP during joint experimentation. For the top-yielding farmers in 2019, median was zero delay and negative weeding time delay is not possible, hence a lower whisker is absent.

**Table 5.4** Household socio-economic characteristics of lower-, middle- and top-yielding farmers, Doho 2021.

| Characteristic | Lower (n = 28) | Middle (n = 29) | Top (n = 29) | S.e.d | p-value |
|---|---|---|---|---|---|
| ***Household characteristics*** | | | | | |
| Household head's education | 0.36 | 0.48 | 0.41 | 0.13 | 0.64 |
| Farmer's education | 0.46 | 0.48 | 0.34 | 0.13 | 0.53 |
| Duration in rice growing (years) | 17.6 | 17.8 | 17.8 | 3.01 | 0.99 |
| Attended training on rice farming | 0.96 | 0.90 | 0.93 | 0.07 | 0.61 |
| Household size | $8.75^{a}$ | $12.6^{b}$ | $10.2^{ab}$ | 1.55 | 0.05 |
| Herd size (TLU) | 0.87 | 1.81 | 1.71 | 0.46 | 0.09 |
| Number of small ruminants (TLU) | $0.13^{a}$ | $0.32^{b}$ | $0.22^{ab}$ | 0.08 | 0.05 |
| Total livestock value ($\times 10^6$ UGX) | 1.15 | 2.56 | 2.44 | 0.86 | 0.20 |
| Total household land area (ha) | 0.96 | 1.38 | 1.32 | 0.29 | 0.30 |
| Total value of household land ($\times 10^6$ UGX) | 9.45 | 13.4 | 12.3 | 3.05 | 0.43 |
| Land area under rice growing (ha) | 0.43 | 0.57 | 0.48 | 0.12 | 0.48 |
| ***Labour in rice production*** | | | | | |
| Family labour $ha^{-1}$ $season^{-1}$ | 17.7 | 25.5 | 18.5 | 5.30 | 0.28 |
| Hired labour $ha^{-1}$ $season^{-1}$ | 25.2 | 24.8 | 19.3 | 7.04 | 0.65 |
| Cost of hired labour $ha^{-1}$ $season^{-1}$ ($\times 10^6$ UGX) | 0.62 | 0.85 | 0.66 | 0.14 | 0.24 |
| ***Sources of income year$^{-1}$ ($\times 10^6$ UGX)*** | | | | | |
| Rice (net) | 5.48 | 5.38 | 5.82 | 0.84 | 0.89 |
| Other crops | $0.24^{a}$ | $0.67^{ab}$ | $0.92^{b}$ | 0.33 | 0.02 |
| Livestock | 0.28 | 0.54 | 0.53 | 0.29 | 0.60 |
| Off-farm | 1.47 | 0.99 | 0.90 | 0.50 | 0.48 |

Values followed by a same letter are statistically the same according to Fisher's post-hoc test, TLU = tropical livestock unit, n = number of farm households in each group.

To test if farmers who had, during the joint experimentation, a higher yield in their FP plots than their RAP plots would differ in yield and practices from farmers who had a lower yield in their FP plots than their RAP plots, these two groups were analysed separately. Farmers who had higher yield on their FP plot compared with their RAP plot during joint experimentation also had on average higher yields after experimentation (4385 kg $ha^{-1}$, median 4401 kg $ha^{-1}$) than farmers who had lower yield under FP plot compared with RAP plot during joint experimentation (4061 kg $ha^{-1}$, median 4153 kg $ha^{-1}$), (Figure 5.4A). However, this yield difference was statistically marginal ($p=0.07$, S.e.d = 176). During the joint experimentation the average FP yields of these two groups was 3922 (median 3854) and 3464 (median 3313) kg $ha^{-1}$, respectively ($p=0.05$, S.e.d = 227). Overall, average yield gain by farmers after joint experimentation was 571 kg $ha^{-1}$, varying between 366 and 776 kg $ha^{-1}$ (Supplementary Table S5.3). The yield gains were not different ($p=0.61$, S.e.d = 260) between these two groups of farmers (Figure 5.4B, Supplementary Table S5.3). At individual farmer's field, a paired t-test showed an average yield gain of 597 (median 630, value ranging between 348 and 846) and 463 (median 420, values ranging 200 – 727) kg $ha^{-1}$, respectively, for farmers who had lower and higher yields under FP plot compared with RAP plot during the joint experimentation (Figure 5.4B, Supplementary Table S5.3). All management practices a year after the joint experimentation were similar among these two groups except weeding time, where 35% of farmers who had higher yield under FP plot compared with RAP plot weeded within 21 DAT, with an average weeding time of 30 DAT ($p<0.001$, S.e.d = 0.08). This was only 4% for farmers who had lower yield under FP plot compared with RAP plot, with an average weeding time of 37 DAT.

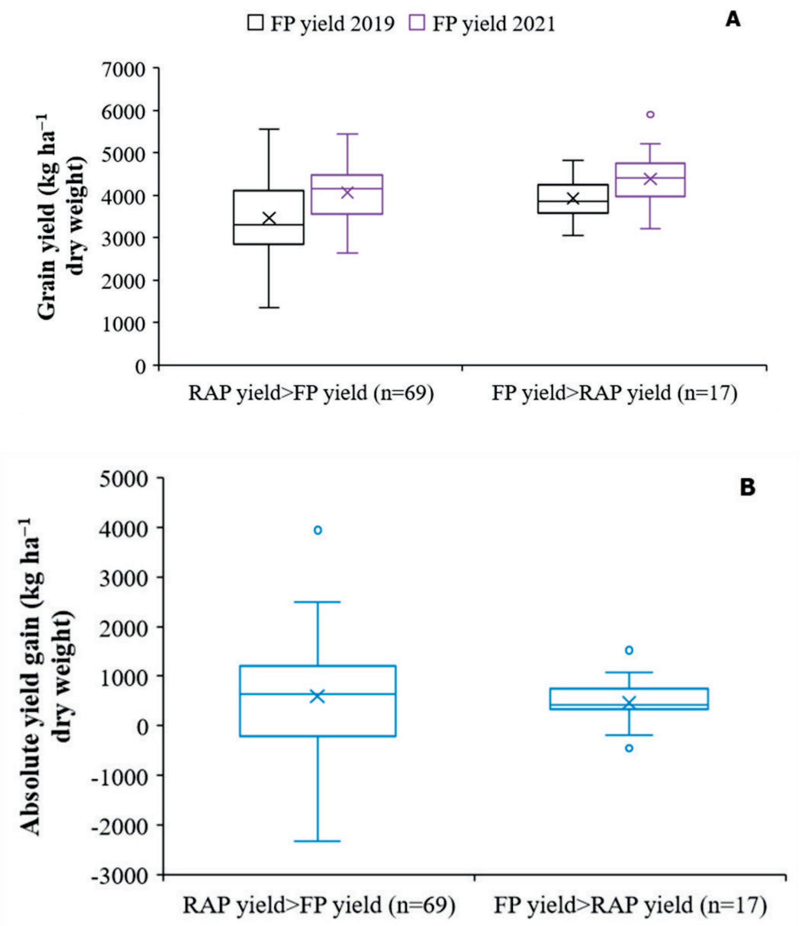


**Figure 5.4** Distribution of grain yield during (2019) and after (2021) joint experimentation (**A**) and yield gain of farmers after participation in joint experimentation (**B**). Absolute yield gain was calculated as the difference between grain yield under FP (farmer's practice) after and during joint experimentation. FP yield 2019 = FP yield during joint experimentation in 2019; FP yield 2021 = FP yield after joint experimentation in 2021; RAP yield>FP yield (n=69) = farmers who had lower yield under FP plot compared with RAP plot, and FP yield>RAP yield (n=17) = farmers who had higher yield under FP plot compared with RAP plot, during joint experimentation; RAP = recommended agronomic practices.

### 5.3.2 Grain yield and management practices of participating and non-participating farmers

Grain yield varied significantly among farmers who participated (participating farmers) and those who did not participate (non-participating farmers) in the joint experimentation ($p=0.05$). Participating farmers had a higher grain yield, averaging 4125 kg ha$^{-1}$ compared with 3893 kg ha$^{-1}$ average grain yield for non-participating farmers (S.e.d = 117). Median yield was 4184 kg ha$^{-1}$ for participating farmers, with grain yield ranging between 2636 and 5905 kg ha$^{-1}$. Median yield was 3971 kg ha$^{-1}$ for non-participating farmers, and grain yield varied from 1930 to 5423 kg ha$^{-1}$ (Figure 5.5). The exploitable yield gap was 20.0 and 24.5%, respectively, for participating and non-participating farmers, when the average of top-decile yield from all farmers' fields after joint experimentation (5158 kg ha$^{-1}$) was taken as attainable farm yield.

We observed differences in some management practices between participating and non-participating farmers. Sixteen percent of participating farmers used certified seed, and 28% transplanted timely, with average transplanting time of 32 DAS, compared with 3 and 13% for non-participating farmers, respectively (Table 5.5). Differences in weeding time (36 vs. 39 DAT) and N amount (24.3 vs. 19.8 kg ha$^{-1}$) were statistically marginal ($p=0.07$), between participating and non-participating farmers. Analysis of household data showed no difference among participating and non-participating farm households, except for training on rice farming which was significantly different ($p<0.001$). More participating farmers (93%) had attended training related to rice production than non-participating farmers (50%) (Table 5.5). Participating farmers had also spent slightly more years in rice growing than non-participating farmers.

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### 5.3.3 Farm households characteristics, farm types and characterisation from clusters

Analysis of household socio-economic data indicated that 86% of the farm households were male headed, with 40% of household heads having attained education higher than primary level (Table 5.6). The average farmer's age was 40 years and 42% of the farmers had attained education higher than primary school. Total household size was on average 10.2 persons. Farmers had on average 1.20 ha of farmland, of which 0.47 ha was under rice production. In terms of labour input in rice production, family and hired labour per rice growing season per ha was on average 22 persons. Regarding application of recommended agronomic practices for rice, 73% of farmers used fertiliser in the nursery bed, 22% transplanted timely (within 28 DAS rice seeds in the nursery), 36% used line transplanting, 76% applied fertiliser in the field, with an average N rate of 22.4 kg ha$^{-1}$ and 12% weeded timely (within 21 DAT rice seedlings, Table 6). Only 11% of the farmers used certified rice seeds, while 98% did field levelling and 95% incorporated rice straw from the previous season into the soil.

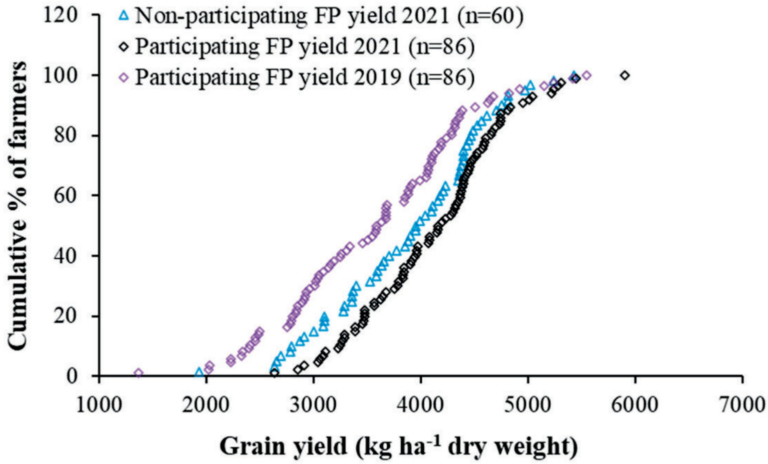


**Figure 5.5** Cumulative distribution of grain yield of farmers after joint experimentation in 2021. Participating farmers are those who participated and non-participating farmers did not participate in the joint experimentation.

**Table 5.5** Management practices and household socio-economic characteristics of participating and non-participating farmers, Doho, 2021.

| Characteristic | Participating farmers (n = 86) | Non-participating farmers (n = 60) | S.e.d | p-value |
|---|---|---|---|---|
| **Management practice** | | | | |
| Field levelling | 0.98 | 0.98 | 0.02 | 0.78 |
| Use of certified seed | 0.16 | 0.03 | 0.05 | 0.01 |
| Use of fertiliser in the nursery bed | 0.73 | 0.73 | 0.07 | 0.99 |
| Timely transplanting | 0.28 | 0.13 | 0.07 | 0.04 |
| Average transplanting time (DAS) | 31.5 | 33.5 | 0.84 | 0.02 |
| Line transplanting | 0.42 | 0.28 | 0.08 | 0.10 |
| Gap-filling | 0.71 | 0.65 | 0.08 | 0.45 |
| Use of fertiliser in the field | 0.78 | 0.73 | 0.07 | 0.53 |
| Timely fertilisation | 0.66 | 0.70 | 0.09 | 0.60 |
| Average fertilisation time (DAT) | 32.0 | 30.8 | 2.03 | 0.56 |
| Average N amount (kg $ha^{-1}$) | 24.3 | 19.8 | 2.54 | 0.07 |
| Timely weeding | 0.10 | 0.13 | 0.05 | 0.60 |
| Average weeding time (DAT) | 35.5 | 39.1 | 1.96 | 0.07 |
| **Household characteristics** | | | | |
| Farmer's education level | 0.43 | 0.40 | 0.08 | 0.72 |
| Attended training on rice farming | 0.93 | 0.50 | 0.06 | $<0.001$ |
| Duration in rice growing (years) | 17.7 | 14.4 | 1.82 | 0.07 |
| Household size | 10.6 | 9.58 | 0.97 | 0.32 |
| Herd size (TLU) | 1.47 | 1.02 | 0.27 | 0.10 |
| Total household land area (ha) | 1.22 | 1.16 | 0.19 | 0.72 |
| Land area under rice growing (ha) | 0.49 | 0.44 | 0.08 | 0.45 |

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| | | | | |
|---|---|---|---|---|
| Family labour $ha^{-1}$ $season^{-1}$ | 20.6 | 24.9 | 3.74 | 0.25 |
| Hired labour $ha^{-1}$ $season^{-1}$ | 23.1 | 19.9 | 3.96 | 0.42 |
| Cost of hired labour $ha^{-1}$ $season^{-1}$ (× $10^6$ UGX) | 0.71 | 0.71 | 0.10 | 0.99 |
| **Income $year^{-1}$ (× $10^6$ UGX)** | | | | |
| Rice (net) | 5.56 | 5.32 | 0.54 | 0.66 |
| Other crops | 0.61 | 0.33 | 0.18 | 0.12 |
| Livestock | 0.45 | 0.34 | 0.17 | 0.48 |
| Off-farm | 1.11 | 0.83 | 0.30 | 0.34 |

DAS = days after sowing, DAT = days after transplanting, TLU = tropical livestock unit, n = number of observations.

Principal component analysis (PCA) and cluster analysis (CA) resulted in identification of three different clusters defined as farm types with their characteristics (Table 5.6). Cluster 1 (farms with less application of RAP) constituted the second largest cluster with 28% (n = 41) of the farms. Of the farmers in this group, 32% used fertiliser in the nursery, 15% transplanted timely, 5% transplanted in line, and 27% applied fertiliser in the field, with the lowest N amount of 7.8 kg $ha^{-1}$. In comparison to the other two clusters, these farmers had moderate land area under rice production (0.45 ha) and expended less cost. Average grain yield was the lowest for them at 3761 kg $ha^{-1}$. However, net income from rice growing in these farms was slightly higher at 5,510,000 UGX (ca. 1,560 USD) $year^{-1}$; in addition to more income from off-farm activities at 1,060,000 UGX (ca. 300 USD). This cluster constituted 26 and 32%, respectively, of participating and non-participating farm households (Supplementary Table S5.2). Cluster 2 (farms with highest level of application of RAP) was the smallest cluster with 24% (n = 35) of the farms. In this group, 71% of the farmers used fertiliser in the nursery, 63% transplanted timely, 69% transplanted in line, and 94% applied fertiliser in the field, with the highest N application rate of 32.5 kg $ha^{-1}$. These farmers also had the largest land area under rice production (0.60 ha) and the highest production cost. Average grain yield was the highest at 4342 kg $ha^{-1}$, however, with the lowest net income from rice production at 5,030,000 UGX (ca. 1,425 USD) $year^{-1}$, but the highest income from other crops. The lower income from rice production could be attributed to the higher expenditure on labour. Overall, these farms have more diversified sources of income compared with the other clusters. Thirty percent of participating and 15% of non-participating farm households made up this cluster. Cluster 3 (farms with moderate application of RAP) was the largest cluster with 48% (n = 70) of the total farms studied. Of the farmers in this cluster, 98% used fertiliser in the nursery, 6% transplanted timely, 39% used line transplanting, and 96% applied fertiliser in the field, with average N amount of 26.0 kg $ha^{-1}$. These farmers had slightly smaller land area under rice production (0.42 ha), with higher production cost. Grain yield was moderate in this cluster at 4031 kg $ha^{-1}$, and leading to a net income from rice production of 5,500,000 UGX (ca. 1,560 USD) $year^{-1}$. Participating and non-participating farm households that made up the cluster were 44 and 53%, respectively (Supplementary Table S5.2).

**Table 5.6** Characteristics of farm households and the identified clusters including the p-value of one-way analysis of variance of differences between farm types.

| Characteristic | Cluster 1 (n = 41) | Cluster 2 (n = 35) | Cluster 3 (n = 70) | Mean (n = 146) | p-value |
|---|---|---|---|---|---|
| **Components of RAP adopted** | | | | | |
| Field levelling | 1.00[b] | 0.91[a] | 1.00[b] | 0.98 | 0.01 |
| Use of certified seed | 0.02[a] | 0.43[b] | 0.00[a] | 0.11 | <0.001 |
| Use of fertiliser in the nursery bed | 0.32[a] | 0.71[b] | 0.98[c] | 0.73 | <0.001 |
| Timely transplanting | 0.15[a] | 0.63[b] | 0.06[a] | 0.22 | <0.001 |
| Line transplanting | 0.05[a] | 0.69[c] | 0.39[b] | 0.36 | <0.001 |
| Gap-filling | 0.68[a] | 0.94[b] | 0.56[a] | 0.68 | <0.001 |
| Use of fertiliser in the field | 0.27[a] | 0.94[b] | 0.96[b] | 0.76 | <0.001 |
| Timely weeding | 0.12 | 0.14 | 0.10 | 0.12 | 0.81 |
| Timely fertilisation | 0.55[a] | 0.82[b] | 0.63[a] | 0.65 | 0.04 |
| Average N amount (kg $ha^{-1}$) | 7.76[a] | 32.5[c] | 26.0[b] | 22.4 | <0.001 |
| Organic input | 0.93 | 0.97 | 0.94 | 0.95 | 0.70 |
| Average transplanting time (DAS) | 32.8[b] | 28.9[a] | 33.8[b] | 32.3 | <0.001 |
| Average weeding time (DAT) | 40.5[b] | 32.0[a] | 37.4[b] | 37.0 | 0.01 |
| Average fertilisation time (DAT) | 35.8[b] | 26.9[a] | 33.1[b] | 32.4 | <0.001 |
| **Rice production and farming knowledge** | | | | | |
| Grain yield (kg $ha^{-1}$ dry weight)[1] | 3761[a] | 4342[c] | 4031[b] | 4030 | 0.001 |
| Duration in rice growing (years) | 15.8 | 17.6 | 16.1 | 16.4 | 0.75 |
| Attended training in rice farming | 0.63 | 0.86 | 0.77 | 0.75 | 0.07 |
| **Socio-economic characteristics** | | | | | |
| Age of household head | 45.4 | 47.2 | 44.3 | 45.3 | 0.64 |

| | | | | | |
|---|---|---|---|---|---|
| Gender of household head | 0.88 | 0.94 | 0.81 | 0.86 | 0.19 |
| Household head's education | 0.32 | 0.49 | 0.41 | 0.40 | 0.32 |
| Age of farmer | 41.9 | 40.9 | 38.7 | 40.1 | 0.50 |
| Gender of farmer | 0.63[ab] | 0.83[b] | 0.56[a] | 0.64 | 0.02 |
| Farmer's education | 0.29 | 0.51 | 0.44 | 0.42 | 0.13 |
| Farmer participated in OFT[2] | 0.54 | 0.74 | 0.54 | 0.59 | 0.11 |
| Household size | 10.2 | 10.1 | 10.2 | 10.2 | 0.99 |
| Family labour $ha^{-1}$ $season^{-1}$ | 22.6 | 23.5 | 21.7 | 22.4 | 0.92 |
| Hired labourer $ha^{-1}$ $season^{-1}$ | 22.8 | 21.0 | 21.6 | 21.8 | 0.94 |
| Total labour cost $ha^{-1}$ $year^{-1}$ ($\times 10^6$ UGX) | 2.48[a] | 3.13[b] | 3.03[b] | 2.90 | <0.001 |
| Total household land area (ha) | 1.17 | 1.49 | 1.06 | 1.20 | 0.17 |
| Land area under rice growing (ha) | 0.45 | 0.60 | 0.42 | 0.47 | 0.12 |
| Herd size (TLU) | 1.45 | 1.37 | 1.14 | 1.28 | 0.58 |
| Cattle (TLU) | 1.14 | 1.02 | 0.91 | 1.00 | 0.72 |
| Small ruminants (TLU) | 0.21 | 0.23 | 0.19 | 0.21 | 0.71 |
| Poultry (TLU) | 0.09[b] | 0.11[b] | 0.04[a] | 0.07 | <0.001 |
| **Income $year^{-1}$ ($\times 10^6$ UGX)** | | | | | |
| Rice (net) | 5.51 | 5.03 | 5.50 | 5.39 | 0.75 |
| Other crops | 0.25[a] | 0.91[b] | 0.43[a] | 0.50 | 0.02 |
| Livestock | 0.42 | 0.62 | 0.30 | 0.41 | 0.27 |
| Off-farm | 1.06 | 1.05 | 0.93 | 1.00 | 0.91 |

[1] Estimated based on harvest from 16 $m^2$ within individual farmer's field, [2] Joint experiment conducted on-farm in 2019. Values followed by a same letter are not statistically different according to Fisher's post-hoc test, when no letters are provided there were no statistical differences. n = number of farm households in each cluster.

## 5.4 Discussion

This study showed that top-yielding farmers during joint experimentation still had the highest average yield after experimentation compared with the lower- and middle-yielding farmers during experimentation. Yet, the lower-yielding farmers made the highest yield gains (Figure 5.1). The higher yield gains by the lower-yielding farmers could be attributed to a significant improvement in management practices after experimentation. Generally lower-yielding farmers improved their weed management, and fertiliser use, amount and timing (Table 5.3 and Figure 5.2). Even though lower-yielding farmers made larger yield gains, the overall yields recorded by farmers are still low, for the rice variety grown, when compared with yields observed under researcher-managed on-farm trials in the same study area (Awio et al., 2021). Grain yields recorded in this study are, however, higher than yields earlier reported under farmers' practice in the study area (Awio et al., 2022; Senthilkumar et al., 2020). The lack of yield gain by the top-yielding farmers might imply that at their current management level these farmers could not further raise their grain yields beyond the level observed during experimentation, probably because the observed current N input could be too low (which was up to a maximum of 68 kg N ha$^{-1}$ after experimentation from 46 kg N ha$^{-1}$ maximum rate during experimentation), in combination with lack of P and K application. It may therefore be necessary that farmers in this production system increase N rates, and P and K application be emphasised based on field inherent fertility to further raise grain yields as current farmers' fertilisation strategies do not put into consideration P and K application (Awio et al., 2022). This should be in addition to improved crop management practices, like proper timing of weeding and fertiliser application. Large yield gains have been reported in the same location under researcher management when N, P and K rates were increased from 80-40-40 to 100-50-50 kg ha$^{-1}$ N, P and K, respectively (Awio et al., 2021). The results of our study are consistent with the findings of Ogada and Nyangena (2015) who observed higher yield gains, due to adoption of improved management practices, by farm households that had lower to medium grain yield than farm households at the upper end of the yield distribution. Shaibu et al. (2021) reported that the highest benefits from scaling up and adoption of improved management practices would be derived by low resource-endowed farm households. Similarly, Ainembabazi et al. (2018) showed that adoption of improved crop varieties would benefit poor farm households more than better-off households. However, in our present study there was no clear difference in resource endowment of lower, middle and top yielding farm households. Farmers who observed higher grain yield in recommended agronomic practices (RAP) plot compared with their FP plot during experimentation realised larger yield gains than farmers who had lower yield under RAP compared with FP plot, an indication that the former farmers learnt something from the joint experimentation which they were able to apply in their fields and make some gains in grain yields. Franke et al. (2010) in on-farm trials found that farmers copied management practices from experimental treatments, in some cases competing in terms of yield with the researcher-managed plots. This observation could point to the broader influence on-farm experimentation can have on farmer's yield improvements the subsequent seasons, something we observe in the present study.

Participating farmers had a slightly but significantly higher grain yield and application of some of the improved rice management practices compared with non-participating farmers (Figure 5.5 and Table 5.5). This shows the potential benefit of exposing farmers to RAP, through participatory learning, on boosting rice yields in Uganda and similar rice production systems in sub-Saharan Africa. The findings further underscore the point that participating farmers learnt something from the joint experimentation and were able to apply that in their fields during the subsequent seasons, resulting in higher grain yields. Similar observation was made by Senthilkumar et al. (2018) who showed improvements in the implementation of RAP for rice by farmers and subsequently increased grain yields after participatory on-farm trials with farmers. Krupnik et al. (2012) and Senthilkumar et al. (2018) noted that farmers learnt by doing to better implement the components of RAP during the course of time the participatory trials were conducted. Kondylis et al. (2017) observed that directly training farmers resulted in a large increase in adoption of sustainable land management practices among farmers. Joint experimentation with farmers can therefore be an interesting way of directly training farmers where learning by doing is facilitated. This farmer training combined with farmers' own experiences with recommended agronomic practices can be used as a tool in rice farming extension efforts to transform rice production, triggering a positive change in the participating farmers' crop management practices, grain yield and livelihoods (Senthilkumar et al. 2018). This, however, requires an enabling environment for rice farmers to increase their production through the adoption of RAP components, for instance, improved access to certified seeds of high-yielding varieties and fertilisers at affordable prices, access to locally adapted simple weeding tools, and fair access to rice markets among others. Joint experimentation can also provide better feedback to research and extension on innovations or innovation components that will not work under local farmers' conditions.

The results of our study indicate that distinguished farm types varied in adoption of improved management practices for rice and grain yield, but not in resource endowment or socio-economic characteristics (Table 5.6). This may imply that farmers in this production system have the capacity of reaching a higher yield level when improved management practices are applied. The lack of difference in resource endowment among farm types could suggest that wealth is not an important factor in adopting improved management practices for rice in the current production system and rice scheme. Our study finding, however, contrasts with previous studies which reported household wealth and other socio-economic parameters to be key in adoption of innovations. For instance, study of Urfels et al. (2021) in tropical Asia showed that household resource endowment determined timing of rice planting, in addition to ecosystem and climatic factors. In SSA, Chekene and Chancellor (2015), Nakano et al. (2018) and Nonvide (2021) noted that farmers' education, age, farming experience and training on improved rice production practices were important in the adoption of improved rice production technologies among rice farmers. Similarly, Fosso and Nanfosso (2016), Hassan et al. (2016) and Lulseged et al. (2016) showed household wealth, off-farm employment, farm size, participation in on-farm trials, and farmers' education to be associated with adoption of improved management practices for maize, e.g., improved weed management, improved seeds, and use of fertiliser. Likewise, Dersseh et al. (2016), Tadesse et al. (2017), and Tadesse et al. (2019) observed that adoption of improved potato varieties and production practices was related to household wealth and educational levels. In the present study, however, these variables were not significantly different among the identified farm types, except farmer's gender. Difference among farm types in attending trainings related to rice farming would be significant at 0.10% probability.

## 5.5 Conclusion

This study indicates that joint experimentation had a larger effect on raising yields of originally lower-yielding farmers and narrowed the yield gap between lower- and higher-yielding farmers, thus bringing farmers closer in their management and outputs. Lower-yielding farmers made more gains compared with higher-yielding farmers, an indication that lower-yielding farmers had more room to raise their yields, as it seemed difficult for higher-yielding farmers to further increase their yields. Despite the larger yield gains by lower-yielding farmers, the overall yields observed by farmers in the study area are still rather limited when compared with researcher-managed yields previously reported on-farm in the same rice scheme. No difference in household resource endowment was observed amongst farm types which could imply that wealth is not a crucial element of adoption of available innovation in this production system, unless all households were limited in further innovating. Further studies aimed at understanding the limitations to why some farmers do not apply packages of RAP despite not being socio-economically different from those farmers who apply, may be relevant to identify appropriate solutions to such bottlenecks hence boosting also these farmers' rice productivity.

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## References

Ainembabazi, J. H., Abdoulaye, T., Feleke, S., Alene, A., Dontsop-Nguezet, P. M., Ndayisaba, P. C., . . . Manyong, V. (2018). Who benefits from which agricultural research-for-development technologies? Evidence from farm household poverty analysis in Central Africa. *World Development, 108*, 28-46. DOI: 10.1016/j.worlddev.2018.03.013

Awio, T., Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Kempen, B., Struik, P. C., & Stomph, T. J. (2021). Micro-nutrients in East African lowlands: Are they needed to intensify rice production? *Field Crops Research, 270*, 108219. DOI: 10.1016/j.fcr.2021.108219

Awio, T., Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Struik, P. C., & Stomph, T. J. (2022). Yields and Yield Gaps in Lowland Rice Systems and Options to Improve Smallholder Production. *Agronomy, 12*(3). DOI: 10.3390/agronomy12030552

Banerjee, H., Goswami, R., Chakraborty, S., Dutta, S., Majumdar, K., Satyanarayana, T., . . . Zingore, S. (2014). Understanding biophysical and socio-economic determinants of maize (Zea mays L.) yield variability in eastern India. *NJAS: Wageningen Journal of Life Sciences, 70-71*(1), 79-93. DOI: 10.1016/j.njas.2014.08.001

Chekene, M. B., & Chancellor, T. S. B. (2015). Factors Affecting the Adoption of Improved Rice Varieties in Borno State, Nigeria. *Journal of Agricultural Extension, 19*(2). DOI: 10.4314/jae.v19i2.2

5

Danlami, A. H., Applanaidu, S.-D., & Islam, R. (2019). A Microlevel Analysis of the Adoption and Efficiency of Modern Farm Inputs Use in Rural Areas of Kano State, Nigeria. *Agricultural Research, 8*(3), 392-402. DOI: 10.1007/s40003-018-0373-z

Danlami, A. H., Islam, R., Applanaidu, S. D., & Tsauni, A. M. (2016). An empirical analysis of fertiliser use intensity in rural Sub-Saharan Africa. *International Journal of Social Economics, 43*(12), 1400-1419. DOI: 10.1108/IJSE-04-2015-0086

Dersseh, W. M., Gebresilase, Y. T., Schulte, R. P. O., & Struik, P. C. (2016). The Analysis of Potato Farming Systems in Chencha, Ethiopia: Input, Output and Constraints. *American Journal of Potato Research, 93*(5), 436-447. DOI: 10.1007/s12230-016-9521-9

Food and Agriculture Organisation of the United Nations (2021). Production data: Crops and livestock products. Retrieved from http://www.fao.org/faostat/en/#data/QC [Accessed September 26, 2021].

Food and Agriculture Organisation of the United Nations (2022). Trade data: Crops and livestock products. Retrieved from https://www.fao.org/faostat/en/#data/TCL [Accessed May 19, 2022].

Fosso, P. K., & Nanfosso, R. T. (2016). Adoption of agricultural innovations in risky environment: the case of corn producers in the west of Cameroon. *Review of Agricultural, Food and Environmental Studies, 97*(1), 51-62. DOI: 10.1007/s41130-016-0008-3

Franke, A. C., Berkhout, E. D., Iwuafor, E. N. O., Nziguheba, G., Dercon, G., Vandeplas, I., & Diels, J. (2010). Does crop-livestock integration lead to improved crop production in the savanna of West Africa? *Experimental Agriculture, 46*(4), 439-455. DOI: 10.1017/S0014479710000347

Giller, K. E., Tittonell, P., Rufino, M. C., van Wijk, M. T., Zingore, S., Mapfumo, P., . . . Vanlauwe, B. (2011). Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural Systems, 104*(2), 191-203. DOI: 10.1016/j.agsy.2010.07.002

Global Yield Gap Atlas (2022). Yield gap for sub-Saharan Africa. Retrieved from https://www.yieldgap.org/gygaviewer/index.html [Accessed July 29, 2022]

Hassan, M. B., Baiyegunhi, L. J. S., Ortmann, G. F., & Abdoulaye, T. (2016). Adoption of striga (striga hermonthica) Management Technologies in Northern Nigeria. *Agrekon, 55*(1-2), 168-188. DOI: 10.1080/03031853.2016.1159587

Jahnke, H. E., Tacher, G., Keil, P., & Rojat, D. (1987). Livestock production in tropical Africa with special reference to the tsetse-affected zone. Livestock Production in

Tsetse Affected Areas of Africa. *International Livestock Centre for Africa and International Laboratory for Research on Animal Diseases, Nairobi, Kenya*, 496.

Kassie, M., Marenya, P., Tessema, Y., Jaleta, M., Zeng, D., Erenstein, O., & Rahut, D. (2018). Measuring Farm and Market Level Economic Impacts of Improved Maize Production Technologies in Ethiopia: Evidence from Panel Data. *Journal of Agricultural Economics, 69*(1), 76-95. DOI: 10.1111/1477-9552.12221

Kassie, M., Shiferaw, B., & Muricho, G. (2011). Agricultural Technology, Crop Income, and Poverty Alleviation in Uganda. *World Development, 39*(10), 1784-1795. DOI: 10.1016/j.worlddev.2011.04.023

KilimoTrust. (2014). Expanding Rice Markets in the East African Community. 64.

Kondylis, F., Mueller, V., & Zhu, J. (2017). Seeing is believing? Evidence from an extension network experiment. *Journal of Development Economics, 125*, 1-20. DOI: 10.1016/j.jdeveco.2016.10.004

Krupnik, T. J., Shennan, C., Settle, W. H., Demont, M., Ndiaye, A. B., & Rodenburg, J. (2012). Improving irrigated rice production in the Senegal River Valley through experiential learning and innovation. *Agricultural Systems, 109*, 101-112. DOI: 10.1016/j.agsy.2012.01.008

Kuivanen, K. S., Alvarez, S., Michalscheck, M., Adjei-Nsiah, S., Descheemaeker, K., Mellon-Bedi, S., & Groot, J. C. J. (2016). Characterising the diversity of smallholder farming systems and their constraints and opportunities for innovation: A case study from the Northern Region, Ghana. *NJAS - Wageningen Journal of Life Sciences, 78*, 153-166. DOI:_10.1016/j.njas.2016.04.003

Lulseged, T., Powell, M., Gift, N., & Kihara, J. (2016). Assessment of maize yield gap and major determinant factors between smallholder farmers in the Dedza district of Malawi. *Nutrient Cycling in Agroecosystems, 105*(3), 291-308. DOI: 10.1007/s10705-015-9692-7

Manda, J., Alene, A. D., Tufa, A. H., Abdoulaye, T., Wossen, T., Chikoye, D., & Manyong, V. (2019). The poverty impacts of improved cowpea varieties in Nigeria: A counterfactual analysis. *World Development, 122*, 261-271. DOI: 10.1016/j.worlddev.2019.05.027

Mottaleb, K. A. (2018). Perception and adoption of a new agricultural technology: Evidence from a developing country. *Technology in Society, 55*, 126-135. DOI: 10.1016/j.techsoc.2018.07.007

Nakano, Y., Tanaka, Y., & Otsuka, K. (2018). Impact of training on the intensification of rice farming: evidence from rainfed areas in Tanzania. *Agricultural Economics, 49*(2), 193-202. DOI: 10.1111/agec.12408

Namyenya, A. (2014). Farmers' willingness to pay for irrigation water: the case of Doho rice irrigation scheme in eastern Uganda. *MSc. Thesis, Makerere University.*, 90.

Nonvide, G. M. A. (2021). Adoption of agricultural technologies among rice farmers in Benin. *Review of Development Economics, 25*(4), 2372-2390. DOI: 10.1111/rode.12802

Ogada, M. J., & Nyangena, W. (2015). Impact of Improved Farm Technologies on Yields: The Case of Improved Maize Varieties and Inorganic Fertilizers in Kenya. *International Conference of Agricultural Economists, Italy.*, 31.

Priegnitz, U., Lommen, W. J. M., Onakuse, S., & Struik, P. C. (2019). A Farm Typology for Adoption of Innovations in Potato Production in Southwestern Uganda. *Frontiers in Sustainable Food Systems, 3*(68). DOI: 10.3389/fsufs.2019.00068

Senthilkumar, K., Tesha, B. J., Mghase, J., & Rodenburg, J. (2018). Increasing paddy yields and improving farm management: results from participatory experiments with good agricultural practices (GAP) in Tanzania. *Paddy and Water Environment, 16*(4), 749-766. DOI: 10.1007/s10333-018-0666-7

Senthilkumar, K., Rodenburg, J., Dieng, I., Vandamme, E., Sillo, S. F., Johnson, J., Rajaona, A., Ramarolahy, J. A., Gasore, R., Abera, B. B., Kajiru, G. J., Mghase, J., Lamo, J., Rabeson, R., & Saito, K. (2020). Quantifying rice yield gaps and their causes in Eastern and Southern Africa. Journal Agronomy and Crop Science, Special Issue: 13, 1-13. DOI: 10.1111/jac.12417

Shaibu, M. B., Azzarri, C., Bekele, H. K., Kornher, L., & von Braun, J. (2021). Scaling-up agricultural technologies: who should be targeted? *European Review of Agricultural Economics*, jbab054. DOI: 10.1093/erae/jbab054

Sinyolo, S. (2020). Technology adoption and household food security among rural households in South Africa: The role of improved maize varieties. *Technology in Society, 60*, 101214. DOI: 10.1016/j.techsoc.2019.101214

Stuart, A. M., Pame, A. R. P., Silva, J. V., Dikitanan, R. C., Rutsaert, P., Malabayabas, A. J. B., . . . Singleton, G. R. (2016). Yield gaps in rice-based farming systems: Insights from local studies and prospects for future analysis. *Field Crops Research, 194*, 43-56. DOI: 10.1016/j.fcr.2016.04.039

Tadesse, Y., Almekinders, C. J. M., Schulte, R. P. O., & Struik, P. C. (2017). Understanding farmers' potato production practices and use of improved varieties in Chencha, Ethiopia. *Journal of Crop Improvement, 31*(5), 673-688. DOI: 10.1080/15427528.2017.1345817

Tadesse, Y., Almekinders, C. J. M., Schulte, R. P. O., & Struik, P. C. (2019). Potatoes and livelihoods in Chencha, southern Ethiopia. *NJAS: Wageningen Journal of Life Sciences, 88*(1), 105-111. DOI: 10.1016/j.njas.2018.05.005

Takahashi, K., Muraoka, R., & Otsuka, K. (2020). Technology adoption, impact, and extension in developing countries' agriculture: A review of the recent literature. *Agricultural Economics, 51*(1), 31-45. DOI: 10.1111/agec.12539

Uganda Bureau of Statistics, U. (2021). Statistical Abstract. 350. Retrieved from www.ubos.org. [Accessed May 19, 2022].

Urfels, A., McDonald, A. J., van Halsema, G., Struik, P. C., Kumar, P., Malik, R. K., . . . Krupnik, T. J. (2021). Social-ecological analysis of timely rice planting in Eastern India. *Agronomy for Sustainable Development, 41*(2), 14. DOI: 10.1007/s13593-021-00668-1

Wanyama, J., Ssegane, H., Kisekka, I., Komakech, A. J., Banadda, N., Zziwa, A., . . . Lubwama, K. F. (2017). Irrigation Development in Uganda: Constraints, Lessons Learned, and Future Perspectives. *J. Irrig. Drain Eng., 143*(5), 10.

Wossen, T., Alene, A., Abdoulaye, T., Feleke, S., Rabbi, I. Y., & Manyong, V. (2019). Poverty Reduction Effects of Agricultural Technology Adoption: The Case of Improved Cassava Varieties in Nigeria. *Journal of Agricultural Economics, 70*(2), 392-407. DOI: 10.1111/1477-9552.12296

## Supplementary materials in Chapter 5

**Supplementary Table S5.1** Factor loadings for the three components from the Principal Component Analysis with eigenvalues and percentage variance accounted for.

| Components of RAP | Principal component | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Field levelling | -0.14 | 0.17 | **-0.71** |
| Use of certified seed | 0.09 | **0.56** | 0.44 |
| Use of fertiliser in the nursery bed | **0.70** | -0.15 | -0.03 |
| Timely transplanting | 0.00 | **0.69** | 0.16 |
| Line transplanting | 0.48 | **0.56** | -0.04 |
| Gap-filling | -0.15 | 0.15 | **0.64** |
| Use of fertilisation in the field | **0.77** | 0.11 | 0.07 |
| Timely weeding | -0.24 | **0.56** | -0.25 |
| Eigenvalue | 1.42 | 1.39 | 1.20 |
| Variance accounted for (%) | 17.8 | 17.4 | 14.9 |
| Cumulative variance accounted for (%) | 17.8 | 35.2 | 50.1 |

RAP = recommended agronomic practices; Values in bold are factor loadings higher than 0.5 or lower than −0.5, used to evaluate the correlations between the factors and the three principal components.

**Supplementary Table S5.2** Characteristics of farm households and the identified clusters, proportion of participating (PF) and non-participating farmers (NPF) in each cluster and p-values of one-way analysis of variance of differences between farm types (clusters).

| Characteristic | Cluster 1 | | | Cluster 2 | | | Cluster 3 | | | Overall mean (n = 146) | p-value |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | PF (n = 22) | NPF (n = 19) | Mean (n = 41) | PF (n = 26) | NPF (n = 9) | Mean (n = 35) | PF (n = 38) | NPF (n = 32) | Mean (n = 70) | | |
| **Components of RAP adopted** | | | | | | | | | | | |
| Field levelling | 1.00 | 1.00 | 1.00$^{b}$ | 0.92 | 0.89 | 0.91$^{a}$ | 1.00 | 1.00 | 1.00$^{b}$ | 0.98 | 0.01 |
| Use of certified seed | 0.05 | 0.00 | 0.02$^{a}$ | 0.50 | 0.22 | 0.43$^{b}$ | 0.00 | 0.00 | 0.00$^{a}$ | 0.11 | <0.001 |
| Use of fertiliser in the nursery bed | 0.27 | 0.37 | 0.32$^{a}$ | 0.73 | 0.67 | 0.71$^{b}$ | 1.00 | 0.97 | 0.98$^{c}$ | 0.73 | <0.001 |
| Timely transplanting | **0.27** | **0.00** | 0.15$^{a}$ | 0.62 | 0.67 | 0.63$^{b}$ | 0.05 | 0.06 | 0.06$^{a}$ | 0.22 | <0.001 |
| Line transplanting | 0.09 | 0.00 | 0.05$^{a}$ | 0.77 | 0.44 | 0.69$^{c}$ | 0.37 | 0.41 | 0.39$^{b}$ | 0.36 | <0.001 |
| Gap-filling | 0.73 | 0.63 | 0.68$^{a}$ | 0.96 | 0.89 | 0.94$^{b}$ | 0.53 | 0.59 | 0.56$^{a}$ | 0.68 | <0.001 |
| Use of fertiliser in the field | 0.32 | 0.21 | 0.27$^{a}$ | 0.92 | 1.00 | 0.94$^{b}$ | 0.95 | 0.97 | 0.96$^{b}$ | 0.76 | <0.001 |
| Timely weeding | 0.09 | 0.16 | 0.12 | 0.12 | 0.22 | 0.14 | 0.11 | 0.09 | 0.10 | 0.12 | 0.81 |
| Timely fertilisation | 0.43 | 0.75 | 0.55$^{a}$ | 0.83 | 0.78 | 0.82$^{b}$ | 0.58 | 0.68 | 0.63$^{a}$ | 0.65 | 0.04 |
| Average N amount ($g\ m^{-2}$) | 0.95 | 0.57 | 0.78$^{a}$ | 3.35 | 2.98 | 3.25$^{c}$ | 2.67 | 2.52 | 2.60$^{b}$ | 2.24 | <0.001 |
| Organic input | 0.91 | 0.95 | 0.93 | 0.96 | 1.00 | 0.97 | 0.89 | 1.00 | 0.94 | 0.95 | 0.70 |
| Average transplanting time (DAS) | 31.5 | 34.3 | 32.8$^{b}$ | 28.7 | 29.4 | 28.9$^{a}$ | 33.4 | 34.2 | 33.8$^{b}$ | 32.3 | <0.001 |
| Average weeding time (DAT) | 38.8 | 42.4 | 40.5$^{b}$ | 31.7 | 32.9 | 32.0$^{a}$ | 36.3 | 38.8 | 37.4$^{b}$ | 37.0 | 0.01 |
| Average fertilisation time (DAT) | **39.6** | **29.3** | 35.8$^{b}$ | 27.3 | 26.0 | 26.9$^{a}$ | 33.7 | 32.4 | 33.1$^{b}$ | 32.4 | <0.001 |
| **Rice production and farming knowledge** | | | | | | | | | | | |
| Grain yield ($g\ m^{-2}$ dry weight)[1] | 386 | 365 | 376$^{a}$ | 438 | 423 | 434$^{c}$ | 411 | 394 | 403$^{b}$ | 403 | 0.001 |
| Duration in rice growing (years) | 17.0 | 14.4 | 15.8 | 18.5 | 14.8 | 17.6 | 17.6 | 14.3 | 16.1 | 16.4 | 0.75 |
| Attended training in rice farming | **0.95** | **0.26** | 0.63 | **0.96** | **0.56** | 0.86 | **0.89** | **0.63** | 0.77 | 0.75 | 0.07 |
| **Socio-economic characteristics** | | | | | | | | | | | |
| Age of household head | 46.0 | 44.8 | 45.4 | 45.9 | 50.9 | 47.2 | 43.9 | 44.9 | 44.3 | 45.3 | 0.64 |
| Gender of household head | 0.86 | 0.89 | 0.88 | 0.96 | 0.89 | 0.94 | 0.82 | 0.81 | 0.81 | 0.86 | 0.19 |
| Household head's education | 0.32 | 0.32 | 0.32 | 0.50 | 0.44 | 0.49 | 0.42 | 0.41 | 0.41 | 0.40 | 0.32 |
| Age of farmer | 43.1 | 40.4 | 41.9 | 42.0 | 37.7 | 40.9 | 40.6 | 36.5 | 38.7 | 40.1 | 0.50 |
| Gender of farmer | 0.64 | 0.63 | 0.63$^{ab}$ | 0.88 | 0.67 | 0.83$^{b}$ | 0.63 | 0.47 | 0.56$^{a}$ | 0.64 | 0.02 |
| Farmer's education | 0.32 | 0.26 | 0.29 | 0.50 | 0.56 | 0.51 | 0.45 | 0.44 | 0.44 | 0.42 | 0.13 |
| Farmer participated in OFT[2] | 1.00 | 0.00 | 0.54 | 1.00 | 0.00 | 0.74 | 1.00 | 0.00 | 0.54 | 0.59 | 0.11 |

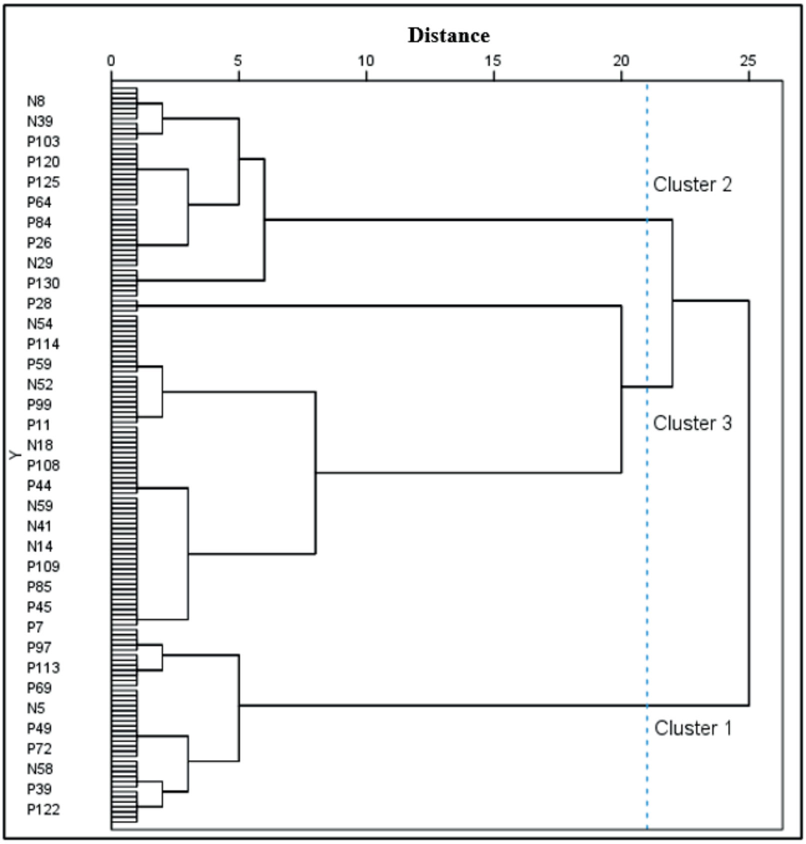
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Household size | 11.6 | 8.53 | 10.2 | 10.7 | 8.33 | 10.1 | 9.82 | 10.6 | 10.2 | 10.2 | 0.99 |
| Family labour $ha^{-1}$ $season^{-1}$ | 21.6 | 23.7 | 22.6 | 23.2 | 24.2 | 23.5 | 18.2 | 25.8 | 21.7 | 22.4 | 0.92 |
| Hired labourer $ha^{-1}$ $season^{-1}$ | 23.1 | 22.4 | 22.8 | 20.5 | 22.3 | 21.0 | 24.8 | 17.7 | 21.6 | 21.8 | 0.94 |
| Total labour cost $ha^{-1}$ $year^{-1}$ (× $10^6$ UGX) | 2.67 | 2.27 | 2.48[a] | 3.16 | 3.06 | 3.13[b] | 3.01 | 3.06 | 3.03[b] | 2.90 | <0.001 |
| Total household land area (ha) | 1.27 | 1.05 | 1.17 | 1.54 | 1.37 | 1.49 | 0.98 | 1.16 | 1.06 | 1.20 | 0.17 |
| Land area under rice growing (ha) | 0.48 | 0.41 | 0.45 | 0.62 | 0.55 | 0.6 | 0.41 | 0.42 | 0.42 | 0.47 | 0.12 |
| Herd size (TLU) | 1.74 | 1.13 | 1.45 | 1.50 | 0.97 | 1.37 | 1.29 | 0.96 | 1.14 | 1.28 | 0.58 |
| Cattle (TLU) | 1.37 | 0.88 | 1.14 | 1.13 | 0.70 | 1.02 | 1.05 | 0.74 | 0.91 | 1.00 | 0.72 |
| Small ruminants (TLU) | 0.23 | 0.18 | 0.21 | 0.25 | 0.19 | 0.23 | 0.20 | 0.18 | 0.19 | 0.21 | 0.71 |
| Poultry (TLU) | 0.12 | 0.06 | 0.09[b] | 0.12 | 0.09 | 0.11[b] | 0.04 | 0.05 | 0.04[a] | 0.07 | <0.001 |
| **Income $year^{-1}$ (× $10^6$ UGX)** | | | | | | | | | | | |
| Rice (net) | 5.92 | 5.02 | 5.51 | 4.77 | 5.80 | 5.03 | 5.71 | 5.26 | 5.50 | 5.39 | 0.75 |
| Other crops | 0.31 | 0.19 | 0.25a | 0.98 | 0.70 | 0.91[b] | 0.54 | 0.31 | 0.43[a] | 0.5 | 0.02 |
| Livestock | 0.55 | 0.26 | 0.42 | 0.67 | 0.48 | 0.62 | 0.26 | 0.34 | 0.30 | 0.41 | 0.27 |
| Off-farm | **1.78** | **0.23** | 1.06 | 1.12 | 0.86 | 1.05 | 0.72 | 1.18 | 0.93 | 1.00 | 0.91 |

[1] Estimated based on harvest from 16 $m^2$ within individual farmer's field, [2] Joint experiment conducted on-farm in 2019. PF = participating farmers (n = 86), NPF = non-participating farmers (n = 60), n = number of farm households in each category. Values followed by a same letter are not statistically different among clusters according to Fisher's post-hoc test, when no letters are provided there were no statistical differences. Values in bold are statistically different between participating and non-participating farmers within the same cluster.

**Supplementary Table S5.3** Results of analysis of variance (ANOVA), and a paired sample t-test comparing yields during (2019) and after (2021) joint experimentation to assess individual farmer's yield gain

| Category | Average yield gain (kg ha$^{-1}$) | p-value** | Lower 95% confidence limit | Upper 95% confidence limit |
|---|---|---|---|---|
| Lower-yielding farmers (n = 28) | 1358[c] | <0.001 | 1027 | 1689 |
| Middle yielding farmers (n = 29) | 473[b] | <0.001 | 252 | 695 |
| Top-yielding farmers (n = 29) | -91.7[a] | 0.54 | -397 | 213 |
| **p-value*** | **<0.001** | | | |
| **S.e.d** | **199** | | | |
| | | | | |
| RAP yield > FP yield (n = 69) | 597 | <0.001 | 348 | 846 |
| FP yield > RAP yield (n = 17) | 463 | 0.002 | 200 | 727 |
| **p-value*** | **0.61** | | | |
| **S.e.d** | **260** | | | |
| | | | | |
| Overall yield gain (n = 86) | 571 | <0.001 | 366 | 776 |

** p-value is for the test of the null hypothesis that average yield gain for the farmer's category is equal to 0 (paired t-test); * p-value is for the test of the null hypothesis that average yield gain among the farmer's category is the same (ANOVA); RAP yield > FP yield = farmers who had lower yield under farmers' practice (FP) plot compared with recommended agronomic practices (RAP) plot, and FP yield > RAP yield = farmers who had higher yield under FP plot compared with RAP plot, during joint experimentation. Values followed by a different letter are statistically different according to Fisher's post-hoc test.




**Supplementary Figure 5.1** Dendrogram for the Cluster Analysis. On the y-axis are the farm households. Farm households with "P" and "N" at the beginning of the codes are participating and non-participating farm households. The dashed line represents the agglomeration coefficient (the distance between the clusters) and the selected cut-off point for forming the three cluster solutions.

# 6

# CHAPTER 6.

## General discussion

## 6.1 Background

Meeting the demand for staple food crops is a challenge sub-Saharan Africa (SSA) continues to grapple with. Low crop productivity is an important contributor to the inability of SSA to meet its food demand. With the projected increase in SSA population and future food demand, SSA is likely to be at the greatest food security risk, if the current low crop productivity levels persist, compared with other regions of the world (van Ittersum et al., 2016). Increasing crop productivity per unit of available arable land, hence closing the yield gap between actual farm yields and potential yield, is thus needed if SSA is to meet its food demand and become more food secure on existing agricultural land (Koning et al., 2008; Pradhan et al., 2015; Tilman et al., 2011). This will reduce reliance on large imports and crop area expansion into marginal lands and forest areas (Brink & Eva, 2009; van Ittersum et al., 2016; van Oort et al., 2015).

Low crop productivity in SSA farm lands is attributed to, among other factors, soil fertility constraints and sub-optimal soil and crop management. In an attempt to address the low soil fertility constraint, NPK fertilisers are applied. Considering the fluctuating fertiliser prices caused by geopolitical problems of fertiliser exports and energy prices, relying on fertilisers to boost crop productivity in order to address the food demand of SSA becomes a challenge. Yet, NPK fertilisation alone is not always giving better yields. Response to NPK fertilisation could be influenced by micro-nutrients (Kihara et al., 2017; Vanlauwe et al., 2015; Wortmann et al., 2019), recommended agronomic practices (RAP) (Nhamo et al., 2014; Touré et al., 2009), and inherent soil fertility (Kihara & Njoroge, 2013; Vanlauwe et al., 2006). Nevertheless, micro-nutrient fertilisation has gained little attention among smallholder farmers, whereas farmers' application of RAP tends to be sub-optimal. Likewise, inherent soil fertility level varies among farmers' fields because of differences in crop management practices. Better understanding of the contribution of the use of RAP either under researcher guidance or under farmer management, of inherent soil fertility differences between fields and of possible limitations in terms of secondary or micro-nutrients is therefore required to understand how NPK use efficiency and crop productivity can be substantially enhanced.

This thesis used lowland rice growing areas in Uganda and Tanzania as study sites and rice as the study crop. It aimed at quantifying the magnitude of the effect of micro-nutrients, RAP under researcher guidance and as applied by farmers, and inherent fertility on NPK use efficiency and grain yields of lowland rice. It also aimed at identifying feasible options to boost smallholder nutrient use efficiency and productivity. In order to achieve these aims, several studies including researcher-managed on-farm trials (Chapter 2), participatory (researcher- and farmer-managed) on-farm trials (Chapters 3 and 4), and a follow-up evaluation study through household surveys and farmers' field assessments (Chapter 5), were conducted. In this Chapter, main findings of each preceding chapter are provided, and the results are integrated to create insights for options to enhance productivity and nutrient use efficiency of lowland rice by smallholder farmers in SSA.

## 6.2 Summary of study findings

Figure 6.1 presents a summary of the main findings of the studies reported in this thesis and their implications. In Chapter 2, we showed that adding secondary nutrients (such as Mg and S) and micro-nutrients (like B, Cu, Mn and Zn ) to NPK further enhanced grain yield in Tanzania but not in Uganda. However, the additional yield gains were lower than the gains made with only NPK application, compared to unfertilised control yields. This finding indicates that secondary nutrients and micro-nutrients can safely be omitted in lowland rice production in these areas. Effects of applying only NPK, and NPK plus secondary and micro-nutrients were only significant when water supply was adequate. These effects were minimal under poor water management, where crops suffered from drought, even when good crop management practices were applied. This means that for good agronomic practices and fertilisation to be effective in improving rice productivity, proper water management is key. We further showed that applying secondary and micro-nutrients only without NPK resulted in yields that were similar to unfertilised control plots, and lower compared to only NPK fertilisation. This finding shows that adding other nutrients than NPK would not be required in a first step in enhancing rice productivity nor do these nutrients co-determine use efficiency of N, P or K thus, the need to first focus on attaining full yield potential from NPK application.

6

We demonstrated in Chapter 3 that RAP with or without fertilisation both under researcher- and farmer-management significantly increased grain yield compared to farmers' practice (FP), meaning that farmer's application of RAP when water supply is adequate, followed by NPK fertilisation, can substantially boost rice productivity. RAP without fertilisation gave the highest mean net income, while fertiliser costs made RAP+NPK to give the lowest mean net income, an indication that fertilisation poses a risk to profit at current rice and fertiliser prices. Exploitable yield gaps of 12 – 44% (i.e., 720 – 2730 kg ha$^{-1}$) were observed among farmers, demonstrating considerable potential for farmers to increase rice yields. Timing of weeding was the main factor that contributed to yield variation among fields, implying that realising yield gains requires that farmers with good water management should combine timely weeding (i.e., weeding within 2 – 3 weeks after transplanting) with other crop management practices.

In Chapter 4 we showed that a large variation existed in NPK uptake among farmers' fields managed in a same way, indicating differences in indigenous nutrient supply among fields. Delaying weeding beyond recommended weeding time decreased fertiliser nutrient use efficiencies, indicating that appropriate weeding time is necessary to allow plants to efficiently utilise nutrients from indigenous sources, and from fertilisers when farmers decide to apply. Interaction between indigenous nutrient supply and delay in weeding reduced use efficiencies of applied nutrients. This indicates a need for site-specific fertilisation strategies based on naturally available nutrient levels and proper weeding. Delayed fertilisation also reduced fertiliser use efficiencies, implying that fertiliser application needs to be synchronised with the correct crop stage for optimal uptake and utilisation by crops.

We revealed in Chapter 5 that farmers who had lower yields during joint experimentation subsequently improved their management practices and yields one year later, compared with farmers that had middle- and top-yields during the joint experimentation, reducing farmer-to-farmer differences. This means that joint learning with farmers had a greater potential of raising grain yield of poor-yielding farmers than that of already better-yielding farmers. Farmers who observed higher grain yield in their RAP plot compared with their FP plot during experimentation realised larger yield gains than farmers who had lower yield under RAP compared with FP plot, an indication that the former farmers learnt something from the joint experimentation which they were able to apply in their fields and enhanced grain yields. Farmers that participated in the joint experimentation improved their management practices and had higher grain yield compared with those that did not participate, further showing the potential benefit of exposing farmers to RAP, through participatory learning, on boosting rice yields. Different farm types were identified, which differed in their application of RAP. However, these farm types had small differences in household characteristics, an indication that wealth was not crucial in innovation adoption in the current production and farming systems. In the succeeding sections of this thesis chapter, I discuss the implications of these results in relation to enhancing productivity and nutrient use efficiency in lowland rice by smallholder farmers in SSA.

## 6.3 Boosting rice productivity in sub-Saharan Africa

An important aim of this thesis was to identify practicable options through which smallholder farmers can improve lowland rice productivity, which is a requirement for SSA to meet its rice demand while relying less on imports or crop area expansion. On-farm evaluation of the effects of secondary and micro-nutrients applied together with NPK under recommended agronomic practices (Chapter 2), recommended agronomic practices with or without fertilisation implemented under researcher- and farmer-management (Chapter 3), and effect of participatory learning with farmers (Chapter 5) on lowland rice yield made it possible to identify viable options through which smallholder farmers could enhance their productivity. Findings from this thesis indicate that different options are available for smallholder farmers to improve lowland rice productivity; however, these options must be applied in a certain systematic sequence in order to be effective, without which minimal or no positive effects of such options could be observed. In the sub-sections below, I present these options and propose the order in which they should be implemented to avoid negative experiences and to ensure considerable yield gains are realised by smallholder farmers in SSA.

### 6.3.1 Proper water management

Good water management is a component of recommended agronomic practices [i.e., integrated management practices aimed at improving yields (Mkanthama, 2013; Senthilkumar et al., 2018)] that is critical in lowland rice cultivation. Water is essential for seed germination, nutrient uptake from the soil, photosynthesis, and transport of nutrients and photo-assimilates. Rice requires ample water supply, either from irrigation or rainfall, respectively, under irrigated or rainfed agro-ecologies. In this thesis, substantial yield gains were observed with recommended crop management practices and fertilisation only where water supply was adequate in terms of timing and quantity, but not under poor water management, where crops suffered from drought, even if otherwise good crop management practices were executed (Table 6.1). The low yields observed under insufficient water supply were due to poor grain filling that resulted in lower harvest indices compared to similar treatments under adequate water supply. The fact that yield gains under recommended crop management practices with or without fertilisation was only possible with adequate water supply shows that water is the first production input that needs to be in adequate supply in lowland rice fields if smallholder farmers are to boost rice productivity. Otherwise, improving other crop management practices, including fertiliser application, when water supply is poor will not increase rice yields. For lowland rice production, field levelling, bunding and timely irrigation is essential for proper water management to allow for adequate water supply to rice fields during rice crop growth. Field levelling and bunding are especially crucial in managing and conserving water in rice fields during likely water shortage (GRiSP, 2013).

Drought, caused by insufficient rainfall, is a major production constraint to rice cultivation in rainfed agro-ecosystems (Balasubramanian et al., 2007; Dramé et al., 2013). Drought effects on rice productivity depend more on rainfall distribution during the cropping season rather than total rainfall, where the most devastating effects are experienced when it occurs just prior to flowering, which can result in substantial grain yield loss (Dramé et al., 2013; Wassmann et al., 2009). Under current climatic conditions, many rainfed production areas are already drought-prone and droughts are likely to become more intense and more frequent in the future (Wassmann et al., 2009), which will result in decreased food security and increased vulnerability of poor rural farmers (Bates et al., 2008). Consequently, proper water management strategies aimed at ensuring that adequate water is supplied to rice fields during the cropping cycle, and also saving excess water for use in the succeeding season are absolutely essential for increasing lowland rice production under existing climate conditions. These strategies could include farmers' adoption of technologies that can be implemented during land preparation, crop establishment, and during the crop growth period to control and save water, for instance, constructing field channels to convey water to and from each field or a small group of fields, field levelling, and bunding (Bouman et al., 2007). Touré et al. (2009), and Becker and Johnson (2001) observed about 40% more rice yields due to improved water management practice by bunding, compared to fields without bunds. Similarly, Kwesiga et al. (2019) reported 40% higher yields due to bunding and field levelling than yields from farmers' practice without levelling and bunding. These findings indicate that any rice production areas that can support proper field levelling and bunding would indeed be good places to aim for enhanced rice productivity. For rainfed lowland agro-ecosystems and upland production system where rice is part of the farming systems, rice production could be enhanced when water management is well done. For upland crops, management practices will need to be aligned with available water as much as possible. In rainfed agro-ecosystems, investments by regional governments are necessary to facilitate area-specific feasible solutions to the water problem, e.g., in construction of irrigation infrastructures, if smallholder farmers are to sustainably improve rice productivity. In the irrigated agro-ecosystems, good water management would require reliable irrigation scheme management so aspects of communal management where local or regional authorities and strong social organisations are involved would be required. Strengthening the functioning of existing irrigation schemes would equally be relevant. In general, efficient management and/or improvement of existing irrigation infrastructures is important to ensure adequate water supply in irrigated lowlands, and to avoid submergence and development of salinity, acidity or nutrient toxicity that can limit rice yield improvement (Balasubramanian et al., 2007; Sahrawat, 2005).

### 6.3.2 Recommended crop management practices

Next to proper water management, application of recommended crop management practices by farmers, even if fertilisers are not included, could greatly enhance rice productivity. Management practices, for instance timely planting (sowing or transplanting), which allows uniform and vigorous seedling establishment, timely weeding and harvesting can help farmers improve rice yields (Kyalo et al., 2020; Oo & Usami, 2020). In this thesis, results of participatory on-farm trials, where recommended crop management practices were applied in addition to proper water control under researcher-guidance and farmer-management (Chapter 3), showed that recommended crop management practices without fertiliser application significantly increased rice yields by ca. 12% (510 kg $ha^{-1}$) compared with farmers' current practice. This shows that for farmers with adequate water supply, rice yields can be considerably enhanced by implementing good crop management practices even if fertilisers are not applied. Timely weeding is generally required to improve rice production. Timing of weeding was a major component of recommended agronomic practices that brought about yield variation among farmers' fields. Delayed weeding under current farmers' practice (FP) resulted in an average seasonal grain yield reduction of 500 kg $ha^{-1}$ (about 12%). Moreover, when fertiliser was applied under FP and weeding implemented late, an average seasonal yield loss of 200 kg $ha^{-1}$ (ca. 5%) due to weeds was observed, with yield reduction of up to 1800 kg $ha^{-1}$ (ca. 43%) noted (Table 6.2). Delay to weed by a single day resulted in an average yield reduction of 62 kg $ha^{-1}$, with yield loss of between 49 to 74 kg $ha^{-1}$ per day estimated. These findings further point to the important role of executing improved crop management practices first, especially timely weeding, before thinking of fertiliser application in increasing crop productivity.

| Key findings | Implications |
|---|---|
| **Chapter 2**<br>▪ NPK and micro-nutrients were only effective when water supply was adequate, but not under poor water management, even when good crop management was applied.<br>▪ Micro-nutrients further enhanced grain yield in Tanzania but not in Uganda; however, the yield gains were lower than gains made with only NPK application.<br>▪ Applying micro-nutrients without NPK resulted in yields similar to unfertilised control yields, and lower than yields from only NPK fertilisation. | ▪ Proper water management is key for good agronomy and fertilisation to effectively improve rice productivity.<br>▪ Micro-nutrients can safely be omitted in lowland rice production.<br>▪ Micro-nutrients do not co-limit yield and use efficiency of N, P or K so, research needs to first focus on attaining full yield potential from NPK application. |
| **Chapter 3**<br>▪ RAP with or without fertilisation under either researcher- or farmer-management increased grain yield compared to FP.<br>▪ RAP alone resulted in a higher profit, compared with RAP+NPK application.<br>▪ Exploitable yield gaps of 12-44% were recorded among farmers.<br>▪ Timing of weeding majorly contributed to yield variation among fields. | ▪ When farmers apply RAP under adequate water supply, and fertilisation, rice productivity can be enhanced.<br>▪ Fertilisation poses a risk to farmers' profit at current rice and fertiliser prices.<br>▪ Considerable potential exists for farmers in SSA to increase rice yields.<br>▪ Realising yield gains requires that farmers with good water control combine weeding within three weeks with other crop management practices. |
| **Chapter 4**<br>▪ NPK uptake varied among farmers' fields under similar management.<br>▪ Late weeding decreased fertiliser nutrient use efficiencies.<br>▪ Interaction of indigenous nutrient supply and delayed weeding reduced fertiliser nutrient use efficiencies.<br>▪ Late fertilisation also reduced fertiliser use efficiencies. | ▪ Differences exist in indigenous nutrient supply among fields.<br>▪ Weeding within three weeks is necessary for efficient utilisation of nutrients from indigenous and fertiliser sources.<br>▪ Need for site-specific fertilisation strategies based on indigenous nutrient supply levels and proper weeding.<br>▪ Need to synchronise fertiliser application with correct crop stage for optimal uptake and utilisation. |
| **Chapter 5**<br>▪ Farmers who had lower yields during joint experimentation improved their management practices and yields a year later than middle- and top-yielding farmers.<br>▪ Farmers who observed higher grain yield in their RAP plot recorded larger yield gains than farmers who had lower yield under RAP.<br>▪ Farmers that participated in joint experimentation improved their management practices and grain yield compared with those that did not participate.<br>▪ Farms differed in application of RAP, however, with minimal differences in household characteristics. | ▪ Joint learning with farmers had a greater potential of raising yield of poor-yielding farmers than that of already better-yielding farmers.<br>▪ Farmers were able to learn from joint experimentation, and applied what was learnt and enhanced yields.<br>▪ Exposing farmers to RAP, through participatory learning, has a potential benefit of boosting rice yields.<br>▪ Wealth was not an important factor in innovation adoption in the current production and farming systems. |

**Figure 6.1** Summary of key findings from the chapters 2 to 5 and their implications. RAP = recommended agronomic practices; FP = farmers' practice.

**Table 6.1** Grain yield and yield components under different water management strategies in Uganda (2017) and Tanzania (2016). All plots were researcher managed following recommended crop management practices.

| **Water management strategies** | **Grain yield (kg ha$^{-1}$)** | **Panicles m$^{-2}$** | **Filled spikelets panicle$^{-1}$** | **Filled grains m$^{-2}$ (×10$^{3}$)** | **1000-grain weight (g)[3]** | **Dry matter HI (%)[4]** |
|---|---|---|---|---|---|---|
| **Uganda 2017** | | | | | | |
| Good water management without fertilisation[1] | 4592[c] | 316[b] | 71.8[b] | 22.2[c] | 20.8[a] | 50.6[c] |
| Poor water management without fertilisation[2] | 815[a] | 198[a] | 19.0[a] | 3.95[a] | 20.5[a] | 19.4[a] |
| Good water management + fertilisation[1] | 8636[d] | 577[c] | 73.4[b] | 41.6[d] | 20.7[a] | 46.2[b] |
| Poor water management + fertilisation[2] | 1740[b] | 366[b] | 23.6[a] | 8.15[b] | 21.2[a] | 21.4[a] |
| p-value | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **0.15** | **<0.001** |
| S.e.d. | 241 | 23.3 | 5.32 | 1.18 | 0.28 | 1.43 |
| **Tanzania 2016** | | | | | | |
| Good water management without fertilisation[1] | 3871[b] | 181[bc] | 112[c] | 12.0[b] | 32.2[b] | 48.2[b] |
| Poor water management without fertilisation[2] | 1214[a] | 122[a] | 63.8[a] | 4.45[a] | 27.1[a] | 39.5[a] |
| Good water management + fertilisation[1] | 5316[c] | 202[c] | 123[c] | 16.3[c] | 32.6[b] | 55.8[c] |
| Poor water management + fertilisation[2] | 1886[a] | 168[b] | 93.2[b] | 6.52[a] | 27.9[a] | 31.8[a] |
| p-value | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| S.e.d. | 306 | 15.9 | 7.77 | 9.71 | 0.66 | 3.81 |

[1]Good water management or control under irrigated lowland conditions resulted in adequate water supply during cropping cycle. [2]Poor water control under rainfed lowland conditions resulted in insufficient water supply during cropping cycle. [3]Difference in 1000-grain weight between countries was due to varietal difference planted at the two sites. [4]Dry matter harvest index (HI) was calculated as the ratio of filled grains over total above-ground dry matter. Values within columns and countries followed by the same letter are not statistically different according to a Fisher's post hoc test.

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Rice is exceptional in that proper water management allows a single weeding, a case in the present studies under irrigated conditions where weeding was done once followed by flooding with irrigation water. But as timely weeding seemed challenging and might require forms of communal management, potential gains could be made by introducing simple hand-weeding tools such as those demonstrated by Rodenburg et al. (2015) where also line (trans)planting may become an advantage. Line planting allows ease of weeding operation by facilitating easy movement of the weeding tools between rows of rice crops. In the current studies, line transplanting alone under present weed management practices did not improve grain yield. However, where line transplanting and timely weeding was implemented, higher grain yield compared to yields under FP or line transplanting only, were recorded (Figure 3.5, Chapter 3). To improve labour efficiency of weed management, line transplanting would, however, be recommended in improving the efficiency of these simple weeding tools. Where hiring labour may be a support to the local economy, delayed weeding for lack of labour should be avoided as it had major impact on resource use efficiency and productivity. Consequently supporting local labour productivity with simple weeding tools should be considered by regional or national governments as a mean of supporting the development of small industries in support to agriculture.

Results from Chapter 3 of this thesis show no significant effect of transplanting time or seedling age on grain yield, contrasting reports stating that seedling age is a major agronomic factor that influences grain yield (Kyalo et al., 2020; Lampayan et al., 2015; Liu et al., 2017). This lack of effect of seedling age on grain yield could indicate that farmers in this production system currently transplant reasonably timely, requiring no need to emphasise changes in their practices. Also in this thesis, no major pest and disease problems emerged during the trials but this in fact would have changed findings if these had occurred in the study sites. Monitoring pest and disease problems that may emerge and taking appropriate management options to deal with the problem would be crucial in improving rice productivity. Overall, to ensure appropriate use of recommended agronomic practices (RAP) in order to deliver intended benefits, farmers may need experiential or joint learning where they are able to check what they are told about specific RAP components to be able to make their own appreciation of the usefulness and applicability of the practices in their current production setting.

During the participatory on-farm trials, farmers jointly learnt about recommended agronomic practices, and were able to select and apply in their fields recommended management practices, which they saw were within their reach, and these resulted in yield gains of up to 26% (ca. 920 kg ha$^{-1}$) by these farmers (Figure 3.5, Chapter 3). For example, significant yield gains (ca. 14 – 26%) were realised by those farmers who implemented timely weeding alone, or in combination with other improved management practices (line transplanting and fertiliser application), compared with current FP yields. Likewise, in a period of one year after the participatory learning, farmers that improved their management practices compared with their earlier management practices during the participatory trials, realised considerable yield gains of about 1400 kg ha$^{-1}$ (ca. 52%, Chapter 5). This further demonstrates the potential for lowland rice farmers to improve grain yield through improved crop management practices under sufficient water supply. Previous studies, e.g., Nhamo et al. (2014); Senthilkumar (2022); Senthilkumar et al. (2018); Stuart et al. (2018) have equally highlighted the crucial role recommended agronomic practices can play in boosting rice yields and closing the yield gap, also for other crops (Abate et al., 2015; Asante et al., 2022; Sanchez, 2015; van Ittersum et al., 2016). Nhamo et al. (2014) and Rodenburg et al. (2014) noted that recommended agronomic practices should be considered an integral component of any strategy aimed at increasing rice yields in SSA. Facilitating farmers' learning about improved crop management practices through joint experimentation on farmers' own fields could allow farmers and extension service staff to learn what works under local farmers' conditions, how it works and what it takes, but also what does not work and why. Making this a mutual learning could allow extension service staff to help in tailoring management practices to fit local conditions, and stimulate farmers' adoption of improved management practices feasible in a given local environment to improve productivity. This is in addition to improving the quality of extension services given to farmers as one-on-one interaction with extension staff and learning by doing are facilitated. I propose here that implementing recommended crop management practices under adequate water supply is the second step farmers can undertake to improve rice productivity, even when fertilisers are not included. Proper water and crop management practices should form the basis of any efforts aimed at lowland rice intensification in SSA, all the other options can then build on these steps. Otherwise, without these steps all efforts may not deliver the desired target of improved smallholder productivity, hence improved food and income security.

### 6.3.3 N, P and K fertiliser application

Once recommended water and crop management practices (Chapter 3) have been implemented, NPK fertiliser use is the succeeding management practice that farmers can implement to boost rice yields. Results of the participatory on-farm trials (Chapter 3) indicated that applying NPK in addition to recommended crop management practices resulted in yield gains of ca. 19 and 33%, compared with yields under recommended agronomic practices alone and farmers' practice, respectively. However, fertiliser application with poor water and weed management did not bring about grain yield improvement (Tables 6.1 and 6.2). Similar results of lower yield gains from fertilisation under poor weed management have previously been observed from NPK fertiliser application in rice (Haefele et al., 2000; Tippe et al., 2020) and maize (Jamil et al., 2012). These findings support the argument that implementing the other components (especially good water and weed management) of recommended agronomic practices first, and thereafter applying fertiliser, is a logical sequence of steps for smallholder rice farmer to improve their yields and hence income otherwise yield enhancement from fertiliser application without improved crop management practices may not be realised or profitable.

Although NPK application under recommended agronomic practices significantly increased grain yields, the rates applied (100:50:50 N, P, and K kg $ha^{-1}$, respectively) in this study resulted in reduced net income (USD 46.3 $ha^{-1}$) compared with the net income (USD 222 $ha^{-1}$) from implementing recommended agronomic practices only without fertiliser application (Chapter 3). This means that for farmers who opt to apply fertilisers, appropriate rates based on field-specific nutrient demands should be used, as fertiliser costs pose a risk of investing with no or minimal returns. Much lower fertiliser doses than used in this study, as also tested by some of the farmers, would seem a more logical step in intensification. This may require further joint experimentation with farmers to determine what these lower fertiliser doses could be, that farmers are able to implement. Also, balanced fertilisation would be crucial to optimise productivity and profitability. Balanced fertilisation at appropriate rates should be coupled with targeting fertiliser application at correct crop growth stages to enhance response to fertiliser application.

**Table 6.2** Yield loss due to delayed weeding and fertilisation on farmers' fields, Doho rice irrigation scheme, Uganda, 2019.

| Management practice | Unit of estimate | Yield loss (kg ha$^{-1}$ at 14% MC)[3] Average | Range From | Range To | p-value | Standard error |
|---|---|---|---|---|---|---|
| Delayed weeding under FP[1] | Season$^{-1}$ | 500 | 77.9 | 2395 | <0.001 | 7.57 |
| Delayed weeding with fertilisation under FP | Season$^{-1}$ | 200 | 59.3 | 1802 | <0.001 | 15.1 |
| Delayed weeding under FIP[2] | Season$^{-1}$ | 300 | 69.8 | 2244 | 0.003 | 9.31 |
| Delayed weeding with fertilisation under FIP | Season$^{-1}$ | 15.2 | 19.3 | 49.6 | 0.38 | 17.0 |
| Delay in weeding | Day$^{-1}$ | 61.6 | 48.8 | 74.4 | <0.001 | 6.28 |
| Delay in weeding with fertilisation | Day$^{-1}$ | 43.0 | 18.6 | 66.3 | <0.001 | 11.7 |
| Delay to apply fertiliser | Day$^{-1}$ | 22.1 | 10.5 | 32.6 | <0.001 | 5.58 |

[1]FP = farmers' practice, [2]FIP = farmers' intensification practice. [3]Grain yield is reported at 14% moisture content (MC).

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Considering that fertiliser usage among farmers in SSA is still very low (Bado et al., 2018; Sheahan & Barrett, 2017), due to limited availability and high costs (Chianu et al., 2012), improving fertiliser access by smallholder farmers is necessary if farmers are to increase fertiliser use and realise yield gains associated with fertiliser application. Providing the required infrastructures (such as good roads, markets, and agro-input shops) to lower farm gate price of fertilisers (or other inputs) and increase farm gate price of produce could be a sustainable and effective way to increase fertiliser availability to and use by farmers. This could be coupled with appropriate government policy that governs price setting in the input and produce markets, resulting in favourable input-output price ratios. There may also be a need for a comprehensive analysis of what is currently failing in the input and output market systems that limits profitability of fertiliser use. This could result in finding local solutions to solving local challenges causing poor fertiliser access and use. Providing fertiliser subsidies to farmers has also been shown to be relevant in increasing fertiliser use and grain yield (Koussoubé and Nauges, 2017; Sanchez, 2015). While subsidies may increase fertiliser use and improve grain yields, various governments in the SSA region need to ensure the effectiveness of the subsidy program to deliver on the main target of improving smallholder crop productivity. Where the subsidy program does not deliver on this target, it may be worthwhile to adopt alternative approaches to increasing fertiliser use by farmers to ensure improvement in grain yields. For instance, Njoroge (2019) proposed a non-subsidy-based approach to improving fertiliser access, which would be government led where all relevant stakeholders are engaged with the aim to cause structural and policy changes that would bring about reduction in fertiliser costs. It may also be necessary for the regional governments to put in place strategies to stabilise rice prices, including having public rice reserves and ensuring a well-functioning market system (Abokyi et al., 2018; Kornher & Kalkuhl, 2013). Better and stable rice prices would make it attractive for farmers to invest in improved management practices, including fertiliser use, for improved grain yields.

### 6.3.4 Secondary and micro-nutrient fertiliser application

While NPK fertilisation under recommended crop management practices has been shown to improve rice yields, there are indications that micro-nutrients limit rice productivity, and their application in addition to NPK can augment NPK use efficiency, and crop yields (Atique-ur et al., 2014; Dicko et al., 2018; Dimkpa & Bindraban, 2016; Kihara et al., 2017). In Chapter 2 of this thesis, the contribution of NPK, and NPK +

secondary and micro-nutrients on East African lowland rice yield was assessed. The aim was to understand whether there are yield gains from NPK fertilisation alone, or there is need for addition of micro-nutrients, to realise optimal yield gains from NPK fertilisation in these lowlands. Results from the researcher-managed on-farm trials showed that next to NPK application under good water and crop management practices, adding secondary and micro-nutrients can enhance grain yield. The yield gains from secondary and micro-nutrients were, however, limited and not consistent across locations; with small but significant effects on the fluvisols of Tanzania when added to NPK fertilisation and not on the plinthosols and laterite of Uganda. The additional yield gains from secondary and micro-nutrients when applied with NPK were lower than the gains made with only NPK application compared to unfertilised control yields (Table 6.3). These results could downplay the general assumption of micro-nutrient limitation to yield in SSA, especially in rice production areas with similar soil characteristics as in the lowlands where these trials were conducted. Although secondary and micro-nutrient application could further boost grain yield beyond the yield levels obtained with NPK application, the findings further showed that applying only secondary and micro-nutrients without NPK resulted in yields similar to unfertilised control plots (Table 6.3); indicating NPK as the major limitation to yield where gains from secondary and micro-nutrients can likely only be realised when applying optimum NPK rates, without which secondary and micro-nutrients alone cannot improve grain yields. This implies that achieving the maximum possible yield from NPK application should be the priority focus for farmers in SSA, after which secondary and micro-nutrients might be included in fertilisation strategies aimed at top yields. For a region where fertiliser use is still limited, it is not reasonable to advocate for application of secondary and micro-nutrient fertilisers (which results in minimal yield gains yet increases production costs) when even NPK use is far below recommended rates (Bado et al., 2018; Sheahan & Barrett, 2017). It is therefore plausible to conclude that secondary and micro-nutrients can be safely omitted by farmers without any income penalty as yield gains from application are lower, making investments in micro-nutrient fertilisers risky at present. Location-specific assessments of real secondary and micro-nutrient limitations, by determining bio-available amounts in the soil, may then be required to guide application by farmers. A summary of the options and proposed steps in which the options should be applied for lowland rice intensification are presented in Figure 6.2.

The original assumption of this study that micro-nutrients are important in limiting rice productivity and their application with NPK under good agronomic practices would enhance NPK use efficiency and grain yield under different soil types proved to be wrong. Micro-nutrients did not, as expected, explain the poor fertiliser use efficiencies of N, P or K. For example using data in Table 6.3, agronomic efficiency [AE, defined as grain yield increase per unit of nutrient applied – used for short-term assessment of nutrient use efficiency (Dobermann, 2007)] of N under irrigated condition, averaged over the two seasons, was 13 kg grain $kg^{-1}$ N applied without secondary and micro-nutrients. With secondary and micro-nutrients added to NPK, N AE ranged between 17 – 21 kg $kg^{-1}$ for the different NPK + secondary and micro-nutrient treatments. The N AE values with and without secondary and micro-nutrients at this study site (Tanzania) look the same, and are similar to N AE values reported for Tanzania and other rice growing areas across SSA without secondary and micro-nutrient application (Meertens et al., 2003; Tsujimoto et al., 2019). So secondary and micro-nutrient yield effect and role in explaining the use efficiency of fertilisers could not be proven. This finding contradicts reports of previous studies (for instance of Atique-ur et al., 2014, 2015; Kihara et al., 2017) on the role of micro-nutrients in enhancing rice production. The results of this study may be true for lowland rice production systems with similar management practices and soil properties. For lowland rice areas where soil survey may indicate bio-available amounts of these nutrients to be below critical levels, the results may not hold true. For upland rice production systems, micro-nutrient limitations may be expected in addition to NPK as uplands are net top soil erosion areas. There may be need for research to assess micro-nutrient effects in lowland areas with bio-available contents below critical levels and in upland rice production systems to provide an indication of whether micro-nutrients co-limit rice production or not. Also there may be need to keep monitoring areas like in Tanzania if further depletion might be occurring warranting a different fertilisation strategy.

**Table 6.3** Grain yield under irrigated and rainfed lowland conditions, for different fertiliser treatments in Msufini and Idete, Kilombero valley, Tanzania, 2015 and 2016.

| Treatment | Msufini - Irrigated Lowland | | Idete - Rainfed Lowland |
|---|---|---|---|
| | Grain yield (kg ha$^{-1}$) 2015 | Grain yield (kg ha$^{-1}$) 2016 | Grain yield (kg ha$^{-1}$) 2015 |
| Control – no fertilisation | 3087$^{a}$ | 3734$^{a}$ | 2686$^{a}$ |
| NPK | 4064$^{b}$ | 4814$^{b}$ | 4958$^{b}$ |
| NPK+BZnMgS soil applied | **4606**$^{c}$ | **5414**$^{c}$ | **6826**$^{c}$ |
| NPK+BZnCuMgS soil applied | – | **5409**$^{c}$ | – |
| NPK+BZnMnCuMgSMo foliar applied | 4237$^{bc}$ | 5261$^{bc}$ | 5947$^{bc}$ |
| NPK+BZnMoSi foliar applied | 4208$^{bc}$ | 5347$^{bc}$ | 6032$^{bc}$ |
| BZnMnCuMgSMo foliar applied | 3287$^{a}$ | 4023$^{a}$ | 2977$^{a}$ |
| ZnBMgS soil applied | – | 4011$^{a}$ | – |
| Mean | 3915 | 4751 | 4905 |
| S.e.d. | 151 | 183 | 384 |
| p-value contrast 1$^{1)}$ | **<0.001** | **<0.001** | **<0.001** |
| p-value contrast 2$^{1)}$ | **0.19** | **0.08** | **0.45** |
| p-value contrast 3$^{1)}$ | **0.03** | **<0.001** | **<0.001** |

All plots were managed under recommended agronomic practices, including water management in Msufini. Idete received adequate rain during the entire crop growth period. $^{1)}$ Contrast 1: Control vs NPK only, contrast 2: Control vs secondary and micro-nutrients only, and contrast 3: NPK only vs NPK + secondary and micro-nutrients. – means treatment was not implemented that season. Values in bold indicate NPK + secondary and micro-nutrient treatments that resulted in the largest yield gain compared to the unfertilised control plot. Values followed by the same letters within columns are not statistically different according to a Tukey's post hoc test.

### 6.3.5 Farmers' engagement on adoption of RAP and implications for innovation development aimed at improving productivity at smallholder farms

Chapter 5 of this thesis assessed 1 year later the change in management practices and grain yield of farmers who participated in a joint experimentation in which different components of recommended agronomic practices for rice were tested. Results showed that farmers who took part in the joint experimentation (participating farmers) implemented better some components of recommended agronomic practices after the joint experimentation compared with those farmers who did not participate in the joint experimentation (non-participating farmers). As a result, participating farmers had a higher grain yield (4125 kg $ha^{-1}$) compared with non-participating farmers (3893 kg $ha^{-1}$). This means that during the joint experimentation, participating farmers were able to learn something about RAP that resulted in their improved implementation of RAP in their fields the subsequent season and hence grain yields. This shows that engaging farmers through participatory learning has a potential benefit to aid the adoption of management practices by smallholder farmers in SSA that can help them improve their rice yields. This joint learning may also allow a more critical assessment of the profitability of improved management practices under farmers' conditions and thereby their application domain and bottlenecks.

Among the participating farmers, those who had lower yields under FP during joint experimentation improved their management practices, adopting more of the components of RAP, compared with farmers who had middle or top yields. This resulted in a significantly higher yield gain by the former farmers (averaging 1358, with a range of 1027 and 1689 kg $ha^{-1}$) than those who had middle (averaged 473, ranged between 252 and 695 kg $ha^{-1}$) and top (−91.7, −397 to 213 kg $ha^{-1}$) yields. Similarly, farmers who observed higher grain yield in their RAP plot compared with their FP plot during experimentation realised larger yield gains (597, 348 to 846 kg $ha^{-1}$) than farmers who had lower yield under RAP compared with FP plot (463, 200–727 kg $ha^{-1}$). These results further emphasise that farmers' learning occurred during the joint experimentation, where farmers were able to apply what is learnt in their fields the following seasons, resulting in higher grain yields. Senthilkumar et al. (2018) reported a similar observation with rice farmers after taking part in a participatory on-farm trials where farmers improved their implementation of RAP and hence realised improved grain yields. The fact that farmers who already had high yields under FP during joint experimentation could not make large yield gains (they couldn't further raise their yield), may indicate that these farmers learnt that under their current management practices and socio-economic conditions they couldn't further improve their management beyond their capacity to further improve their yields so decided to stay within their limit. The results of this study imply that a participatory approach to promoting new innovations, aimed at enhancing crop productivity on smallholder farms, may be a viable option to ensure innovation adoption as learning by doing on farmers' own fields to better implement the new innovation is encouraged, as also observed by Kondylis et al. (2017). For innovation developers, engaging farmers through participatory learning can be a useful platform where better feedbacks are provided on innovations or innovation components that may not be feasible under local farmers' conditions. These feedbacks can be useful in developing innovations that address farmers' problems and are applicable under farmers' prevailing environmental and socio-economic conditions. For example, during the participatory trials in Chapter 3, farmers who did random transplanting indicated that it was costly and time-consuming to transplant in line. In the study of Chapter 2, farmers noted that it would be tedious to do field spraying with large volumes of water in order to supply minute quantities of micro-nutrients to rice crops. In addition, mixing of these nutrients to come up with a solution of appropriate nutrient concentrations was a real problem for farmers, which made them less interested in foliar nutrient application. To farmers, delivering common fertilisers like urea already blended with the micro-nutrients, if necessary, for soil application or developing micro-nutrient formulations ready to be sprayed to crops would be of interest. This kind of feedback is what research in fertiliser industry for instance needs in order to develop fertiliser formulations and packages that are user friendly. From the above discussions, I recommend that improving rice production by smallholder farmers in SSA requires first solving the water problem in rice production areas through proper water management. Next to this is implementing improved crop management practices, and NPK fertilisation. Where soil survey and research results show real co-limitation to yield, then micro-nutrient fertilisation (Figure 6.2).



## 6.4 Optimising fertiliser nutrient use efficiency in smallholder farms of SSA

Results from the studies of this thesis have shown the potential for smallholder farmers in SSA to substantially increase crop productivity through fertiliser application. However, to sustainably improve crop productivity through fertilisation, enhancing nutrient use efficiency of the applied nutrients is essential (Dobermann, 2007; Fixen et al., 2015). Findings in this thesis provide insights about ways through which smallholder farmers can optimise on-farm fertiliser nutrient use efficiency. In Chapter 4, results of data from participatory on-farm trials under irrigated lowland rice conditions indicated large variation in indigenous nutrient supply between fields under similar management. Fertiliser nutrient use efficiencies decreased with increasing indigenous nutrient supply. Delaying weeding and fertilisation time also decreased fertiliser nutrient use efficiencies. Interaction between indigenous nutrient supply and delay in weeding likewise reduced use efficiencies of applied nutrients. These results suggest that enhancing fertiliser nutrient use efficiencies requires site-specific nutrient application based on inherent soil fertility levels and proper weed management. Timely weeding was critical for crop response to fertiliser application where use efficiencies dropped when weeding was delayed (Chapters 3 and 4). Weeds compete with crops for nutrients from both soil and fertiliser sources. For instance, Touré et al. (2009), and Becker and Johnson (2001) reported reduction in fertiliser N agronomic efficiency due to high weed pressure in rice fields compared to the less weed-infested fields. This means that for smallholder farmers, applying fertilisers based on soil nutrient demands must be coupled with timely weeding as nutrient application may be inefficient when crops suffer from weed infestation. Proper weed management is necessary to avoid weed competition and allow crops efficiently utilise the applied nutrients. Next to proper weed management, targeting nutrient application at correct crop growth stages would be needed to enhance use efficiency. This will synchronise application with the crop stage(s) when uptake and subsequent use by the crops is optimal.

Low fertiliser nutrient use efficiencies were recorded in this study where high N, P and K rates (100, 50 and 50 kg ha$^{-1}$ N, P and K) were used. For example, agronomic efficiency (AE) averaged 8.41 and 17.9 kg grain kg$^{-1}$ nutrient applied for N and P or K, respectively (Table 6.4). These values were similar to 6.32 and 18.2 kg kg$^{-1}$ for N and P/K, respectively, under farmers' intensification practice where lower rates were applied. Observed N AE for this study was similar to N AE reported in similar rice production system in SSA. For instance, under researcher-managed trials with identical application rates to this study, N AE values of between 10 and 27 kg kg$^{-1}$ were reported (Tsujimoto et al., 2019). Under farmer management with high N rates (110-200 kg N ha$^{-1}$) across production systems in SSA, N AE of -1 to 19 kg kg$^{-1}$ have been reported (Tsujimoto et al., 2019). Slightly higher N AE values of 15–33 kg kg$^{-1}$ were observed under researcher management with low N rates of 30 kg N ha$^{-1}$ (Meertens et al., 2003).

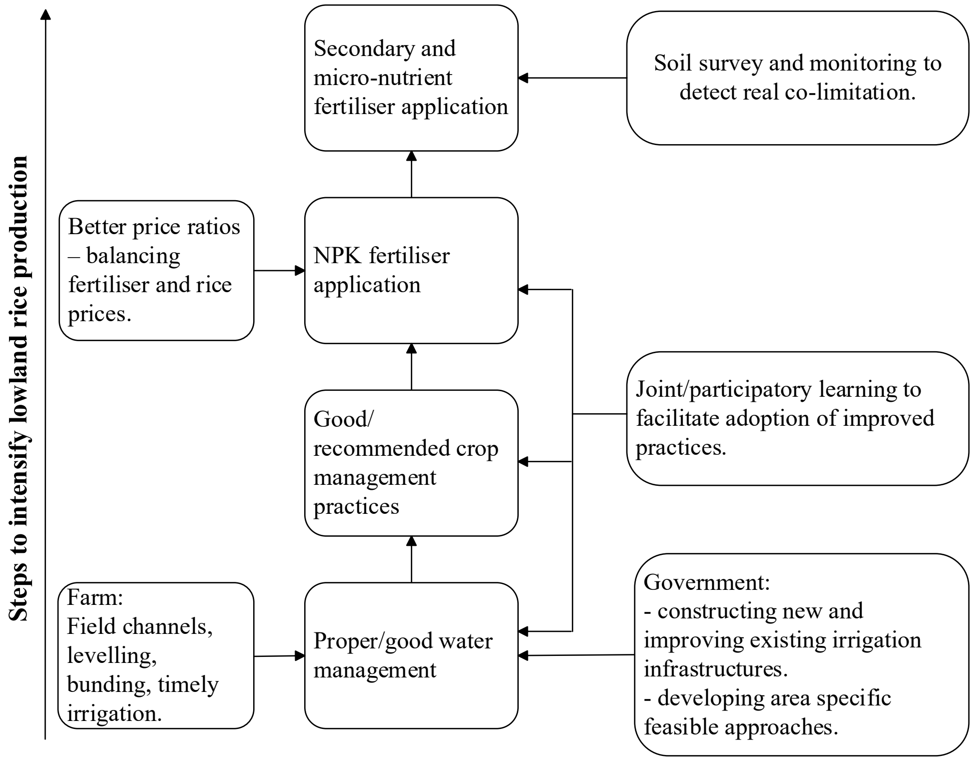


**Figure 6.2** Options to intensification of lowland rice production and proposed steps of application.

Likewise, AE of P and K was similar to reported values of 15-40 and 8-20 kg kg$^{-1}$, respectively (Fixen et al., 2015). Although AE values in this study are identical to values reported in rice production systems across SSA, wide ranges in the AE of applied N, P and K observed (Table 6.4) illustrate strong differences in nutrient use efficiency between fields. This further underscores the need for field specific nutrient application in order to optimise use efficiency. Similar AE values reported with low and high application rates in this study indicates a need for further joint experimentation with farmers to determine appropriate lower nutrient rates that farmers could use under local farming conditions, as the high rates appear uneconomical. This joint research should also incorporate the aspect of fertilisation strategies including timing application and spreading the fertiliser over the crop growth period, and aspects of other improved crop management practices.

**Table 6.4** Agronomic efficiency of N, P and K for different treatments on-farm under irrigated lowland condition, Doho – Uganda, 2019

| **Treatment** [a] | **AE (kg grain kg$^{-1}$ nutrient applied)** | |
|---|---|---|
| | N | P or K [b] |
| FP | -7.42 (-100 - 68.8) | - [c] |
| FIP | 6.32 (-85.9 - 75.7) | 18.2 (-18.1 - 62.0) |
| RAP+NPK | 8.41 (-0.55 - 22.2) | 17.9 (-1.09 - 44.4) |
| **S.e.d.** | 5.39 | 6.33 |
| **p-value** | 0.06 | 0.93 |

[a] FP = farmers' practice, FIP = farmers' intensification practice, RAP+NPK = recommended agronomic practices with N, P and K fertilisation at 100, 50 and 50 kg ha$^{-1}$, respectively. N rates under FP and FIP were between 6.8 – 46 kg ha$^{-1}$, P and K rates under FIP were 0 – 27.2 kg ha$^{-1}$. [b] P and K were always applied in the ratio of 1:1, resulting in identical AE values. [c] P or K were not applied under FP. Values in parentheses are ranges.

## 6.5 Opportunities for future research

In this thesis, I evaluated the contribution of recommended agronomic practices (RAP) either under researcher guidance or farmer management, inherent soil fertility and field management practices, and secondary and micro-nutrients to NPK use efficiency and crop productivity, with the aim to identify possible options through which smallholder farmers can enhance NPK use efficiency and crop yields. Sub-Saharan Africa needs to increase its crop productivity in order to be able to meet the food demand of its growing population and become more food secure on existing crop land. Rice is one of SSA's major cereals where its consumption rate is growing more rapidly among the population. Increasing rice productivity on smallholder farms can help SSA deal with the challenge of rising food demand. Several options through which smallholder farmers can improve use efficiency of fertiliser nutrients and grain yield have been identified. However, there are emerging questions from the findings of this thesis that remain to be addressed.

Micro-nutrients have been shown to limit rice productivity where their application together with NPK has been reported to enhance NPK use efficiency and grain yields (Atique-ur et al., 2014; Dicko et al., 2018; Kihara et al., 2017). In Chapter 2, assessment of the contribution of NPK, and NPK + secondary and micro-nutrients on rice yield in the East African lowlands was done. Results from this study showed that secondary and micro-nutrient application together with NPK under otherwise good water and crop management practices can enhance grain yield; however, the yield gains were limited and not consistent across locations. Secondary and micro-nutrient application together with NPK had a small but significant effects on the fluvisols of Tanzania and not on the plinthosols and laterite of Uganda. These results raise a question about the validity of the general assumption of micro-nutrient co-limitation to rice production in SSA (Kihara et al., 2017, 2020). There is need for location-specific assessments to monitor whether and when micro-nutrients become a real limitation to crop productivity improvement in order to guide farmers' fertilisation strategy.

Application of NPK fertilisers under recommended crop and water management practices improved grain yields on-farm (Chapters 2 and 3). However, the high rates applied in this study (100:50:50 N, P, and K kg ha$^{-1}$, respectively) were uneconomical resulting in lower net income compared to recommended agronomic practices only without fertilisation (Chapter 3). Use efficiencies of fertiliser nutrients were also low under these high rates or similar to nutrient efficiencies under farmers' practice where lower rates were applied (Chapter 4). The question remains on what exactly are the appropriate NPK rates based on farmers' field conditions that can be used as more logical doses to enhance use efficiencies and allow for sustainable rice intensification. There is need for further joint research with farmers to determine what the appropriate dose or range of doses could be. Despite the yield gains from fertiliser application, fertiliser use among farmers remains low with very low application rates (Bado et al., 2018; Tsujimoto et al., 2019). There is a need for a comprehensive analysis of the challenges causing failures in the fertiliser value chain that limits fertiliser access and use. This may help to come up with local initiatives to address local challenges to poor fertiliser access and use.



Timing of weeding was a major component of recommended agronomic practices that resulted in yield variation among farmers' fields. Delayed weeding caused significant yield losses even when fertilisers were applied (Chapter 3), and decreased fertiliser nutrient use efficiencies (Chapter 4). Interaction between indigenous nutrient supply and delayed weeding likewise reduced use efficiencies of applied nutrients. There seems to be a need for investigation into simple, locally adapted weeding tools to improve labour efficiency of weed management. Also there is need for research to develop site-specific nutrient recommendations based on proper weed management.

Studies in this thesis have shown that smallholder farmers in East Africa and SSA at large have the opportunity to enhance lowland rice productivity, and hence income and food security. To be able to achieve increase in productivity, farmers need to ensure proper water management as the first step towards intensification. Next to proper water management is good or recommended crop management practices, especially timely weeding. Proper water management and good agronomic practices should form the foundation for all other steps aimed at lowland rice intensification. NPK fertiliser application can then be used to further enhance yield, however, appropriate rates based on inherent soil fertility levels need to be used, which would also help enhance use efficiencies of the applied fertiliser. Secondary and micro-nutrients may be applied in addition to NPK to further improve grain yield but to a limited extent.

**References**

Abate, T., Shiferaw, B., Menkir, A., Wegary, D., Kebede, Y., Tesfaye, K., . . . Keno, T. (2015). Factors that transformed maize productivity in Ethiopia. *Food Security, 7*(5), 965-981. DOI: 10.1007/s12571-015-0488-z

Abokyi, E., Folmer, H., & Asiedu, K. F. (2018). Public buffer stocks as agricultural output price stabilization policy in Ghana. Agriculture & Food Security, 7(1), 69. DOI: 10.1186/s40066-018-0221-1

Asante, P. A., Rahn, E., Zuidema, P. A., Rozendaal, D. M. A., van der Baan, M. E. G., Läderach, P., . . . Anten, N. P. R. (2022). The cocoa yield gap in Ghana: A quantification and an analysis of factors that could narrow the gap. *Agricultural Systems, 201*, 103473. DOI: 10.1016/j.agsy.2022.103473

Atique-ur-Rehman, R., Farooq, M., Nawaz, A., & Ahmad, R. (2014). Influence of boron nutrition on the rice productivity, kernel quality and biofortification in different production systems. *Field Crops Research, 169*, 123-131. DOI: 10.1016/j.fcr.2014.09.010

Atique-ur-Rehman, R., Farooq, M., Nawaz, A., Rehman, A., & Iqbal, S. (2015). Soil Application of Boron Improves the Tillering, Leaf Elongation, Panicle Fertility, Yield and its Grain Enrichment in Fine-Grain Aromatic Rice. *Journal of Plant Nutrition, 38*(3), 338-354. DOI: 10.1080/01904167.2014.963120

Bado, V. B., Djaman, K., & Mel, V. C. (2018). Developing fertilizer recommendations for rice in Sub-Saharan Africa, achievements and opportunities. *Paddy and Water Environment, 16*(3), 571-586. DOI: 10.1007/s10333-018-0649-8

Balasubramanian, V., Sie, M., Hijmans, R. J., & Otsuka, K. (2007). Increasing Rice Production in Sub-Saharan Africa: Challenges and Opportunities. In D. L. Sparks (Ed.), *Advances in Agronomy,* 94, 55-133.

Bates, B. C., Kundzewicz, Z. W., Wu, S., & Palutikof, J. P., Eds. (2008). Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. *IPCC Secretariat, Geneva*, 210.

Becker, M., & Johnson, D. E. (2001). Improved water control and crop management effects on lowland rice productivity in West Africa. *Nutrient Cycling in Agroecosystems, 59*(2), 119-127. DOI: 10.1023/A:1017585328904

Bouman, B. A. M., Lampayan, R. M., & Tuong, T. P. (2007). Water management in irrigated rice: coping with water scarcity. *International Rice Research Institute, Los Baños (Philippines)*, 54.

Brink, A. B., & Eva, H. D. (2009). Monitoring 25 years of land cover change dynamics in Africa: A sample based remote sensing approach. *Applied Geography, 29*(4), 501-512. DOI: 10.1016/j.apgeog.2008.10.004

Chianu, J. N., Chianu, J. N., & Mairura, F. (2012). Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. *Agronomy for Sustainable Development, 32*(2), 545-566. DOI: 10.1007/s13593-011-0050-0

Dicko, M. K., Traoré, L., Kouyaté, Z., Koné, M., Sidibé, B., Kamissoko, N., . . . Diakité, C. H. (2018). Response of Rice, Maize and Millet to Fertilizers in Mali. In A. Bationo, D. Ngaradoum, S. Youl, F. Lompo, & J. O. Fening (Eds.), *Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems: Volume 1* (pp. 139-155). Cham: Springer International Publishing.

Dimkpa, C. O., & Bindraban, P. S. (2016). Fortification of micronutrients for efficient agronomic production: a review. *Agronomy for Sustainable Development, 36*(1), 7. DOI: 10.1007/s13593-015-0346-6

Dobermann, A. (2007). Nutrient use efficiency – measurement and management. International Fertilizer Industry Association, Paris, France, 30.

Dramé, K. N., Manneh, B., & Ismail, A. M. (2013). Rice genetic improvement for abiotic stress tolerance in Africa. In: Wopereis, M.C.S., Johnson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa's Rice Promise. *CAB International, Wallingford, UK*, 144-160.

Fixen, P., Brentrup, F., Bruulsema, T., Garcia, F., Norton, R., & Zingore, S. (2015). Nutrient/fertilizer use efficiency: measurement, current situation and trends. In:

6

Managing Water and Fertilizer for Sustainable Agricultural Intensification. Drechsel, P., Heffer, P., Magen, H., Mikkelsen, R. and Wichelns, D. (Eds). 8-38.

GRiSP (Global Rice Science Partnership), (2013). Rice Almanac, 4th edition. International Rice Research Institute, Los Baños (Philippines), 283.

Haefele, S. M., Johnson, D.E., Diallo, S., Wopereis, M. C.S., Janin, I. (2000). Improved soil fertility and weed management is profitable for irrigated rice farmers in Sahelian West Africa. *Field Crops Research, 66*(2), 101-113. DOI: 10.1016/S0378-4290(00)00066-6

Jamil, M., Kanampiu, F.K., Karaya, H., Charnikhova, T., Bouwmeester, H.J. (2012). Striga hermonthica parasitism in maize in response to N and P fertilisers. *Field Crops Research, 134*, 1-10. DOI: 10.1016/j.fcr.2012.03.015

Kihara, J., & Njoroge, S. (2013). Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. *Field Crops Research, 150*, 1-8. DOI: 10.1016/j.fcr.2013.05.025

Kihara, J., Sileshi, G. W., Nziguheba, G., Kinyua, M., Zingore, S., & Sommer, R. (2017). Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. *Agronomy for Sustainable Development, 37*(4), 25. DOI: 10.1007/s13593-017-0431-0

Kihara, J., Bolo, P., Kinyua, M., Rurinda, J., & Piikki, K. (2020). Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops. Environmental Geochemistry and Health. DOI: 10.1007/s10653-019-00499-w

Kondylis, F., Mueller, V., & Zhu, J. (2017). Seeing is believing? Evidence from an extension network experiment. *Journal of Development Economics, 125*, 1-20. DOI: 10.1016/j.jdeveco.2016.10.004

Koning, N. B. J., Van Ittersum, M. K., Becx, G. A., Van Boekel, M. A. J. S., Brandenburg, W. A., Van Den Broek, J. A., . . . Smies, M. (2008). Long-term global availability of food: continued abundance or new scarcity? *NJAS - Wageningen Journal of Life Sciences, 55*(3), 229-292. DOI: 10.1016/S1573-5214(08)80001-2

Kornher, L., & Kalkuhl, M. (2013). Food Price Volatility in Developing Countries and its Determinants. Quarterly Journal of International Agriculture, 52(4), 277–308.

Koussoubé, E., & Nauges, C. (2017). Returns to fertiliser use: Does it pay enough? Some new evidence from Sub-Saharan Africa. *European Review of Agricultural Economics, 44*(2), 183-210. DOI: 10.1093/erae/jbw018

Kwesiga, J., Grotelüschen, K., Neuhoff, D., Senthilkumar, K., Döring, T. F., & Becker, M. (2019). Site and Management Effects on Grain Yield and Yield Variability of Rainfed Lowland Rice in the Kilombero Floodplain of Tanzania. *Agronomy, 9*(10). DOI: 10.3390/agronomy9100632

Kyalo, G., Chemining'wa, G., Nhamo, N., & Mussgnug, F. (2020). Effects of Improved Nursery Management, Seedling Transplanting Age and Split Nitrogen Fertilizer Application on Growth and Yield of Lowland Rice in Eastern Uganda. *Journal of Agricultural Science, 12*(8), 144-151. DOI: 10.5539/jas.v12n8p144

Lampayan, R. M., Faronilo, J. E., Tuong, T. P., Espiritu, A. J., de Dios, J. L., Bayot, R. S., . . . Hosen, Y. (2015). Effects of seedbed management and delayed transplanting of rice seedlings on crop performance, grain yield, and water productivity. *Field Crops Research, 183*, 303-314. DOI: 10.1016/j.fcr.2015.08.014

Liu, Q., Zhou, X., Li, J., & Xin, C. (2017). Effects of seedling age and cultivation density on agronomic characteristics and grain yield of mechanically transplanted rice. *Scientific Reports, 7*(1), 14072. DOI: 10.1038/s41598-017-14672-7

Meertens, H. C. C., Kajiru, G. J., Ndege, L. J., Enserink, H. J., & Brouwer, J. (2003). Evaluation of on-farm soil fertility research in the rainfed lowland rice fields of Sukumaland, Tanzania. Experimental Agriculture, 39(1), 65-79. DOI: 10.1017/S0014479702001060

Mkanthama, J. M. (2013). An Analysis of use of Good Agricultural Practices in Rice Production: A Case Study of Bagamoyo and Dakawa Areas, Tanzania. *MSc. Thesis, Kenyatta University of Agriculture and Technology.*, 110.

Nhamo, N., Rodenburg, J., Zenna, N., Makombe, G., & Luzi-Kihupi, A. (2014). Narrowing the rice yield gap in East and Southern Africa: Using and adapting existing technologies. *Agricultural Systems, 131*, 45-55. DOI: 10.1016/j.agsy.2014.08.003

Njoroge, S. K. (2019). Feed the crop, not the soil! Explaining variability in maize yield responses to nutrient applications in smallholder farms of western Kenya. *PhD Thesis, Wageningen University, Wageningen, The Netherlands*, 169. DOI: 10.18174/503185

Oo, S. P., & Usami, K. (2020). Farmers' Perception of Good Agricultural Practices in Rice Production in Myanmar: A Case Study of Myaungmya District, Ayeyarwady Region. *Agriculture, 10*(7). DOI: 10.3390/agriculture10070249

Pradhan, P., Fischer, G., van Velthuizen, H., Reusser, D.E., & Kropp, J.P. (2015). Closing Yield Gaps: How Sustainable Can We Be? *PLoS ONE, 10*(6), e0129487. DOI: 10.1371/journal.pone.0129487

Rodenburg, J., Zwart, S. J., Kiepe, P., Narteh, L. T., Dogbe, W., & Wopereis, M. C. S. (2014). Sustainable rice production in African inland valleys: Seizing regional potentials through local approaches. *Agricultural Systems, 123*, 1-11. DOI: 10.1016/j.agsy.2013.09.004

Rodenburg, J., Saito, K., Irakiza, R., Makokha, D. W., Onyuka, E. A., & Senthilkumar, K. (2015). Labor-Saving Weed Technologies for Lowland Rice Farmers in sub-Saharan Africa. *Weed Technology, 29*(4), 751-757. DOI: 10.1614/WT-D-15-00016.1

Sahrawat, K. L. (2005). Iron Toxicity in Wetland Rice and the Role of Other Nutrients. *Journal of Plant Nutrition, 27*(8), 1471-1504. DOI: 10.1081/PLN-200025869

Sanchez, P. A. (2015). En route to plentiful food production in Africa. *Nature Plants, 1*(1), 14014. DOI: 10.1038/nplants.2014.14

Senthilkumar, K. (2022). Closing rice yield gaps in Africa requires integration of good agricultural practices. *Field Crops Research, 285*, 108591. DOI: 10.1016/j.fcr.2022.108591

Senthilkumar, K., Tesha, B. J., Mghase, J., & Rodenburg, J. (2018). Increasing paddy yields and improving farm management: results from participatory experiments with good agricultural practices (GAP) in Tanzania. *Paddy and Water Environment, 16*(4), 749-766. DOI: 10.1007/s10333-018-0666-7

Sheahan, M., & Barrett, C. B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy, 67*, 12-25. DOI: 10.1016/j.foodpol.2016.09.010

Stuart, A. M., Pame, A. R. P., Vithoonjit, D., Viriyangkura, L., Pithuncharurnlap, J., Meesang, N., . . . Lampayan, R. M. (2018). The application of best management practices increases the profitability and sustainability of rice farming in the central plains of Thailand. *Field Crops Research, 220*, 78-87. DOI: 10.1016/j.fcr.2017.02.005

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences, 108*(50), 20260-20264. DOI: 10.1073/pnas.1116437108

Tippe, D. E., Bastiaans, L., van Ast, A., Dieng, I., Cissoko, M., Kayeke, J., . . . Rodenburg, J. (2020). Fertilisers differentially affect facultative and obligate parasitic weeds of rice and only occasionally improve yields in infested fields. *Field Crops Research, 254*, 107845. DOI: 10.1016/j.fcr.2020.107845

Touré, A., Becker, M., Johnson, D. E., Koné, B., Kossou, D. K., & Kiepe, P. (2009). Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. *Field Crops Research, 114*(2), 304-310. DOI: 10.1016/j.fcr.2009.08.015

Tsujimoto, Y., Rakotoson, Tovohery., Tanaka, Atsuko., & Saito, Kazuki. (2019). Challenges and opportunities for improving N use efficiency for rice production in sub-Saharan Africa. Plant Production Science, 22(4), 413-427. DOI: 10.1080/1343943X.2019.1617638

van Ittersum, M. K., van Bussel, L. G. J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., . . . Cassman, K. G. (2016). Can sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences, 113*(52), 14964. DOI: 10.1073/pnas.1610359113

van Oort, P. A. J., Saito, K., Tanaka, A., Amovin-Assagba, E., Van Bussel, L. G. J., van Wart, J., . . . Wopereis, M. C. S. (2015). Assessment of rice self-sufficiency in 2025 in eight African countries. *Global Food Security, 5*, 39-49. DOI: 10.1016/j.gfs.2015.01.002

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., . . . Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *SOIL, 1*, 491–508. DOI: 10.5194/soil-1-491-2015

Vanlauwe, B., Tittonell, P., & Mukalama, J. (2006). Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. *Nutrient Cycling in Agroecosystems, 76*(2), 171-182. DOI: 10.1007/s10705-005-8314-1

Wassmann, R., Jagadish, S. V. K., Heuer, S., Ismail, A., Redona, E., Serraj, R., . . . Sumfleth, K. (2009). Chapter 2 Climate Change Affecting Rice Production: The Physiological and Agronomic Basis for Possible Adaptation Strategies. In D. L. Sparks (Ed.), *Advances in Agronomy,* 101, 59-122.

Wortmann, C. S., Kaizzi, K. C., Maman, N., Cyamweshi, A., Dicko, M., Garba, M., . . . Serme, I. (2019). Diagnosis of crop secondary and micro-nutrient deficiencies in sub-Saharan Africa. *Nutrient Cycling in Agroecosystems, 113*(2), 127-140. DOI: 10.1007/s10705-018-09968-7

# Summary

Sub-Saharan Africa (SSA) continues to grapple with the challenge of meeting the demand for staple food crops, especially cereals, where self-sufficiency is the lowest compared to the rest of the world. Rice is one of the major cereals in SSA, a main source of calories for households of all income groups, and the second largest source of food energy, next to maize, yet farm yields are very low. The low crop productivity is the reason why SSA is unable to meet the food demand of its population. In order to meet the food demand on available arable land, increasing crop productivity in smallholder farming systems is thus required. This will minimise reliance on large food imports and crop area expansion into marginal lands and forest areas.

Low crop productivity in SSA farm lands is attributed to, among other factors, soil fertility constraints and sub-optimal soil and crop management. In order to address the low soil fertility that limits crop productivity, farmers apply NPK fertilisers. Considering that fertilisers are not easily available to farmers, are costly and their prices are unstable, relying on fertilisers to boost crop productivity in order to address the food demand of SSA becomes a challenge. Yet, fertilisation with only NPK is not always resulting in better yields on farmers' fields. Crop responses to NPK fertilisation can be influenced by other nutrients, recommended agronomic practices (RAP) and inherent soil fertility. On the basis of the background and research questions presented in Chapter 1, the effect of secondary and micro-nutrients (*Chapter 2*), RAP under researcher supervision and as applied by farmers (*Chapter 3*), and inherent fertility on rice yield and NPK use efficiency (*Chapter 4*), and effect of joint experimentation on farmers' management practices and rice grain yield (*Chapter 5*) were quantified for lowland rice.

Micro-nutrients are shown to constrain crop productivity, where their application in combination with NPK has been reported to enhance NPK use efficiency, leading to higher crop yields. In Chapter 2, the contribution of NPK, and combinations of NPK + secondary and micro-nutrients on lowland rice yield was assessed under irrigated and rainfed lowland conditions in Tanzania and Uganda. NPK fertilisation increased grain yields across locations and years under irrigated conditions, compared to yields from good agronomic practices only; but, inconsistent effects were observed under rainfed conditions. Adding secondary nutrients (Mg and S) and micro-nutrients (B, Cu, Mn, and Zn) to NPK further enhanced grain yield in Tanzania but not in Uganda. However, the

additional yield gains were lower than the gains made with only NPK application, compared to unfertilised control yields. Effects of applying only NPK, and NPK plus secondary and micro-nutrients were only significant when water supply was adequate, but not under poor water management, where crops suffered from drought, even when good crop management practices were applied. Applying secondary and micro-nutrients only without NPK resulted in yields that were similar to unfertilised control plots, and lower compared to only NPK fertilisation. These findings demonstrated that for good agronomic practices and fertilisation to be effective in improving rice productivity, proper water management is key. Adding other nutrients than NPK would not be required in a first step in enhancing rice productivity thus, the need to first focus on attaining full yield potential from NPK application.

Recommended or good agronomic practices (RAP), considered as an integrated, coherent set of crop, soil, water, weed, disease, and pest management practices is crucial in enhancing yields along with fertiliser use as they are shown to improve rice yields, compared to farmers' practices (FP). In Chapter 3, the contribution of RAP with or without NPK fertilisation on rice yield and yield gaps was assessed. RAP with or without fertilisation significantly increased grain yield by 12 and 33%, respectively, compared to FP. RAP without fertilisation gave the highest mean net income (ca. USD 220 $ha^{-1}$), while fertiliser costs made RAP+NPK to give the lowest mean net income (ca. USD 50 $ha^{-1}$). Exploitable yield gaps of 720 – 2730 kg $ha^{-1}$ were observed among farmers. Timing of weeding was the main factor that contributed to yield variation among fields, with average grain loss of 62 kg $day^{-1}$ of delayed weeding. The findings of this chapter demonstrated that application of RAP when water supply is adequate, followed by NPK fertilisation, can substantially boost rice productivity and farmers have considerable potential to increase rice yields, although fertilisation at current rice and fertiliser prices poses a risk to farmer's profit. Realising yield gains requires that farmers with good water management should combine timely weeding (i.e., weeding within 2 – 3 weeks after transplanting) with other crop management practices.

Fertilisers remain an expensive crop production input for most rice farmers in SSA. Improving fertiliser nutrient use efficiency is important for increasing both fertiliser use and rice yield, thus increasing farmers' returns on fertiliser investment. Chapter 4 investigated on-farm, under irrigated lowland rice conditions, how indigenous nutrient supply and management practices affected N, P, and K uptake, agronomic efficiency and recovery efficiency of fertiliser, and physiological efficiency of nutrients taken up.

A large variation in indigenous N, P, and K supply was observed among farmers' fields. Indigenous N supply reduced apparent N recovery, and agronomic and physiological N efficiencies independent of treatment. Similarly, physiological efficiencies of P and K decreased with increasing indigenous supply. Delaying weeding and fertilisation, and interaction between indigenous nutrient supply and delayed weeding, reduced fertiliser nutrient use efficiencies. The Chapter findings demonstrated that appropriate weeding time is necessary to allow plants to efficiently utilise nutrients from indigenous sources, and from fertilisers when farmers decide to apply. There is a need for site-specific fertilisation strategies based on soil available nutrient levels and proper weeding, and fertilisation needs to be synchronised with the correct crop stage for optimal uptake and utilisation by crops.

In Chapter 5, after one year of a joint experimentation with farmers where different RAP components for rice were tested, change in management practices and grain yield of participating farmers (participated in the joint experimentation) and non-participating farmers (did not participate) within the same production system was assessed. Participating farmers who had lower yields during joint experimentation subsequently improved their management practices and grain yields, compared with farmers that had middle- and top-yields during the joint experimentation. Similarly, farmers that participated in the joint experimentation improved their management practices and had higher grain yield compared with those that did not participate. Different farm types were identified, which differed in their application of RAP, but not in their household characteristics. These findings demonstrated the potential benefit of exposing farmers to RAP, through participatory learning, on boosting rice yields. Household wealth was not crucial in innovation adoption in the current production and farming systems.

Chapter 6 presents the implications of the results in Chapters 2 – 5 in relation to enhancing smallholder lowland rice productivity and nutrient use efficiency in SSA. In conclusion, proper water management is the first step towards lowland rice intensification, followed by good crop management practices, especially timely weeding. Proper water management and good agronomic practices should form the foundation for all other steps aimed at lowland rice intensification. NPK fertilisers can then be used to further enhance yield, however, appropriate rates based on inherent soil fertility levels need to be used, which would also help enhance use efficiencies of fertiliser nutrients. Secondary and micro-nutrients may be applied in addition to NPK to further improve grain yield but to a limited extent.

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Thomas Awio
Wageningen, The Netherlands
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# List of Publications

**Awio, T.,** Struik, P. C., Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., & Stomph, T. (2023). Indigenous nutrient supply, weeding and fertilisation strategies influence on-farm N, P and K use efficiency in lowland rice. *Nutrient Cycling in Agroecosystems*. DOI: 10.1007/s10705-023-10275-z

**Awio, T.,** Struik, P. C., & Stomph, T. J. (2022). Management practices and rice grain yield of farmers after participation in a joint experimentation. *Frontiers in Sustainable Food Systems, 6*. DOI: 10.3389/fsufs.2022.1009469

**Awio, T.,** Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Struik, P. C., & Stomph, T. J. (2022). Yields and yield gaps in lowland rice systems and options to improve smallholder production. *Agronomy, 12*(3). DOI: 10.3390/agronomy12030552

**Awio, T.,** Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Kempen, B., Struik, P. C., & Stomph, T. J. (2021). Micro-nutrients in East African lowlands: Are they needed to intensify rice production? *Field Crops Research, 270*, 108219. DOI: 10.1016/j.fcr.2021.108219

**Awio, T.,** Karungi, J., Bua, B., & Lamo, J. (2016). Relating water management regimes and rice genotypes with occurrence of insect pests and diseases of rice in Uganda. *Journal of Global Agriculture and Ecology, 4*(1), 12-20.

**Awio, T.,** Bua, B., & Karungi, J. (2015). Assessing the effects of water management regimes and rice residue on growth and yield of rice in Uganda. *Journal of Experimental Agriculture International, 7*(2), 141-149. DOI: 10.9734/AJEA/2015/15631.

# PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

**Review of literature (6 ECTS)**

- How do micronutrients modify crop development, macronutrient uptake and use efficiencies in crops (2017-2018)
- Role of good agronomy in improving crop productivity (2018)

**Writing of project proposal (4.5 ECTS)**

- Micronutrient enriched fertilisers for higher yields and micro-nutritious rice production in Uganda (2017-2018)

**Post-graduate courses (6.3 ECTS)**

- Design of experiments; PE&RC, Wageningen University & Research (2017)
- Plant nutrients in terrestrial ecosystems; PhD School of Science, University of Copenhagen (2018)
- Fundamentals of crop physiology; PE&RC, Wageningen University & Research (2018)

**Laboratory training and working visits (1.5 ECTS)**

- Plant eco-physiology techniques workshop; the plant environmental physiology group, a joint special interest group of the British Ecological Society and the Society for Experimental Biology, Lisbon, Portugal (2018)

**Invited review of (unpublished) journal manuscript (1 ECTS)**

- Field Crops Research: incorporation of rice residue and green gram cultivation saves nitrogen, enhances soil health and sustainability of rice-wheat system (2021)

**Deficiency, refresh, brush-up courses (2 ECTS)**

- Feeding a hungry planet: agriculture, nutrition and sustainability; MOOC (2017)
- Resilience of living systems: from fundamental concepts to interdisciplinary applications (2018)

**Competence strengthening / skills courses (3.6 ECTS)**

- Rice: research to production; International Rice Research Institute, Philippines (2017)
- Scientific and technical report writing, and publishing in peer-reviewed journal; Africa Innovations Institute and Makerere University, Kampala, Uganda (2017)
- Scientific publishing; Wageningen Graduate Schools, Wageningen University and Research (2021)

**PE&RC Annual meetings, seminars and the PE&RC weekend (2.1 ECTS)**

- PE&RC First years weekend (2017)
- WGS PhD Workshop carousel (2017)
- WGS PhD Symposium (2017)
- PE&RC Last year weekend (2020)

**Discussion groups / local seminars or scientific meetings (6.1 ECTS)**

- ENRICH International project workshop and end of project conference (2019)
- Plant-soil interactions (2020-2021)
- CSA Journal club (2020-2021)

**International symposia, workshops and conferences (3.8 ECTS)**

- European society for agronomy congress (2020)
- Farmer-centric on-farm experimentation conference (2021)

# About the Author

Thomas Awio was born in Otuke district, Uganda on 2nd January, 1986. He grew up in a village in the same district where he pursued his primary and ordinary level education. It is only until 2002 at the peak of the LRA insurgency in northern Uganda that he got the opportunity to live in Lira town, now a city. In 2010, he completed a Bachelor degree in Vocational Studies in Agriculture with Education at Kyambogo University, Uganda. In 2011, he received a scholarship from Rockefeller Foundation to pursue Master of Science (MSc) Crop Science at Makerere University, Uganda. During the MSc study, he conducted research on the effects of water management practices, rice residue utilisation and rice genotypes on field performance of rice in Uganda. In 2017, Thomas joined the Crop Physiology group of the Centre for Crop Systems Analysis at Wageningen University & Research as a PhD candidate. His PhD project was part of the NWO-WOTRO funded project in Uganda, with additional funding support from NUFFIC.

Having grown up in the village, working on the farm, Thomas likes working with farmers, supporting them in different ways to ensure farmers improve their productivity. For the past decade he has dedicated his time supporting smallholder farmers across Uganda through training and demonstration of good agronomic practices for enhanced crop productivity. He wishes to further his research on improving productivity of traditional crops, like millet, sorghum, and pigeon peas, for improved food and nutrition security.

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