

## Article

# 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 fertilization 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 fertilization 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<sup>-1</sup>), fertilizer costs made RAP+NPK gave the lowest mean net income (ca. USD 50 ha<sup>-1</sup>). Weeding and fertilization timing contributed most to yield variation among fields. Delay in weeding and fertilization created an average yield loss of 5.3 and 1.9 g m<sup>-2</sup>, 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 fertilization poses a risk to profit at current rice and fertilizer prices. To realize 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



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## 1. Introduction

### 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 [1,2]. In addition, SSA population continues to grow, with the projection that the population will at least double by 2050 and peak by 2100 [3,4]. As a result, cereal demand is expected to triple [2]. 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 [2]. Several studies indicate that meeting the projected food demand requires, at least partly, closing the gap between actual farm yields and potential yield [5–10].

### 1.2. Crop Yield Gap Concept

A crop yield gap is defined as the difference between actual farm yield and potential yield [6]. 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 [6,11–13]. 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 [11] and Stuart et al. [12] defined as the optimum (i.e., profit maximizing) 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 [6,13,14]. In rice production systems, economically attainable yield has been measured as the average of the top decile of farmers' yields [12,14–17]. In this study, we refer to economically attainable yield as the average of the top decile of farmers' yields, denoted as attainable farm yield [11,12]. The difference between actual farm yield and attainable farm yield has been defined as the exploitable yield gap [12], 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 [2,18]. Yet, there will be inadequate arable cropland to support crop area expansion [19]. 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 [2,20,21]. 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 minimize 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 [9,19,22–24]. 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 [25,26].

### 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 [16,27,28]. However, farm yields are very low [17,29–31], associated with poor management practices, especially related to leveling; 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 fertilizers are a major input to enhancing productivity [1,32–36]; nevertheless, SSA farmers on average use only ca. 5–9 kg ha<sup>-1</sup> of fertilizer, which is far below the 50 and 80 kg ha<sup>-1</sup> used in Latin America and Asia, respectively [32]. In addition, on non-responsive soils, yield responses to conventional NPK fertilizers are reported to be poor [37–40]. Thus, fertilizer use alone may not improve farm yields. In contrast to fertilizers 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 fertilizer use as they are shown to improve rice yields, compared to farmers' practices [27,41,42]. Therefore, in the face of the limited accessibility to, and use of fertilizers by farmers, efforts may need to be focused first on available and feasible options for farmers to intensify their production.

Where fertilizer use remains a difficult option for farmers to improve productivity due to limited access and high cost, yield advantages from fertilizers may not be realized if farmers invest in and apply fertilizers without following recommended agronomic (crop management) practices. For instance, lower rice yield gains have been shown from N and P fertilization compared with timely and proper weed management under farmers' practice [43]. Additionally, Tippe et al. [44] reported marginal yield gains from NPK or di-ammonium phosphate fertilization in weed-infested rice fields and noted that consistent yield gains cannot be attained with fertilization at high levels of weed infestation. Similar

results were reported in maize on farmers' fields with N and P fertilization under high weed infestation [45]. Under improved water management practice by bunding, Touré et al. [46] and Becker [47] observed rice yield gains due to fertilization, but not in fields with fertilization without bunds. These findings clearly indicate that even when farmers use fertilizers to improve their productivity, without proper crop and water management, they may not obtain substantial yield gains from fertilizer 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 fertilizers 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.

## 2. Materials and Methods

### 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 [48]. 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 tons of rice harvested each year. The scheme is located in the Lake Kyoga basin agroecological 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 [49]. Soils here are plinthosols, reddish brown in color, sandy loam, and loam textured [50]. 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.

### 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 fertilizer, 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 fertilization under recommended agronomic practices [51]. 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.

### 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 1st, 2nd, 3rd, and 4th 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 utilizing 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 center of each treatment plot to assess grain yield.

### 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 1) and records of such practices were taken; (2) Recommended agronomic practices without fertilization (RAP, implemented by 114 farmers). This represented the different components of recommended agronomic practices that were demonstrated in the earlier study [51], including bunding and field leveling 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 fertilization (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<sup>-1</sup>, 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 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, leveling was completed in the whole farmer's field, using a hand hoe, before treatment plots were installed, making all treatments conducted on equally well leveled 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 fertilizer used urea as N source and few farmers used an NPK blend (17:17:17). All farmers applied the fertilizer 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 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 <sup>-1</sup> ), no P and K.
Recommended agronomic practices without fertilization (RAP, n = 114)	Transplanting time (21–33 DAS), line transplanting, timely weeding (14–25 DAT), and no fertilization.
Recommended agronomic practices with NPK fertilization (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 <sup>-1</sup> 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 <sup>-1</sup> ), P and K (0.00–27.2 kg ha <sup>-1</sup> ) <sup>1</sup> .

Field tillage, bunding, leveling and number of weeding operations (i.e. one weeding) were identical across treatments. <sup>1</sup> 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.

### 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 fertilizer use, rate of application (kg ha<sup>-1</sup>) 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 6th hill within and between rows was sampled. Number of panicles m<sup>-2</sup> was derived from grain yield in g m<sup>-2</sup>, 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<sup>-2</sup>. 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. Fertilizer and labor costs per unit area were quantified by taking records of fertilizer price and costs of all field operations, and the selling price of paddy was fixed at USD 406 t<sup>-1</sup>, 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 (19th 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, fertilizer use, amount and application time was subjected to regression analysis using a generalized 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.

### 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 [12,16,17]. 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 [12], and prevents errors caused by single-field yield outliers [17]. The exploitable yield gap (EYg in  $\text{g m}^{-2}$ ) was calculated as follows:

$$\text{EYg} = \text{AY} - \text{Y}_a \text{ and,}$$

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

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

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. Results

### 3.1. Grain Yield under Different Management Levels

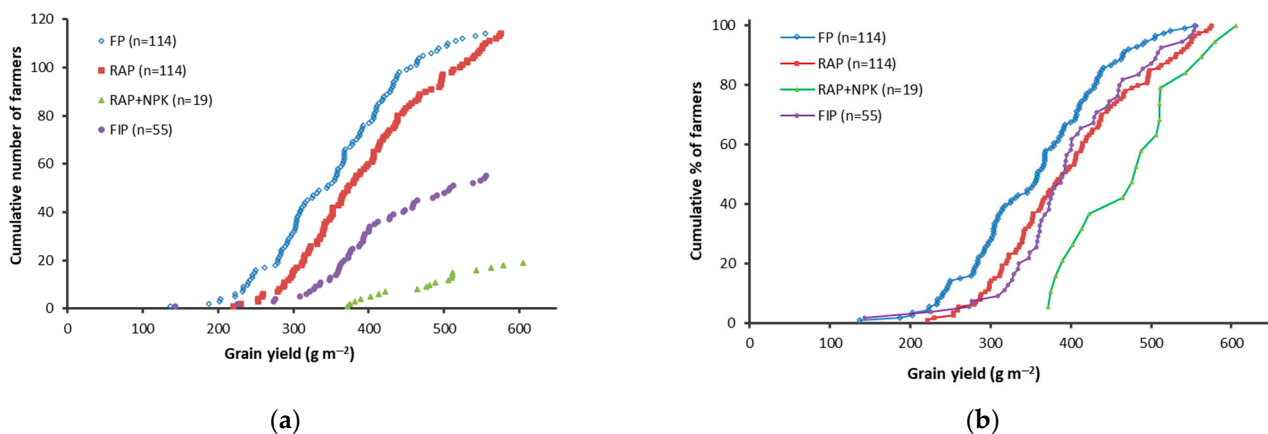
Grain yield varied significantly ( $p < 0.001$ ) among different management levels (treatments) on farmers' fields. Recommended agronomic practices (RAP) without fertilization significantly increased grain yield by 12.2%, compared with farmers' current practice (FP, Table 2). Combining NPK and RAP resulted 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 S1). The yield differences between management levels were explained by a significantly higher number of grains per panicle and filled grains  $\text{m}^{-2}$ . The higher number of filled grains  $\text{m}^{-2}$  was due to significantly more panicles  $\text{m}^{-2}$  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.

**Table 2.** Grain yield and yield components under different management levels on farmers' fields, Doho 2019.

Treatments <sup>1</sup>	Yield (g m <sup>-2</sup> )	Panicles m <sup>-2</sup>	Filled Grains/Panicle	Filled Grains m <sup>-2</sup> (×10 <sup>3</sup> )	Filled Grains (%)	1000-Grain Weight (g)	HI <sup>2</sup> (%)
FP (n = 114)	358 <sup>a</sup>	340 <sup>a</sup>	49.6 <sup>a</sup>	16.5 <sup>a</sup>	68.4 <sup>b</sup>	21.7 <sup>c</sup>	42.2 <sup>b</sup>
FIP (n = 55)	399 <sup>b</sup>	365 <sup>b</sup>	52.2 <sup>b</sup>	18.5 <sup>b</sup>	68.9 <sup>b</sup>	21.6 <sup>bc</sup>	42.7 <sup>bc</sup>
RAP (n = 114)	401 <sup>b</sup>	364 <sup>b</sup>	52.7 <sup>b</sup>	18.7 <sup>b</sup>	68.9 <sup>b</sup>	21.5 <sup>b</sup>	43.0 <sup>c</sup>
RAP+NPK (n = 19)	475 <sup>c</sup>	431 <sup>c</sup>	52.9 <sup>b</sup>	22.5 <sup>c</sup>	63.1 <sup>a</sup>	21.2 <sup>a</sup>	40.2 <sup>a</sup>
Mean	408	375	51.8	19.1	67.3	21.5	42.0
SED	7.0	10.1	1.2	0.3	1.0	0.1	0.5
<i>p</i> -value	<0.001	<0.001	0.01	<0.001	0.05	0.02	0.03

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

Yield distribution among the farmer population indicated that the median of the yields obtained by the population did increase, but not a lot (Figure 1). The median yield for FP was 359 g m<sup>-2</sup> and this shifted by 9.3% to 392 g m<sup>-2</sup> for RAP, which was the same as the 393 g m<sup>-2</sup> for FIP (9.6% over FP). The median yield shifted to 481 g m<sup>-2</sup> for RAP+NPK, which was 34.2% over FP (Figure 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.

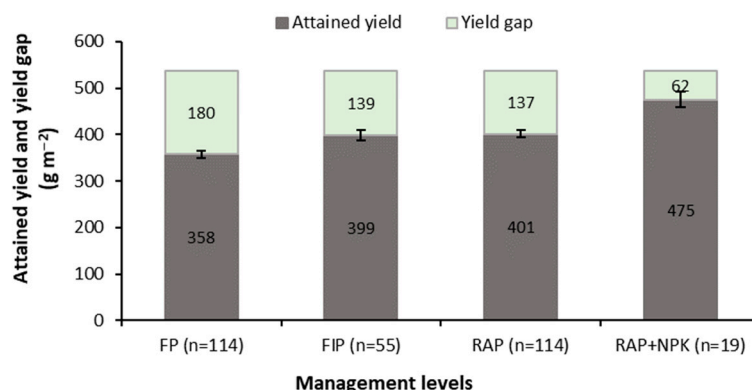


**Figure 1.** Cumulative frequency diagrams of yields obtained under different management levels: farmers' practice (FP), recommended agronomic practices without fertilization (RAP), RAP plus NPK application (RAP+NPK) and farmers' intensification practice (FIP). (a) is plotted as number of farmers and (b) as percentage of farmer population.

### 3.2. Yield Gaps under Different Management Levels

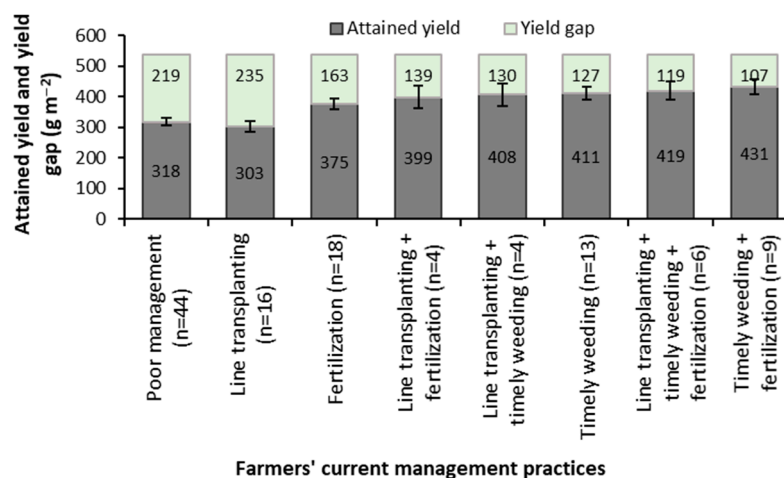
Using the mean (538 g m<sup>-2</sup>) of the top 10-percentile of yields across FP, RAP, and FIP as attainable yield, the exploitable yield gap was between 11.6 and 33.5% of this attainable yield under farmers' conditions (Figure 2). For the median and lower 10-percentile yields (382 and 230 g m<sup>-2</sup>) 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 2.** Attained yield (g m<sup>-2</sup>) under different management levels and the corresponding yield gaps (g m<sup>-2</sup>) 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 fertilization, RAP+NPK = RAP combined with NPK fertilization.

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). 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%), fertilization only (15.8%), timely weeding only (11.4%), timely weeding + fertilization (7.9%), line transplanting + timely weeding + fertilization (5.3%), line transplanting + fertilization (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 + fertilization left the lowest exploitable yield gap of 19.9% (Figure 3).



**Figure 3.** Attained yield (g m<sup>-2</sup>) 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). For instance, considering the mean of top 10-percentile of yields under farmers' practice ( $504 \text{ g m}^{-2}$ ) as attainable yield, an exploitable yield gap of 29.1% ( $147 \text{ g m}^{-2}$ ) existed with the average of current farmers' management practices. However, this exploitable yield gap was reduced to 20.8% ( $105 \text{ g m}^{-2}$ ) and 20.4% ( $103 \text{ g m}^{-2}$ ) with FIP and RAP, respectively, and a further reduction to only 5.7% ( $29 \text{ g m}^{-2}$ ) was made with RAP+NPK (Table 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.** Yields and exploitable yield gaps under different management levels (treatments), Doho 2019.

Treatment	Yield ( $\text{g m}^{-2}$ )	Exploitable Yield Gap ( $\text{g m}^{-2}$ )				
		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 fertilization; and RAP+NPK = recommended agronomic practices combined with NPK fertilization. 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. Causes of Yield Variation among Fields

Major causes of yield variation among fields in descending order of importance were weeding time, fertilization timing, and N, P, and K fertilization, when fertilizers were applied (Table 4). Delayed weeding under FP and FIP decreased yield on average by  $43.0 \text{ g m}^{-2}$  (ranging between  $6.7$  and  $206 \text{ g m}^{-2}$ ) and  $25.8 \text{ g m}^{-2}$  ( $6.0$ – $193 \text{ g m}^{-2}$ ), respectively. The slope estimate from regression analysis showed that a delay of weeding by one day decreased grain yield on average by  $5.3 \text{ g m}^{-2}$  (Table 4). Where fertilizer was applied with late weeding under farmers' practice, an average yield loss of  $17.2 \text{ g m}^{-2}$  due to weeds was observed, with yield reduction varying between  $5.1$  and  $155 \text{ g m}^{-2}$  recorded. Delay of weeding by one day when fertilizer was applied reduced grain yield by an average of  $3.7 \text{ g m}^{-2}$ , with yield loss of between  $1.6$  to  $5.7 \text{ g m}^{-2}$  per day estimated ( $p < 0.001$ , s.e. of slope estimate = 1.01). A regression analysis of the overall effect of fertilization on yield, across all application timings, showed that fertilizer application increased yield on average by  $55 \text{ g m}^{-2}$  per  $\text{g m}^{-2}$  NPK applied, varying between  $35$  and  $75 \text{ g m}^{-2}$  ( $p < 0.001$ , s.e. = 10.3), while a one-day delay to apply the fertilizer reduced this yield gain by an average of  $1.9 \text{ g m}^{-2}$ . Every  $\text{g m}^{-2}$  of N and P+K applied resulted in an average additional grain yield of  $11.0$  and  $18.8 \text{ g m}^{-2}$ , respectively (Table 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 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	<i>p</i> -Value	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Adjusted R <sup>2</sup>
Weeding time (DAT) <sup>1</sup>	−5.3	g m <sup>−2</sup> day <sup>−1</sup>	0.54	<0.001	−6.4	−4.2	0.22
Fertilization timing (DAT)	−1.9	g m <sup>−2</sup> day <sup>−1</sup>	0.48	<0.001	−2.8	−0.9	0.13
N (g m <sup>−2</sup> )	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 <sup>−2</sup> )	18.8	$\frac{\text{g grain m}^{-2}}{\text{g P+K m}^{-2}}$	0.40	<0.001	11.0	26.7	0.06

<sup>1</sup> 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 fertilizer and for 56%, fertilization 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 5). Average nutrient rates for the higher and lower yielding plots were 2.7 and 1.1, and 0.04 and 0 g m<sup>−2</sup> N and P+K, respectively. Generally, lower yielding plots were under poorer management than higher-yielding plots.

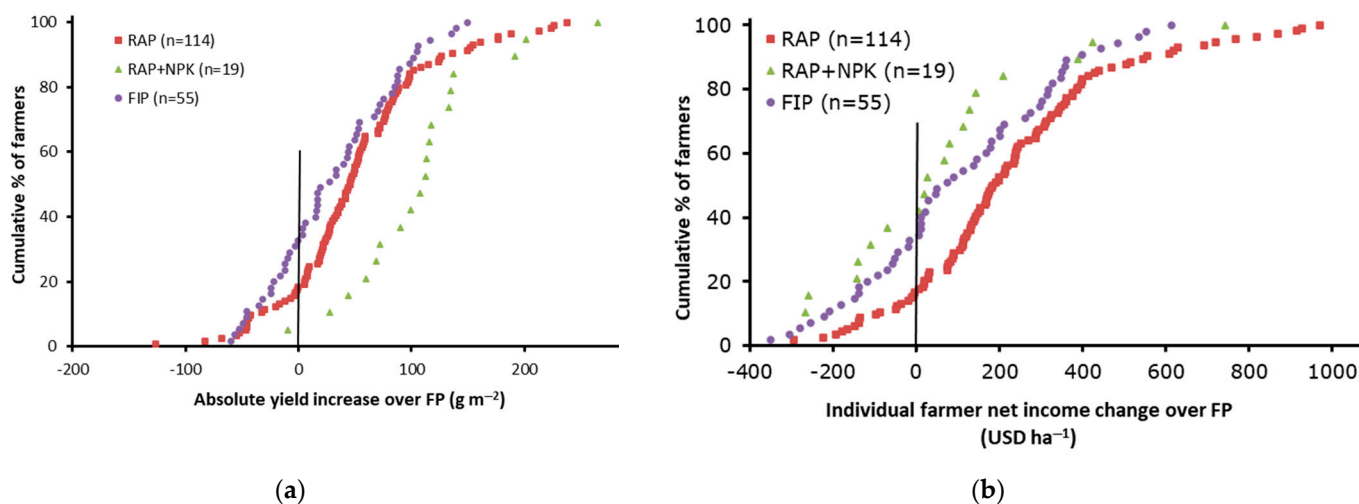
**Table 5.** Percentage of farmers who applied the different management practices, amount of N, P, and K applied (g m<sup>−2</sup>), and the number of days after transplanting (DAT) when management was applied in higher, median, and lower yielding plots on farmers' fields, Doho 2019. n refers to the 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	14–21 DAT (%)	84.6	69.2	17.9
	22–28 DAT (%)	12.8	10.3	0.0
	≥29 DAT (%)	2.6	20.5	82.1
Average weeding time (DAT)	( <i>p</i> < 0.001, SED = 1.5)	19.5	21.9	32.4
Fertilizer use	Yes (%)	46.2	35.9	2.6
	No (%)	53.8	64.1	97.4
Average nutrient rate (g m <sup>−2</sup> )	N ( <i>p</i> < 0.001, SED = 0.64)	2.69	1.71	0.04
	P+K ( <i>p</i> = 0.008, SED = 0.33)	1.06	0.56	0.0
Fertilization time	14–21 DAT (%)	55.6	28.6	0.0
	22–28 DAT (%)	5.6	14.3	0.0
	≥29 DAT (%)	38.9	57.1	100
Average fertilization time (DAT)	( <i>p</i> = 0.24, SED = 9.7)	25.3	32.0	61.0

### 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<sup>−2</sup> (ranging between 10.6 and 39.6 g m<sup>−2</sup>), 43.5 g m<sup>−2</sup> (33.1–54.0 g m<sup>−2</sup>), and 85.8 g m<sup>−2</sup> (58.9–112.8 g m<sup>−2</sup>) due to FIP, RAP, and RAP+NPK, re-

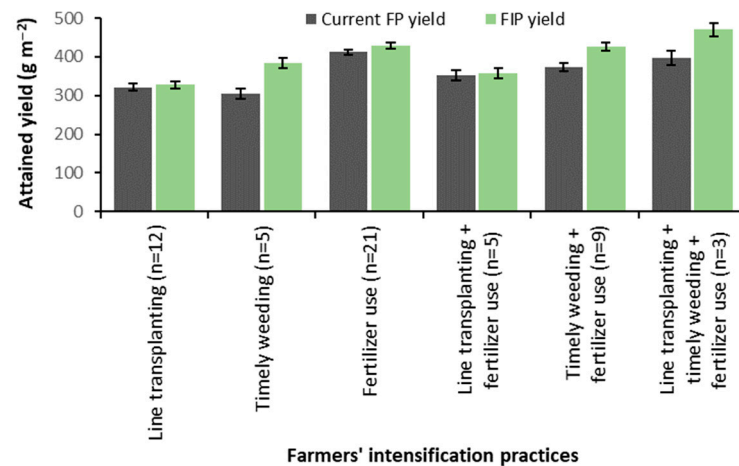
spectively, over FP. The frequency distribution for absolute yield increase over FP, however, indicated there were farmers that recorded yield reductions under improved management practices, while others made large yield gains (Figure 4a). RAP+NPK resulted in the largest yield gains (Figure 4a) with mean yield gain of  $109.6 \text{ g m}^{-2}$ , however, with the lowest net income gains by farmers due to fertilizer costs (Figure 4b). RAP gave the highest mean net income (USD  $222 \text{ ha}^{-1}$ ) followed by FIP (USD  $105 \text{ ha}^{-1}$ ), and RAP+NPK (USD  $46.3 \text{ ha}^{-1}$ ).



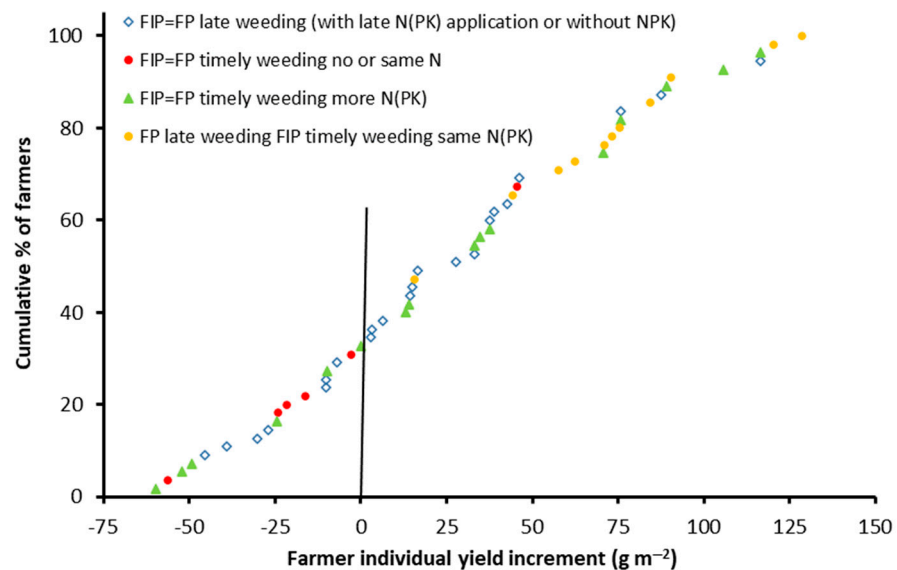
**Figure 4.** Cumulative frequency for absolute yield increment (a) and net income (b) over farmers' practice due to the improved management packages tested: recommended agronomic practices without fertilization (RAP), recommended agronomic practices combined with NPK application (RAP+NPK) and farmers' intensification practice (FIP) plotted as percentage of farmer population.

Under FIP, the different intensification options which farmers considered feasible and, thus, evaluated included line transplanting, timely weeding, fertilizer 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 5). Timely weeding as a single intensification option, and combined with line transplanting and fertilization, resulted in the highest yield gains of  $80$  and  $73 \text{ g m}^{-2}$ , respectively, compared with yield under current practice for farmers who implemented these management practices as their intensification options.

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  $75 \text{ g m}^{-2}$  and ranging from  $16$  to  $129 \text{ g m}^{-2}$  (Figure 6, yellow closed circles). Farmers who did timely weeding under both FP and FIP but increased fertilizer rate under FIP observed an average yield increment of  $25 \text{ g m}^{-2}$ , with the yield increment ranging from  $-60$  to  $117 \text{ g m}^{-2}$  (Figure 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 fertilizer rate, increased fertilizer rate only or increased fertilizer rate and applied NPK blend instead of urea, had yield increments ranging from  $-46$  to  $116 \text{ g m}^{-2}$  with an average yield increment of  $18 \text{ g m}^{-2}$  (Figure 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 ( $-13 \text{ g m}^{-2}$ ) (Figure 6, red closed circles).



**Figure 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.



**Figure 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 fertilization (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).

#### 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<sup>-1</sup> to 4000 kg ha<sup>-1</sup>, by those farmers currently weeding late or by ca. 5.6% for farmers weeding timely but not

using fertilizers (Figure 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 2 and Figure 4a). Our findings are, therefore, in general agreement with the discussion of Pradhan et al. [9] 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 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 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 fertilization 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 [52–56].

Cumulative distribution of net income from improved management practices showed a shift in net income to the lower side from RAP+NPK application (Figure 4b) due to high fertilizer costs (e.g., Urea (46% N) at USD 1.0 kg<sup>-1</sup>; NPK (17:17:17) blend at USD 1.1 kg<sup>-1</sup>), indicating that the nutrient rates used in this study may not be economic at current rice and fertilizer prices as there is a risk of investing in fertilizers with no or very low returns on the investment. The lower economic returns from fertilizer application at higher rates shown by this study could partly explain why farmers do not use fertilizers or use low to moderate nutrient rates. This suggests that to realize increased rice production with fertilization at current market prices, there is a need for the government to subsidize fertilizers, in line with Koussoubé et al. [57] and Sanchez [58] who showed that subsidies can increase fertilizer use and cereal yields in SSA.

Significant yield gains were realized 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 5 and 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 [27,41], even without fertilizer 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 fertilizer rate under FIP (Figure 6). Other choices in intensification did not show such consistent positive effect (Figure 6). This supports the need for farmers to conduct timely weeding first, and only after then apply moderate fertilization as a next step, a position also supported by prior studies [43,44].

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 2 and 3). The yield gaps observed in this study are within the range of yield gaps reported for rice in SSA [15–17] and in Asia [12], 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 [9,27]. Timely weeding alone reduced the yield gap to 24% compared with 44% yield gap due to poor management under current farmers' practice (Figure 3).

The major factors resulting in yield variations among plots in descending order of significance were timing of weeding and fertilizer application (where applied), and level of N and P+K applied (Table 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 fertilization, are low without timely weeding (cf. also [15,27,31,59–61]). Although fertilizer application has been reported in many studies to boost yields [1,34,62,63], yield gains from fertilization were severely reduced by late weeding in this study (Table 4). On the contrary, yield gains from fertilizer application were substantial where weed management was optimal (Figures 5 and 6). Several studies report rice yield gains due to N application where weeds were suppressed using good leveling and bunds, enabling proper water control within plots as part of weed management [41,46,47,60]. Consequently, better weed management which depends on time, labor 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. [64] to improve labor 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 [65,66], and studies reporting substantial yield reduction by transplanting rice seedlings between 20 and 35-day-old [65–69]. However, contrasting findings have also been reported [70,71]. 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 emphasize changes to their practices.

## 5. Conclusions

We demonstrate that adhering to recommended agronomic practices (RAP), even without fertilizer application, significantly contributes to yield gain and income and reduces the yield gap. Additional yield gain can be realized with NPK fertilizer 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 fertilizer 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 labor 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 fertilizer 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.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy12030552/s1>, Supplementary Table S1: On-farm grain yield ( $\text{g m}^{-2}$ ) for four treatments and four different planting lots, Doho, 2019.

**Author Contributions:** Conceptualization, Methodology, Validation: T.A., K.S., C.O.D., G.W.O.-N. and T.J.S.; Investigation: T.A.; Formal analysis, Writing—Original draft preparation: T.A., P.C.S. and T.J.S.; Writing—Reviewing and editing: K.S. and C.O.D. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data presented in this study are available upon request to the corresponding author and under the condition that the identity of participating farmers can be protected.

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