Sustainable intensification in Western Kenya: Who will benefit?

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ABSTRACT

Sustainable Intensification (SI) is essential for Sub-Saharan Africa (SSA) to meet the food demand of the growing population under conditions of increasing land scarcity. However, access to artificial fertilizers is limited, and the current extension system is not effective in serving smallholder farmers. This paper studies farmers' response to improved fertilizer availability under field conditions. Data on farms and families were collected from 267 smallholder farms, while data on fertilizer use and crop response to fertilizer were collected on 127 farm plots. Fertilizer applications and maize yields were measured, and benefit to cost ratio (BCR) of fertilizer application was calculated and to assess its effect on food security. Farm household typologies were used to determine differences in farm endowment and food security classes. Fertilizer application did not significantly improve maize yields in 2017 due to unfavorable weather conditions and pest infestations, whereas significant yield responses were observed in 2018. Consequently, fertilizer application was economically beneficial (BCR > 1) for only 45% of the farmers in 2017, compared to 94% in 2018 when 80% of the farmers passed the technology adaptation point (BCR > 2). Surprisingly, economic returns did not vary significantly between household types, implying that fertilizer application provides comparable benefits across all farm types. This is partly explained by the fact that soil fertility varied little between farm types (soil carbon content, for example, showed no correlation with farmer endowment). Still, large differences were observed in farmers' willingness to invest in larger fertilizer applications. Only a small proportion of farmers is expected to increase fertilizer applications as recommended. Our work demonstrates the need to address risks for smallholders and shows that socio-economic aspects are more important than biophysical constraints for policies promoting sustainable intensification.

1. Introduction

The strong population growth in Sub-Saharan Africa (SSA), doubling the SSA population within the next 30 years (United Nations and Department of Economic and Social Affairs, 2019), call for an increase in crop production to meet the growing demand for food. Until recently, this increase was largely based on cropland expansion (van Ittersum et al., 2016). In many densely populated areas, however, further expansion is not possible. With limited resources to enable food imports, increasing yields on existing farmland are the most feasible option for many countries. Fortunately, there is ample opportunity to improve crop yields (van Ittersum et al., 2016) and attention to input subsidy programmes lowering the cost of fertilizer has been renewed (Jayne et al., 2018a). However, it cannot be assumed that all farmers are easily adopting new technology (Glover et al., 2016). Farmers have other alternatives for investment and often choose alternative strategies to improve their livelihoods (Dixon et al., 2001). In many Sub-Saharan

African countries soil fertility is low (Hengl et al., 2017) and declines due to negative nutrient balances (Lassaletta et al., 2014; Stoorvogel and Smaling, 1998). Currently, a small proportion of smallholder farmers is producing sufficient surplus food to feed the nation, while most smallholders are farming for subsistence (Frelat et al., 2016). This means that production increase needs to come from only a small proportion of available cropland. But who will grow the crops needed to provide food for the growing and emerging cities?

Sustainable intensification (SI) has many shades of green, but needs to increase inputs in environments with a large yield gap (Pretty et al., 2011; Struik and Kuyper, 2017). Potential financial benefits of investments in crop cultivation is the key driver for SI (Franke et al., 2014; Komarek et al., 2017; Messina et al., 2016), but also the need for cash to pay for health, education and to purchase food between harvests may be important drivers (Mutoko et al., 2014). Soil fertility is the major constraint for production in SSA (Breman et al., 2019; Giller et al., 2011), and fertilizer use is one of the key ingredients for improved

Table 1
Elevation, dominant soil types, agro-climatic zone (ACZ), and three variables consisting of ACZ (growing degree days (GDD), aridity index (AI), and temperature seasonality (TS)) in the survey districts.

Province	Western Kenya				Nyanza	Rift Valley
District	Bungoma	Busia	Butere	Kakamega	Siaya	Nandi
Elevation (m)	2150–2160	1150–1250	1280–1400	1480–1690	1300	2050–2060
Dominant soil types	Acrisol	Acrisol	Acrisol	Acrisol	Acrisol	Acrisol
	Nitisol	Graysol		Ferralsol	Nitisol	Lixisol
ACZ[a] (Code)	7701	7701	7701	7701	7701	7801
	6701			6501	7501	
	6601					
GDD[b] (°Cd)	5950–8564	7112–8564	7112–8564	5950–8564	7112–8564	7112–8564
AI[c]	7786-10,181	8686-10,181	8686-10,181	6589–7785	6589–7785	10,182–12,876
				8686–10,181	8686–10,181	
TS[d]	0-3832	0-3832	0-3832	0–3832	0–3832	0–3832

[a] ACZ classification is composed of GDD, AI, and TS, as described in Van Wart et al. (2013).
[b] Calculated as the cumulative annual average temperature with a non-crop-specific base temperature (0 °C).
[c] Calculated by mean annual precipitation (mm × 100)/mean annual potential evapotranspiration (mm × 100).
[d] Calculated by the standard deviation of the 12 mean monthly temperatures × 100.

productivity in SSA through SI approach along with improved seeds and rotations (Giller et al., 2015; Franke et al., 2018; Mungai et al., 2016). Investing in fertilizers may be risky for smallholders (Mitiku, 2014), especially when soil conditions are poor. Both infertile fields with large yield gaps (Tittonell and Giller, 2013) and strong risk exposure of farmers may lead to poverty traps (Yesuf and Bluffstone, 2009). When compared to better-endowed farmers, poor farmers are exposed to larger financial risks (Oyinbo et al., 2019), and are more risk-averse due to limited education (Outreville, 2015). They often show greater employment diversification (Cieslik and D'Aoust, 2018). Resource endowment strongly varies between farmers, as is reflected in the area of cropland or the number of animals on the farm (Rufino et al., 2008). Through the preferential application of manure by farmers to more responsive fields (Tittonell et al., 2007) and the centripetal force of animals, strong soil fertility gradients that have emerged result in large differences in soil nutrient stocks (Njoroge et al., 2017). This means that responses to any new technology (Franke et al., 2014) and adoption of fertilizer will be dictated by farm endowment class, but also by the distance to a local market, age and education level of the household head (Ogada et al., 2014). Differences between farms in crop response to fertilizer is further enlarged by unbalanced nutrient applications and accelerating mining of already limited soil nutrients (Njoroge et al., 2018). A decade ago, transportation costs were strongly affecting price gradients of both inputs and products from the city (Tittonell et al., 2008). Inputs suppliers are now providing farmers inputs at a reasonable price throughout Western Kenya (Burke and Lobell, 2017; Jin et al., 2017) and effectively reducing these price gradients. However, most subsidy programmes specifically target better-off farmers as this gives them a larger chance of success (Jayne et al., 2018b).

Farm typologies have been used to classify farm households based on their resource endowment and to categorize their market orientation (Tittonell et al., 2010) and food security (Hammond et al., 2017). A better understanding of farm typologies concerning their fertilizer use may provide insight into what group of farmers will most likely invest in intensification (Franke et al., 2016). It is expected that well-endowed smallholders with a larger proportion of relatively fertile soils living in the vicinity of a city will have a better benefit to cost ratio (BCR) and respond more greatly to incentives to intensify than poor farmers living with a worse BCR at a larger distance to the market, further amplified by differences in education level.

Smallholder fields are very variable in both soil fertility and yield (Burke and Lobell, 2017; Jin et al., 2017) and their responses to fertilizer applications (Ichami et al., 2019). The variable yield response to input use in smallholder fields is a key reason why the green revolution had limited success in SSA (Jayne et al., 2018b). The largest variability in soil fertility is found within and between farms, on relatively short

distances. Tittonell et al. (2013) suggested using knowledge about on-farm soil fertility gradients to develop strategies for adjusted nutrient applications. Insights on the importance of animal manure (Njoroge et al., 2019; Rufino et al., 2008) are expected to provide a direct link between farmer socio-economic status and BCR, with clear differences between regions.

This paper aims to identify strategies to enhance SI to increase farm income and food availability by defining who can benefit from fertilizer use and which farmers are likely to adopt SI technologies. The first objective of the paper is to understand better how farm and field characteristics affect crop responses to balanced fertilizer applications. The second objective is to verify how socio-economic insights can be used to better tailor fertilizer recommendations to farmers' and farm households' needs.

2. Material and methods

2.1. Study area and selection of farmers

This study included farmers in the region of Western Kenya, in the provinces of Western Kenya, Nyanza and Rift Valley. The elevation and dominant soil types, agro-climatic zones (ACZ) in the study area are shown in Table 1 along with data on growing degree days, annual aridity index and temperature seasonality that were used to construct the ACZ (Van Wart et al., 2013). Farmers participated in this experiment were mainly from the Western Kenya Province, distributed over the Busia, Bungoma, Kakamega and Vihiga districts (81.3%), while a smaller number of farmers (17.7%) were located in the Siaya (Nyanza Province) and Nyandi (1.0%) districts (Rift Valley Province).

The selection of farmers was done in two phases. First, 267 farmers were included in an interview to collect data on farm size, family conditions, and other socio-economic conditions. Next, fertilizer management data were collected from a sub-set of the farmers that were interviewed. A total of 127 plots were monitored (Table 2). One plot was selected from each farm. All farmers were served by a social business (Agrics Ltd.) providing seeds, fertilizers, agro-chemicals and advice, similar to other social businesses operating in the region (e.g. OneAcreFund). Farmers were organized in groups and frequently advised by extension workers from Agrics. Input costs and service programs for these farmers were similar to those of most farmers in the region.

The study area has one main cropping period during the long rain season (March–August) plus a minor cropping period during the short rain season (September–January). Potential yields under rainfed conditions when nutrients are not limiting are 8–10 t/ha for the region, whereas actual yields on the majority of smallholder farms in this

Table 2
Number of the observations in the survey districts.

Number of observations	District						Total
	Bungoma	Busia	Butere	Kakamega	Siaya	Nandi	
	2017						
Interviewed households	28	17	35	64	22	4	170
Harvested fields	14	7	14	33	14	0	82
	2018						
Interviewed households	10	0	31	25	31	0	97
Harvested fields	6	0	12	13	14	0	45
			Total number of interviews over 2 seasons				267
			Total number of harvest fields over 2 seasons				127

region are approximately 1.9 t/ha (van Ittersum et al., 2016). Results from on-farm trials over 11 seasons in the Siaya region of Western Kenya, showed that under good management averages of 5.5 t/ha of maize grain can be harvested twice a year by applying NPK fertilizer at moderate rates (Njoroge et al., 2019; Njoroge et al., 2017).

A stratified farmer selection protocol was used to ensure adequate representation of prevailing farm types, socio-economic strata, soil types, agro-climate zones and farming areas in the region. First, villages were pre-selected to ensure that all major soil types, working regions of Agrics and agro-climatic zones were covered in the survey. In each selected village, six farmers were selected and interviewed including three clients of Agrics and three comparable farmers located nearby in 2017 and in 2018. Most participating farmers in 2017 were not available for 2018 and other farmers were selected. On all farms, one maize field was identified and a soil sample was collected to evaluate soil fertility. On fields of the selected Agrics clients' plots were marked in the long rain season to measure the grain yield response to fertilizer applications.

2.2. Plot design and soil sample analysis

Plots of 10 by 10 m were marked in selected farmer fields and georeferenced at the start of the season. Before the growing season, 10–15 sub-soil samples from 0 to 10 cm were taken in an "hourglass" sampling pattern, thoroughly mixed and sent to Crop Nutrition Laboratory Services (CropNuts, Nairobi, Kenya http://cropnuts.com/) for wet chemical analysis. Soils samples were air-dried, sieved (2 mm), and analysed for soil texture, cation exchange capacity, pH and electric conductivity, organic carbon and nutrient contents. Standard wet chemistry analysis procedures were used with ICP-OES following a Mehlich-3 extraction for all nutrients except P, for which an Olsen extraction was used. The pH in a 1:2 (soil to water) dilution was determined potentiometrically. Sand, silt and clay contents were determined with a hydrometer, while organic carbon contents were determined spectroscopically (samples from 2017) or with a Walkley-Black method (samples from 2018).

2.3. Agronomic practices and harvests

Hybrid maize seeds and NPK fertilizers were delivered before seeding to 82 farmers in 2017 and 45 farmers in 2018. The amounts of NPK fertilizer were tailored to field conditions using geodata and farmer observations, aiming at 80% of water-limited potential yields (van Ittersum et al., 2016) in 2017 which was reduced to 50% in 2018. Farmers were demonstrated how to apply good agronomic practices in 2017. Basal- and top-dress fertilizer applications were conducted by field staff in 2017, farmers being responsible for weeding, insect control, animal disturbance, etc. Plant emergence rates were recorded to assess plant density. The fertilizer products, which were used in this study are listed in Table S1. A total of 30 plots in 2017, and all plots (48) in 2018 were subdivided into two plots, enabling comparisons between fertilized and non-fertilized plots in the same field. In 2017,

field teams selected plots and controlled sowing and fertilizing and farmers' engagement with the project was sub-optimal resulting in sub-optimal field management. This was better in 2018 when farmers had full control over the plots. In both years, the field team observed management practices and measured actual fertilizer applications in the plots gravimetrically. Plant density was recorded to monitor plant emergence and survival rates. A few (4 in 2017, 3 in 2018) farmers harvested the plots before field teams arrived to record yields, resulting in 82 and 45 recorded fields in 2017 and 2018 respectively. At harvest, the number of plants, the number of ears (cobs), grain moisture content (DICKEY-John Mini GAC, Illinois, USA) and weights of ears and total biomass were recorded in the field in 2 or 3 quadrats of 15 m^2.

2.4. Socio-economic characterisation

Farmers were interviewed twice, the first time early in the main growing season and the second time after maize harvest. Data from the interviews were compared and triangulated. When the answers from farmers in the interviews deviated or did not match, additional consultations took place with local surveying teams to check the outcomes (following approaches by Tittonell et al., 2010 and Alvarez et al., 2018). Data then were corrected; if this was not possible, the records were eliminated. This triangulation was done to increase reliability which reduces the so-called "one snapshot in time" effect, discussed by Alvarez et al. (2018) expressing the uncertainty in capturing dynamic socio-economic aspects with a single socio-economic interview per season. The types of questions for the triangulation are: number of meals/day and duration of food shortage, number of persons in the household earning an off-farm income, etc. The in-season interview provided data on household status, social-economic status and agronomic practices. A digital questionnaire was implemented in a smartphone application, and the completion of the interview took approximately 30 min. The post-harvest survey recorded customer experience and socio-economic indicators adapted from the Rural Household Multi-Indicator Survey (RHoMIS) as presented by Hammond (et al., 2017). Further, tropical livestock units (TLU), and off-farm income per household were calculated (Hammond et al., 2017).

2.5. Analysis of socio-economic data

Tittonell et al. (2010, 2005) developed a farm typology for Western Kenya based on off-farm income, age of the household head, farm size (ha), number of persons in the household, TLU and food self-sufficiency. This typology included five clusters reflecting endowment and market orientation and was based on a combined Principle Component (PC) and Cluster Analysis (CA) using the k-means approach, which was also used by Mutoko et al. (2014). All variables were first normalized. In our study, 76.9% of total variation was explained by only 4 PCs. The first two principal components, exceeding Kaiser's criterion with an eigenvalue > 1.00, were retained and accounted for 45.1% of the variance. The biplots of PC1 and PC2 and variable contributions derived from the factor loadings are provided in the supplementary materials

(Fig. S1). After conversion to PCs, the k-means clustering method was used with the "k" set to 5 clusters. This method belongs to a non-hierarchical clustering method that clusters data into k centres, minimizing the sums of squares of points assigned to clusters centres. We followed the same procedure as Tittonell et al. (2010) and Mutoko et al. (2014) with default settings (nstart set to 25, ten iterations as maximum, Hartigan-Wong algorithm) using R-software. As recommended by Alvarez et al. (2018), a correlation analysis to remove redundant variables and an evaluation of possible outlier samples was performed prior to the analysis.

2.6. Comparisons of farm typologies

Means and median values were used to categorize five farm clusters using the results of earlier studies (Mutoko et al., 2014; Tittonell et al., 2010). The following farm types (FT) were identified: better endowed farmers with larger dependency on off-farm income (FT-1); medium endowed farmers with a strong market orientation and a relatively large number of livestock (FT-2); medium endowed farmers with a diversified income (FT-3); farmers with limited endowment and generating income from off-farm engagements such as unskilled and seasonal employment (Tittonell et al., 2010; Mutoko et al., 2014) (FT-4); farmers with limited endowment, causal off-farm income and low food sufficiency (FT-5). Characteristics of the clusters were evaluated with variables not used in the clustering process, including number of meals per day; duration of food shortage; the number of household members earning an off-farm income; the proportion of food purchases from markets and other farmers. Cluster means of biophysical and field management data were compared with previous studies in the area (Mutoko et al., 2014; Tittonell et al., 2010).

2.7. Socio-economic assessment

Several indicators were calculated to assess the impact of fertilizer use on farm income. BCR is a well-known variable to evaluate the economic impact and potential increase in income of farmers. BCR is defined here as: the monetary value of the total amount of grain yield (KSh/ha) divided by the investment in production including seeds, fertilizer and insecticide (KSh/ha). Additional costs such as hiring labour, rent of equipment and transport were not included in the calculations. Farmers did not use irrigation. Generally, a BCR of 2:1 is considered as a minimum for a likely adoption of new technology (Ronner et al., 2016). Seed cost was 225 KSh/kg associated with the advised plant density for this region (53,333 plants/ha). The fertilizer price per kg of nutrient was lower in 2018 than in 2017. The price of maize was based on the official Kenyan average cross-region market price of October in 2017 and 2018 (National Agriculture Information Service Kenya), one month after the long-rain season when harvesting was completely finished in all regions. Prices were 3444 and 2103 KSh/kg maize grain in 2017 and 2018, respectively. The difference can be partly explained by the impact of the Fall Armyworm (FAW; *Spodoptera frugiperda* J E Smith, Lepidoptera: Noctuidae), and drought in the northern regions of Kenya in 2017, that depressed maize production while 2018 was a favourable growing season.

The average and marginal value to cost ratio (AVCR and MVCR) are well-known indicators of the financial impact of fertilizers. AVCR is calculated as:

$$AVCR = \frac{\left(\frac{kg\ grain}{ha} \times \frac{KSh}{kg\ grain} \right)}{\left(\frac{kgN}{ha} \times \frac{KSh}{kgN} \right)}$$

AVCR and MVCR are very similar, but MVCR only considers the cost ratio of yield responses to N applied, i.e. yield increases over a control field without N application. An AVCR of 3.0 and MVCR of 2.0 are considered risk-neutral for SSA countries where rain-fed maize is

produced in high-risk environments (Ragasa and Chapoto, 2017; Sheahan et al., 2013; Theriault et al., 2018). While BCR covers the input cost of fertilizer, improved seed and insecticide, the focus of AVCR is on the revenue relative to the investment in N fertilizer. Given that BCR receives criticism for the limited applicability for the assessment of vulnerability to hazard or risk such as natural disastar of flood or drought (Shreve and Kelman, 2014), the combined approach by using VCR, considered as a well-known indicator of the riskiness of the fertilizer use (Ragasa and Chapoto, 2017), can overcome the limitation of the BCR. Hence, BCR and AVCR are complimentary and both indicators are used for studies in Sub-Saharan countries (Tovihoudji et al., 2018; Gitari et al., 2019).

Using one type of these indicators (e.g. BCR and VCR) does not fully illustrate the degree of the economic impact at the farm level. It is necessary to associate with another household indicator. The partial profit was computed at farm level as the total monetary value (in USD) of harvested grain minus expenditure of agricultural inputs for the farm (Komarek et al., 2018b). The exchange rate used was 1 USD: 100 KSh for both years. The proportion of fertilizer-derived income was calculated as partial profit for the farm divided by total annual income, following Frelat et al. (2016).

The total number of household members was converted to male adult equivalents (MAE) to account for the influence of gender and age on energy requirements, following Frelat et al. (2016) and Ritzema et al. (2017).

2.8. Statistical analysis

Post-hoc Tukey and Games-Howell tests were used to examine honestly significant difference (HSD) between farm types for normal and non-normal distributions, respectively. A one-way ANOVA with a non-parametric Kruskal-Wallis test was used to analyze the farm types with unequal sample sizes. Effects were considered significant at $p \leq .05$.

3. Results

Mean maize yields (dry matter) on fertilized plots in 2017 and 2018 was 3.3 and 3.89 ton/ha, respectively. The low yields in 2017 were caused by unfavorable rainfall and large infestations of FAW. We found no differences in socio-economic characteristics of the households and biophysical characteristics of the fields between Agrics farmers and non-Agrics farmers, suggesting that the subset of farmers interviewed adequately represent smallholder farmers in the regions. More details are given below.

3.1. Characteristics of farm types

Farm types that were constructed significantly differed in off-farm income, age, farm size, and duration of self-sufficiency (Table 3). They may be characterized briefly as: farms with a young household head, well endowed (FT-1); large, medium endowed farms (FT-2); medium endowed with a large share of off-farm income (FT-3); farms with an relatively old household head, less endowed with a larger number of livestock (FT-4); and farms with a young household head, less endowed (FT-5). Most of the female-headed households fell into FT-4 and FT-5. Farm size varied between 0.8 and 3.5 ha, available livestock between 1.3 and 5.1 TLU. The largest share of off-farm income (61.7%) was generated by farmers in FT-3. Food self-sufficiency varies between 4.6 and 10.7 months across farm types.

3.2. Comparison with farm types described in previous studies

In comparison to results from 2003 (Tittonell et al., 2010; Tittonell et al., 2005), livestock numbers and field size reported in Table 3 were much lower, which might be explained by asset subdivision in

Table 3

Means (± standard deviations) per endowment cluster of the age of the household head, farm size, tropical livestock units (TLU), off-farm income and months of food self-sufficiency across farm type.

Farm type	Prop.	Age (years)[*]	Household members (#)	Farm Size (ha)	TLU (#)	Off-farm income (%)	Food self-sufficiency (months)
1	0.18	44.0[c] ± 9.3	4.7[d] ± 2.8	0.8[b] ± 0.5	1.3[c] ± 2.4	33.1[b] ± 10.4	10.7[a] ± 3.3
2	0.10	56.3[b] ± 8.5	6.4[bc] ± 2.2	**3.5**[a] ± 0.5	**5.1**[a] ± 1.4	22.2[c] ± 12.5	7.4[bc] ± 2.1
3	0.13	54.3[b] ± 10.6	**8.0**[ab] ± 1.7	1.0[b] ± 0.5	2.9[b] ± 1.7	**61.7**[a] ± 20.8	5.6[cd] ± 1.9
4	0.25	**62.7**[a] ± 9.7	**8.2**[a] ± 2.3	0.9[b] ± 1.4	3.3[b] ± 3.5	9.1[d] ± 22.3	**8.0**[b] ± 4.3
5	0.34	46.3[c] ± 10.8	6.0[c] ± 2.4	0.9[b] ± 0.7	1.4[c] ± 1.6	13.7[cd] ± 17.2	4.6[d] ± 3.6

[*] : Different superscript letters within columns indicate a significant difference ($P < .05$) determined with the Tukey-HSD test. The highest value is shown in bold.
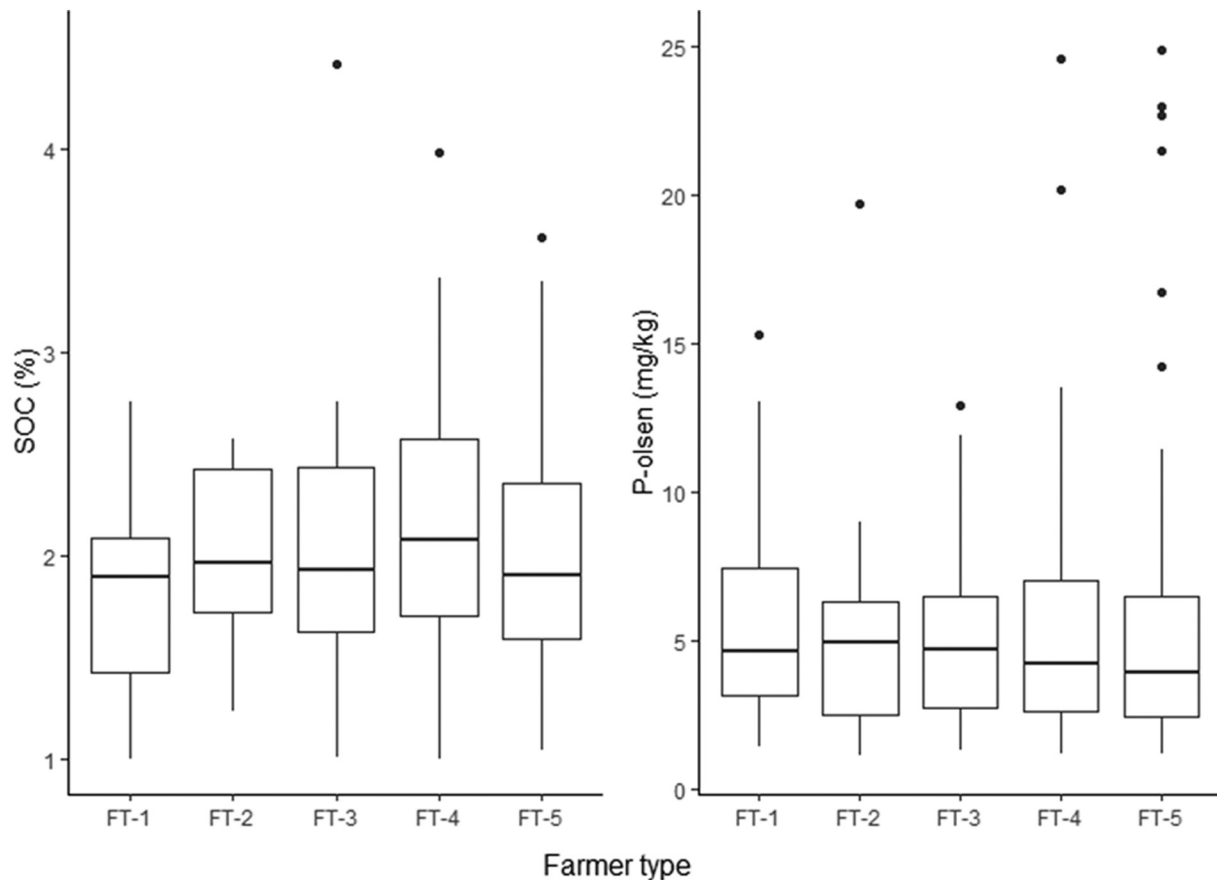

Fig. 1. Boxplots of soil organic carbon content (SOC) and P-olsen content (mg/kg) across the five farm types (FT). Whiskers show the minimum and maximum values; The box shows the 1st and 3rd quartiles; the line shows the median. The dots shows the outliers.

households (Mutoko et al., 2014). Improved food self-sufficiency since 2003 is associated with government subsidy programs for fertilizers and hybrid seeds, and better access to credit and agricultural advice in the study area, both leading to increased crop yields.

3.3. Soil sample analysis

The average SOC and P-Olsen contents of the sampled fields was 1.7% and 3.2 mg/kg, respectively (Fig. 1). No significant differences were observed between plots belonging to different farm types which suggest soil quality is quite even amongst the entire sample. Surprisingly, the SOC content did not correlate with TLU or with the distance between homestead and fields.

3.4. Impact of fertilizer application on maize production

Average fertilizer application in 2017 was 133.2 kg fertilizer N/ha, resulting in an average yield of 3.1 t DM/ha. The non-fertilized plots

this year yielded 1.7 t DM/ha (Fig. 2). The highest yield on fertilized plots was observed for FT-4 (3.3 t DM/ha), while FT-1 had the lowest yield (2.5 t DM/ha). Yield differences between farm types were not significant. The large impacts of FAW infestations were evidenced by strongly reduced plant densities recorded at harvest in 2017 (average of 31,700 plants/ha).

While average fertilizer application in 2018 was 83.7 kg of N/ha (62% of the amount applied in 2017), yields on fertilized plots exceeded those of the previous year with 0.77 t DM/ha. Together, fertilized and non-fertilized plots on average yielded 24% more in 2018. The difference is mainly explained by increased plant density in 2018 (39,918 plants/ha), being 26% higher than density in the previous year. Again, as in 2017, no significant yield differences were observed between farm types (Fig. 2).

3.5. Economic indicators

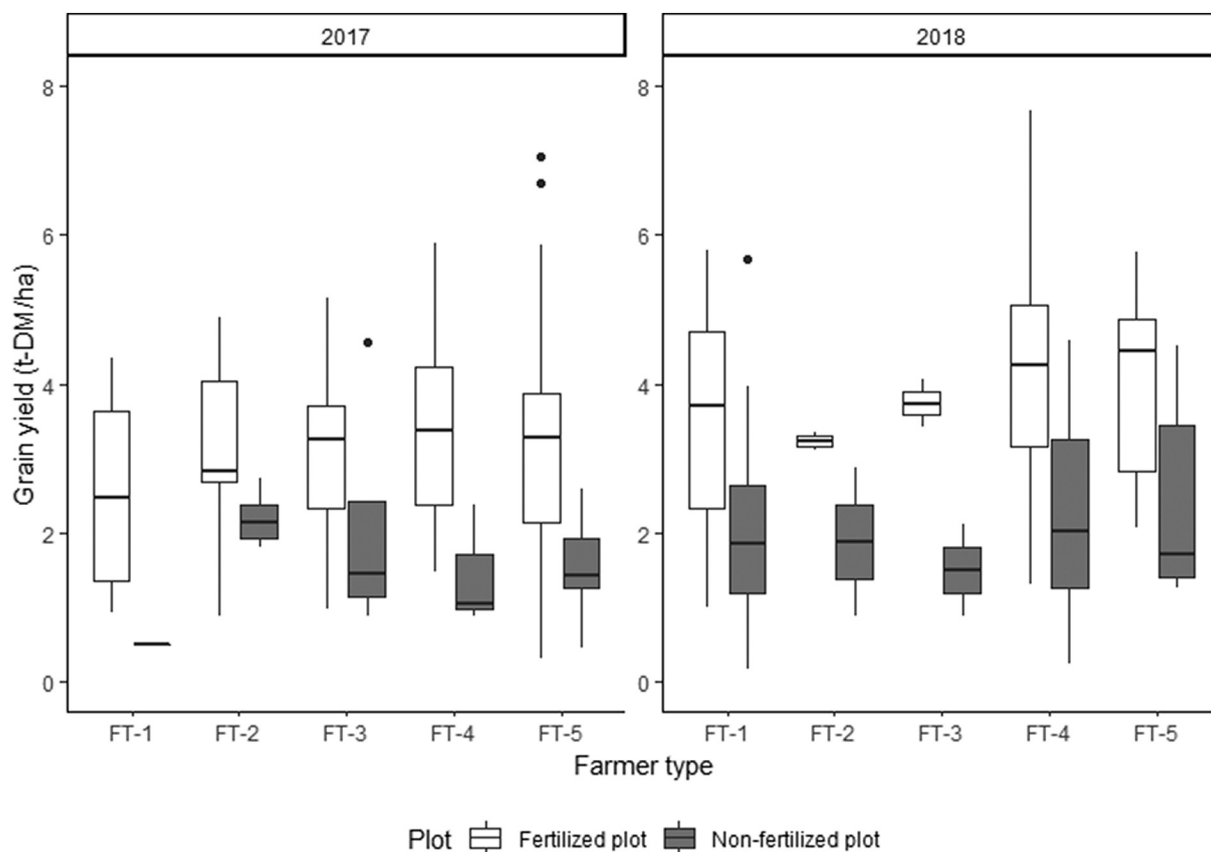The infestation of FAW depressed financial returns in 2017, with

Fig. 2. Grain yield (ton/ha), measured dry matter base in the fertilized plot (white) and non-fertilized plot (gray) in 2017 (left) and 2018 (right) seasons across five farm types (FT). Whiskers show the minimum and maximum values; The box shows the 1st and 3rd quartiles; the line shows the median. The dots show the outliers.

only 45% of farmers reaching the break-even point (BCR > 1) while 9% of farmers achieved BCR > 2 (Fig. 3). Average BCR was 1.28 (± 2.48), and no significant difference in BCR across farm types was found. Only 22% of farmers attained low-risk levels (AVCR > 3), while no farmers reached the break-even point (MVCR = 1) (Fig. 4). The average values for AVCR and MVCR were 2.12 (± 1.15) and 0.011 (± 0.007), respectively. Farm types did not significantly differ in these indicators. Production averaged at 1.30 t of maize grain (DM)/farm with a partial loss of 70.9 USD/farm (Fig. 5). The most severe damage was observed at FT-3, losing 157.2 USD/farm (± 283.3) equivalent to 25.1% of the total annual household income.

In 2018, 80% of farmers achieved a BCR > 2, passing the technology adaptation point, 94% surpassed the risk-neutral point (AVCR > 3 and MVCR > 2). Mean BCR, AVCR, and MVCR were 9.74 (± 5.37), 3.06 (± 1.39), and 4.13 (± 1.78), respectively. The grain: fertilizer price ratio shifted from 0.180 to 0.078 due to favourable seasonal conditions and high crop yields in the second year, affecting the estimates of AVCR and MVCR. However, most farmers had good financial returns in 2018. Observed differences in BCR, AVCR and MVCR between farm types were not significant (p > .1). The average farm production was 0.80 ± 0.46 t DM/farm with a partial profit of 107 ± 78 USD/season. Relatively poor farmers (FT-5) generated 35 ± 43% of their total annual income with extra yields from fertilizer applications.

Most farmers did not apply all fertilizers they purchased in 2018 (Fig. 6), the difference being 8% of the purchased amount. 39% of farmers applied all fertilizers they purchased. The differences between purchased and applied amounts did not differ between farm types.

4. Discussion

Farmers in Kenya need to increase production in order to cover (future) demand for food while satisfying family needs for food and cash earnings. In resource poor regions with large yield gaps, there are no alternatives for fertilizer to improve soil fertility although sustainable intensification has many forms (Struik and Kuyper, 2017). Not all farms are equally equipped to realise enhanced crop output with available land and resources. The results of the second year in this study show that application of N, P and K-fertilizers ensures a good yield response on all farm types, aligning with other studies in the region (Ichami et al., 2019; Njoroge et al., 2019).

Limited access to inputs and unfavorable grain: fertilizer price ratio in East Africa have caused depletion of soil fertility (Ngoze et al., 2008), resulting in low crop yields (Grassini et al., 2013; van Ittersum et al., 2016) and variability in crop fertilizer responses (Kihara et al., 2016; Njoroge et al., 2017, 2019). Availability and use of manure are factors that co-determine residual soil fertility (Njoroge et al., 2019), which is strongly linked to the socio-economic conditions of the farmer (Rufino et al., 2011; Rufino et al., 2007).

Although the relevance of off-farm income in our study is similar to that reported in previous studies (Mutoko et al., 2014; Tittonell et al., 2010), the degree of the dependence on off-farm income across all farm types generally is much lower (except for FT-3) which suggests that on-farm incomes have risen. This could have resulted from the different experimental design between a randomized and unrandomized selection of the samples. While 75% of fertilizer users are found in well-endowed groups in the previous studies (Tittonell et al., 2010; Tittonell et al., 2010), all our farmers in the present work invest in fertilizer and hybrid seeds, implying that their expectation of financial return generated by farming activity is much higher and access to inputs is better.
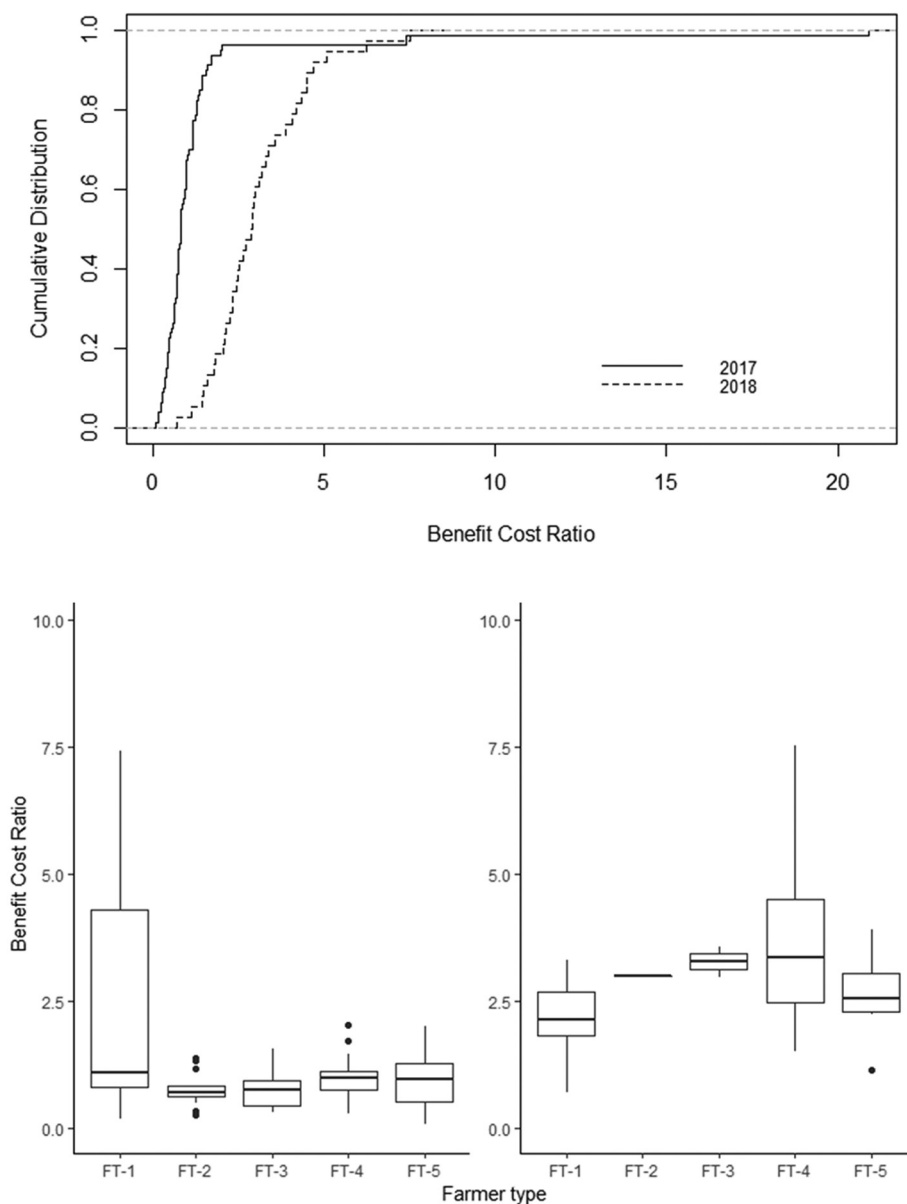
Fig. 3. Cumulative distribution (top) and boxplots (bottom) of Benefit and Cost Ratio (BCR) in 2017 and 2018 seasons across five farm types (FT). Whiskers show the minimum and maximum values; The box shows the 1st and 3rd quartiles; the line shows the median. The dots show the outliers.

It should also be recalled that Tittonell et al. (2010) highlighted the ambiguity of the measurement on the dependence on off-farm income due to difficulties in collecting accurate quantitative income data (data on incomes generally are obtained from interviews with farmers, and cannot be cross-checked).

Farm households have various strategies to improve their livelihoods: expansion, diversification, intensification, increasing off-farm income, or exit from agriculture (Dixon et al., 2001). The outcomes of this study illustrate not only the risks for farmers but also the potential of SI, i.e. increasing fertilizer applications, the use of improved seeds supported by dedicated agronomic advice and its potential impact on crop yields as well as profitability over two years in Western Kenya. It was demonstrated that enhanced fertilizer application could be profitable for all farmers, including those with lower endowments (small farms and low number of livestock), provided growing conditions are not extremely adverse. These results are contrasting to other studies which suggest that expected yield responses to fertilizers on small farms with low animal density and poor soils are often lower (Rufino et al., 2008; Tittonell et al., 2007; Tittonell and Giller, 2013), especially on

outfields located at a larger distance from the homestead (Giller et al., 2011; Tittonell and Giller, 2013). The relatively small variation in maize yield response to NPK fertilizer in our study could be explained by 1) the fact that farmers selected their best fields, i.e. fields where a decent fertilizer response was expected; 2) the relatively small size of most farms (with exception of FT-2 farms) with limited distances to the homestead; 3) a relatively high animal density and manure availability in the region; and 4) the use of NPK fertilizers (Njoroge et al., 2017) and the availability of proper advice and support.

Which farmers, then, are most likely to implement elements of SI under given conditions? Thornton et al. (2018), report that almost half of food-insecure farmers in developing countries are increasing the use of external inputs, yet only 11–14% of smallholder farmers were "stepping-up" and interested in intensifying while 42–70% were "hanging in", and 6–12% were "stepping out". In Western Kenya, these numbers were 20%, 45%, 15%, and 20% respectively according to Valbuena et al. (2015), who studied trajectories of change over 10 years. Thornton et al. (2018) stress the role of a local enabling environment, consisting of supporting organizations, climate information
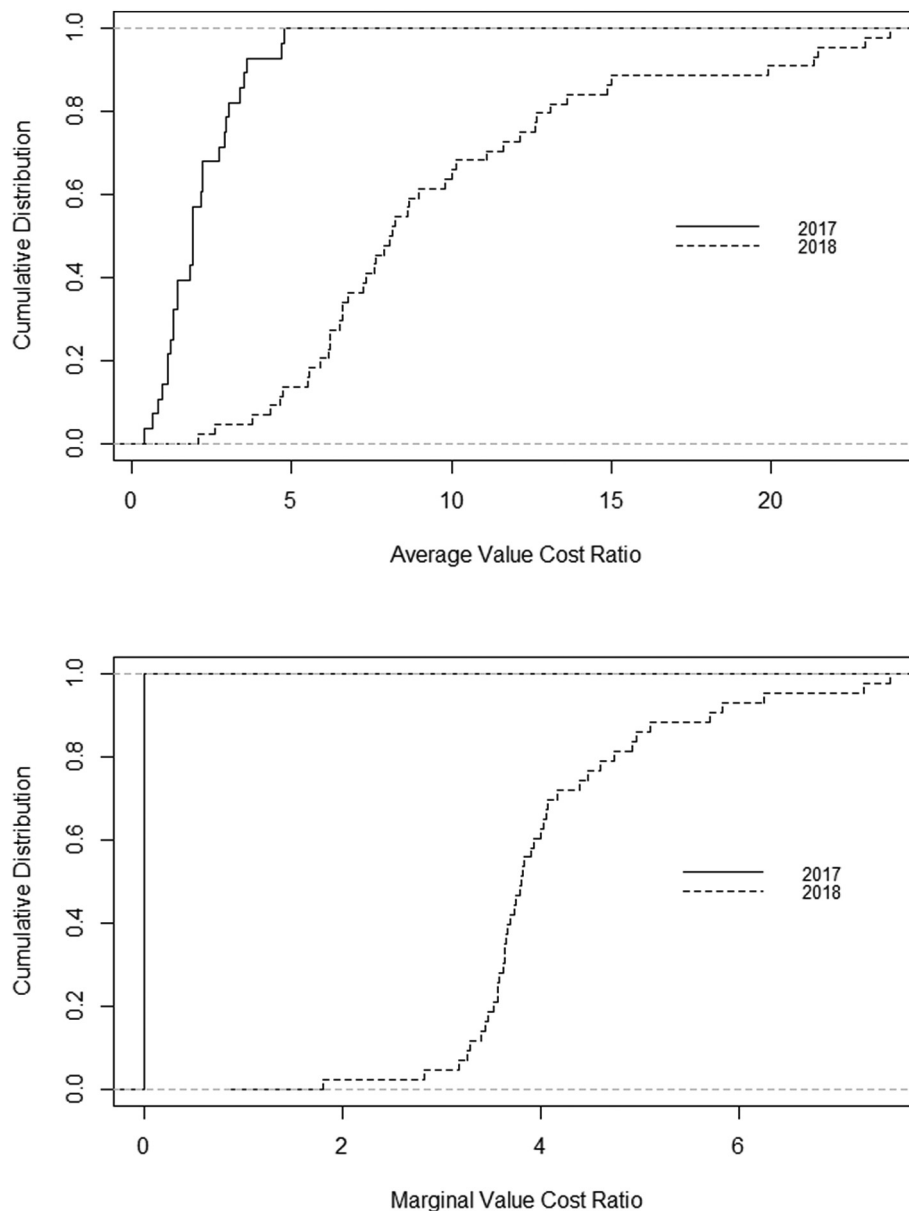
Fig. 4. Cumulative distribution of Average Value Cost Ratio (AVCR) (top) and Marginal Value Cost Ratio (MVCR) (bottom) in two cropping seasons (2017: solid line and 2018: dashed lines).

and community awareness of problems faced by farmers. According to Dixon et al. (2001), the room for intensification will largely be determined by access to credit, seeds, fertilizers and information. Highly variable yields, however, will limit technology adaptation as risk aversion makes smallholder farmers in Kenya hesitant to large investments (Ogada et al., 2014). This is demonstrated in our study by the low profitability of fertilizer applications for 2017, caused by poor rainfall and FAW infestations. Poor smallholder farmers are well known to use a strategy aiming at low risks rather than optimizing yield (Snapp et al., 2003), and intensification in maize-based farming systems under rainfed conditions in SSA countries has been reported to be constraint by risk aversion (Droppelmann et al., 2017; Komarek et al., 2018a).

Only a small number of farmers fully applied purchased fertilizers in plots at the expected rates (Fig. 6), in line with Sime and Aune (2014) who reported that smallholder farmers in Ethiopia generally prefer to apply lower doses than the recommended rates (100 kg/ha of DAP and CAN) to reduce cost and risks. According to Duflo et al. (2011), farmers in Western Kenya may use the fertilizer that was not applied in maize fields elsewhere. Reselling of fertilizers was not reported (Duflo et al.,

2011; Duflo and Banerjee, 2011).

Using farm typology did not pinpoint specific groups applying more fertilizers than other groups due to behavioural heterogeneity. Marenya and Barrett (2009) report that old, female and less educated farmers in Western Kenya applied less fertilizers, suggesting that old fields and poor fertilizer responsiveness, caused by low SOC content, reduced economic returns to fertilizer application. In our study, however, neither SOC nor MVCR in the resource-poor farm types (FT-4 and FT-5) was significantly lower than better-off farm types (Fig. 1 and Fig. 4). The level of education and attitude towards risk aversion are considered important factors determining technology adoption in Western Kenya (Ogada et al., 2014; Wairore et al., 2015). In our case, the education level of the household head was at a similar level across farm types, except for FT-4 with a lower education level when compared to the other farm types ($p < .001$). Moreover, the education level did not result in significant differences in BCR, MVCR, and AVCR. This is in line with Duflo et al. (2008), who observed no link between education level and fertilizer use and its financial return. Education level of the household head in this region is associated with household decision
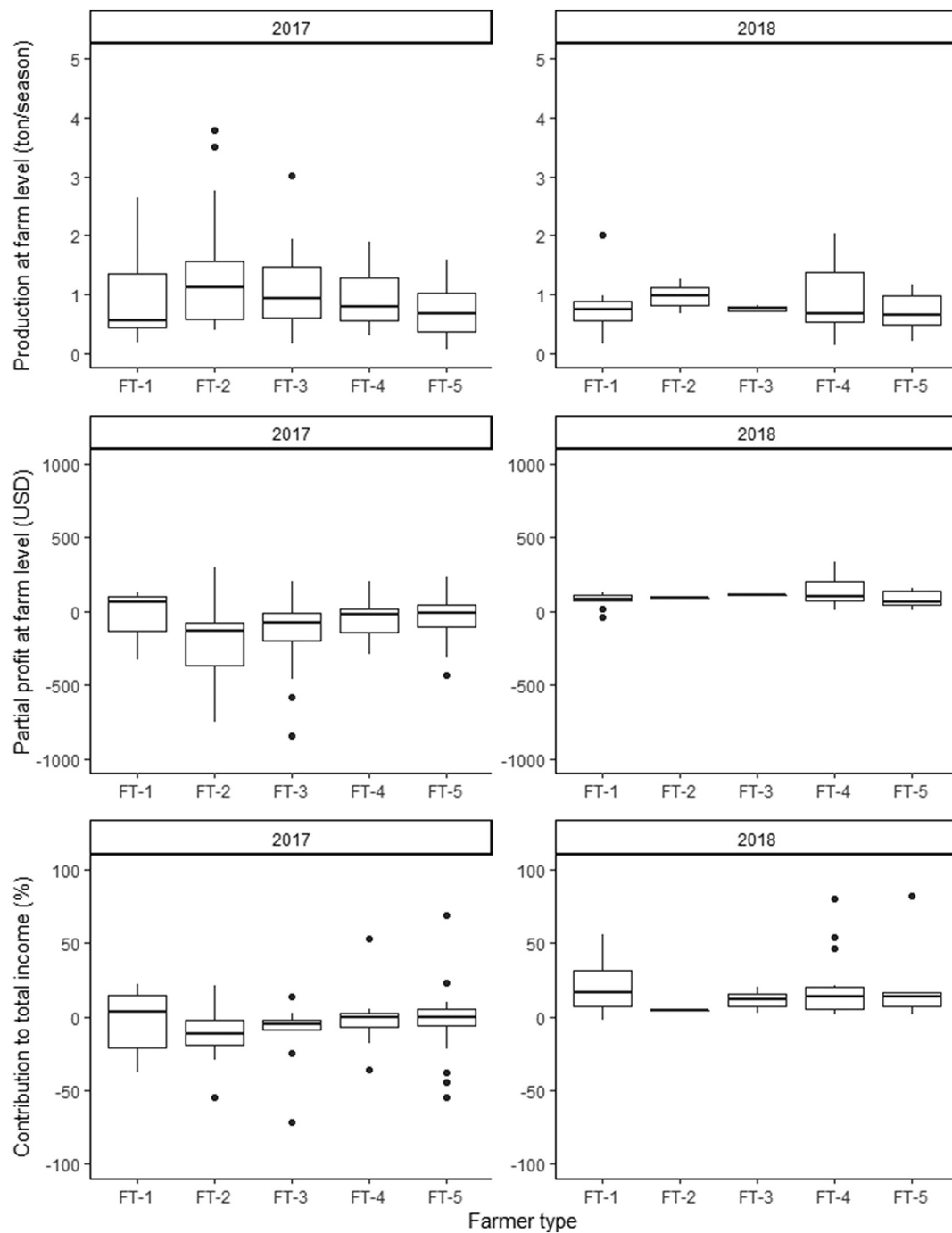
Fig. 5. Impact of fertilizer use on production at farm level (ton/season) (Top), partial profit at farm level (USD/season) (Center), and contribution to total income (%) (Bottom) in 2017 (left) and 2018 (right) cropping seasons across farm types (FT). The box outline shows the 1st and 3rd quartiles; the line in the box represents the median value. Whiskers indicate minimum and maximum values and dots the outliers.

making on the allocation of their resources to off-farm or on-farm activities (Mathenge et al., 2015).

Phosphorus deficiency, frequently observed in the poorest farms in Eastern and Southern Africa (Franke et al., 2016; Franke et al., 2014; Masvaya et al., 2010), did not differ between farm types (Fig. 1). This could be caused by differences in local context with small herd sizes on all farms. An alternative explanation could be that farms have become too small to observe traditional fertility gradients in the landscape resulting from nutrient concentration on homefields by animals.

The profitability of fertilizer use on non-responsive soils in Western Kenya is challenging (Sheahan et al., 2013; Tittonell et al., 2008), low phosphorus contents in acidic soil being the major constraint.

Limitations by strong adsorption can be overcome by the placement of P fertilizer near the seed, strongly improving recovery and uptake (van der Eijk et al., 2006). Njoroge et al. (2018) conclude that NPK fertilizer application on very fertile soils in Western Kenya was not profitable, and AVCR values of 3.1 are only attainable on fields with relatively low control yields. No significant correlation between AVCR and available P content was found in this study, although most soils were below the critical level (10 mg P/kg) (Njoroge et al., 2017).

AVCR and MVCR help to understand profitability as they consider the dynamics of maize and fertilizer prices. These indicators are extensively used to study fertilizer subsidy programs as well as agronomic recommendations for SI policies (Jayne and Rashid, 2013; Koussoubé
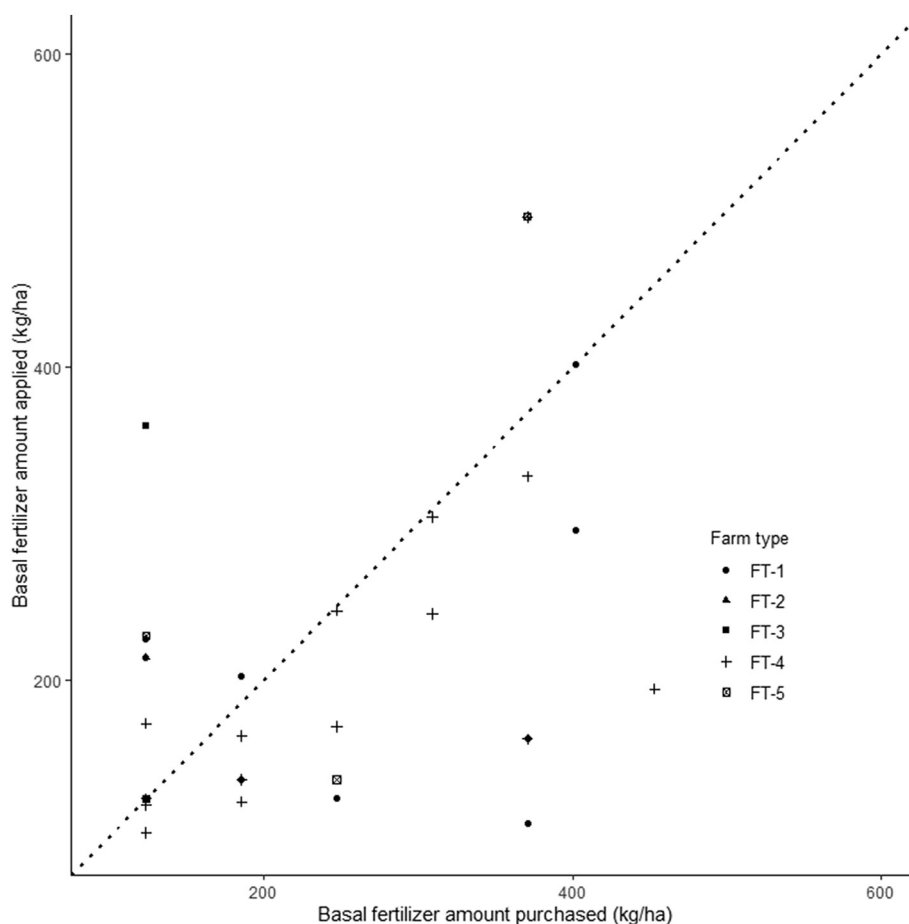
Fig. 6. Comparison between the purchased and applied amount of basal-fertilizer (kg/ha) during the second season (2018) across farm types (FT).

and Nauges, 2017; Liverpool-Tasie et al., 2017; Njoroge et al., 2018). However, neither these indicators (AVCR and MVCR) nor BCR reflect whether the financial return was also generated at farm level. We calculated partial profit and total income at farm level. Low partial profits (Fig. 5) reflect a financial failure where only a small proportion of farms were risk-neutral under rainfed conditions (AVCR≥3, Fig. 4).

Financial gains from fertilizer application in 2018 contributed to 10% to 50% to total household incomes in this year (Fig. 5). Fertilizer application provided financial benefits for all farm types, which is contrasting to findings of Ritzema et al. (2017) who claim that SI in East Africa primarily benefits food-secure and well-endowed households and is offering little perspectives for the most food-insecure-households. Given that fields of resource-poor farmers showed similar biophysical properties and responsiveness to fertilizer (Fig. 1 and Fig. 2), our findings suggest that poor farmers can successfully intensify to overcome food insecurity if they focus on "stepping-up." Particularly in Western Kenya where a wide-range of organizations is focusing on input-intensive management and natural resource management at regional level (Wainaina et al., 2016), different actors (e.g., extension officer, chief, marketer) in farmers' social networks can provide agricultural knowledge and innovation know-how (Adolwa et al., 2017). Strengthening these farmers associations, increasing frequency of farmer encounters (Glover et al., 2019) supported by multi-institutional networks, can be a key factor for capacity building (Kiptot and Franzel, 2019a, 2019b; Kurgat et al., 2018a, b) and trigger synergies between agricultural technology options (Wainaina et al., 2016).

One of the underlying factors affecting yield was household size. Proper field management is important, and family labour availability plays an important role in successful crop management (Kihara et al., 2016). In our study, availability of adult family labour is linked to yield

in 2018 ($p = .01$, see supplementary material Fig. S2). The crucial role of labour for smallholder farming systems is widely reported elsewhere (e.g. Giller et al., 2011).

After collecting data from 13,000 farm households in SSA, Frelat et al. (2016) concluded that household size is a substantial component determining food security. At an average farm size of 0.4 ha, 4.4 MAE is the limit of family size which can provide sufficient food and cash to feed the family; larger households require more land or livestock for food availability. However, the authors did not address the importance of increasing productivity and labour availability for proper field management. In our study, mean yields of large households (MAE > 4.4) was 3.50 ton/ha (± 1.73) in 2017 and 4.17 ton/ha (± 1.61) ton/ha in 2018, while yields for smaller households (MAE < 4.4) were 3.01 (± 0.98) and 3.53 (± 1.24) ton/ha respectively (Fig. S2). This indicates that under good agronomic practices with sufficient labour, suitable pest control, balanced fertilizer application (including N, P as well as K) can provide benefits to all households provided fertilizer costs are low compared to maize prices.

5. Conclusion

On-farm experiments in Western Kenya showed contrasting results over two years: Infestation of the Fall Armyworm and the unfavorable climate conditions in 2017 limited the realisation of the potential of sustainable intensification. The fertilizer application in 2018 resulted in positive economic returns for all farm types under good agronomic practices. Soil characteristics, yield response to fertilizer and BCR showed no significant difference between farm types. Yet, it is expected that smallholders' willingness to take risks and to invest in enhanced fertilizer application in practice is limited. Further study is needed to

identify drivers for SI as well as ways to overcome or limit risks and change risk aversion attitudes in view of profitable fertilizer application. Likely, socio-economic challenges rather than biophysical constraints are most important for countries to address when attempting to increase production on existing farmland.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2020.102831.

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