Field Crops Research 236 (2019) 132–144

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Can yield variability be explained? Integrated assessment of maize yield gaps across smallholders in Ghana

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ARTICLE INFO

Keywords:
Yield gaps
Yield potential
Integrated assessment
Smallholder farms
Crop modelling
Crop experiments
Farm household survey

ABSTRACT

Agricultural production in Ghana should more than double to fulfil the estimated food demand in 2050, but this is a challenge as the productivity of food crops has been low, extremely variable and prone to stagnation. Yield gap estimations and explanations can help to identify the potential for intensification on existing agricultural land. However, to date most yield gap analyses had a disciplinary focus. The objective of this paper is to assess the impact of crop management, soil and household factors on maize (*Zea mays*) yields in two major maize growing regions in Ghana through an integrated approach.

We applied a variety of complementary methods to study sites in the Brong Ahafo and Northern region. Farm household surveys, yield measurements and soil sampling were undertaken in 2015 and 2016. Water-limited potential yield (Y_w) was estimated with a crop growth simulation model, and two different on-farm demonstration experiments were carried out in 2016 and 2017.

There is great potential to increase maize yields across the study sites. Estimated yield gaps ranged between 3.8 Mg ha^{-1} (67% of Y_w) and 13.6 Mg ha^{-1} (84% of Y_w). However, there was no consistency in factors affecting maize yield and yield gaps when using complementary methods. Demonstration experiments showed the potential of improved varieties, fertilizers and improved planting densities, with yields up to 9 Mg ha^{-1}. This was not confirmed in the analysis of the household surveys, as the large yield variation across years on the same farms impeded the disclosure of effects of management, soil and household factors. The low-input nature of the farming system and the incidence of fall armyworm led to relatively uniform and low yields across the entire population. So, farmers' yields were determined by interacting, and strongly varying, household, soil and management factors.

We found that for highly variable and complex smallholder farming systems there is a danger in drawing oversimplified conclusions based on results from a single methodological approach. Integrating household surveys, crop growth simulation modelling and demonstration experiments can add value to yield gap analysis. However, the challenge remains to improve upon this type of integrated assessment to be able to satisfactorily disentangle the interacting factors that can be managed by farmers in order to increase crop yields.

1. Introduction

Agricultural production in sub-Saharan Africa (SSA) should triple to fulfil the estimated food demand in 2050 (Godfray et al., 2010; van Ittersum et al., 2016). In Ghana, as in much of SSA, this is a challenge as yields of food crops are low and productivity is extremely variable and has been stagnating in many areas over recent years (MOFA, 2010). For example, it was estimated that on average, 20% of maize (*Zea mays*) yield potential is achieved across Ghana (GYGA, 2018). In addition, due to climate change, the frequency of drought in SSA is expected to increase (Hulme et al., 2001; IPCC, 2014) and as a result, Ghana's dependence on rain fed agriculture for food production would become more precarious (De Pinto et al., 2012).

Sustainable agricultural intensification is recognised as one of the

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https://doi.org/10.1016/j.fcr.2019.03.022
Received 3 July 2018; Received in revised form 29 March 2019; Accepted 29 March 2019
Available online 09 April 2019
0378-4290/

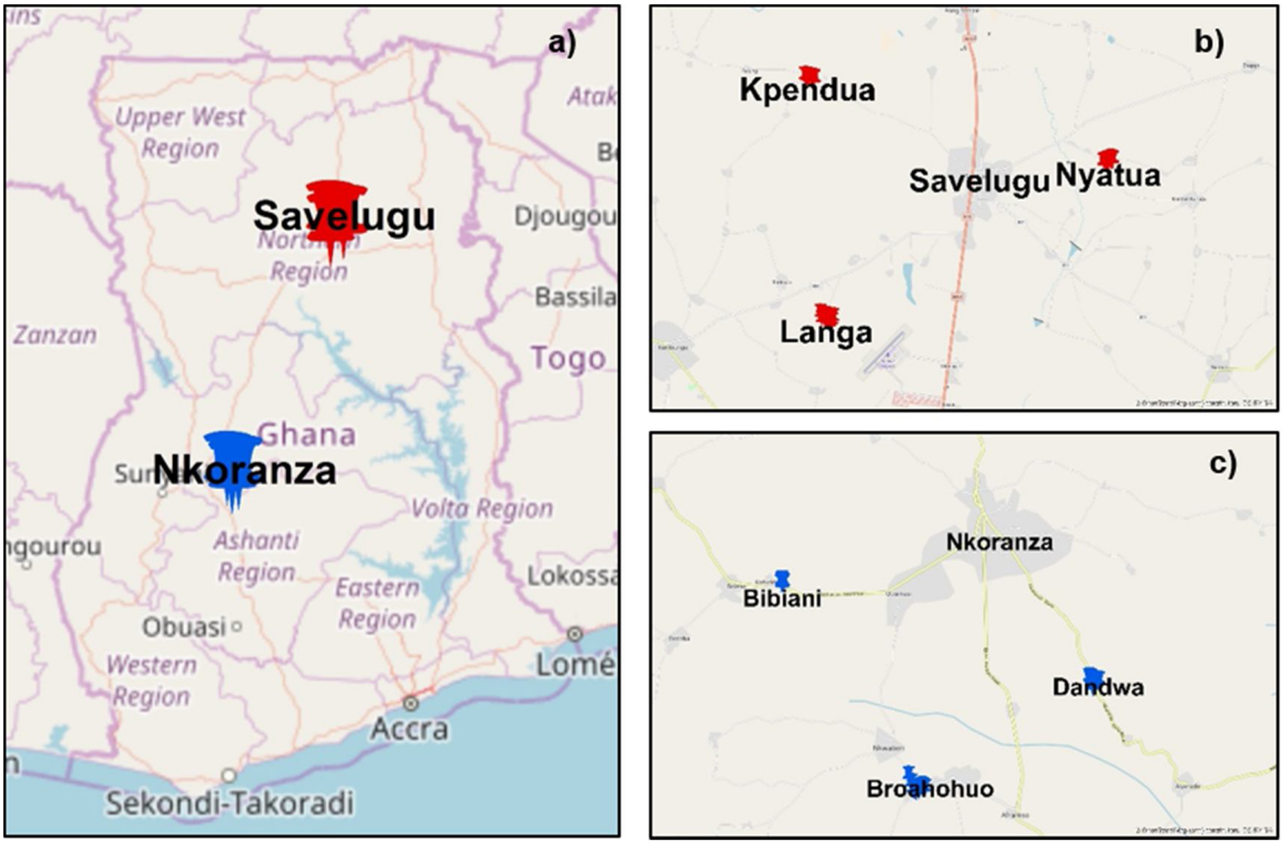

Fig. 1. a) Map of Ghana indicating the location of Nkoranza and Savelugu municipalities in the Brong Ahafo and Northern regions, respectively; b) Location of surveyed villages in Savelugu municipality; c) Location of surveyed villages in Nkoranza municipality.

main strategies for increasing food production (van Ittersum et al., 2016), especially in densely populated areas where the potential to expand agricultural land is limited. Moreover, as experienced in Ghana, available land for farming is becoming increasingly scarce due to population increase and competition with other economic activities (Braimoh and Vlek, 2006).

Yield gap estimations and explanations provide important information on the potential for intensification on existing agricultural land (Laborte et al., 2012; Lobell et al., 2009; Van Ittersum et al., 2013), and provide a starting point for ensuring that intensification happens in a sustainable matter. The yield gap (Y_g) is the difference between actual farmers' yield (Y_a) and yield potential under irrigated (Y_p) or rainfed (Y_w) conditions. Y_p is yield determined by growth-defining factors, i.e. plant characteristics, temperature, CO_2, and solar radiation (Evans, 1996; Van Ittersum and Rabbinge, 1997). Besides the growth-defining factors, Y_w is also influenced by soil type, field topography and precipitation (Evans, 1996; Van Ittersum and Rabbinge, 1997).

A review of yield gap explanation factors indicated that for SSA, fertilization (timing and amount) often explained the yield gap for various crops (Beza et al., 2017). Other analyses found that improving fertilization alone could narrow the yield gap in SSA by 50% (Mueller et al., 2012). In Ghana, increased fertilizer use has been shown to enhance yields, but, a low soil fertility status can limit the yield response (Chapoto et al., 2015). In practice, current fertilizer use in Ghana is low (i.e., on average 5 kg N ha^{-1}) (FAO, 2018) and this has been explained in terms of the risk associated with relatively high costs of fertilizer in relation to the uncertainty in yield gains (Agyare et al., 2014; Sileshi et al., 2010).

Besides fertilization, additional biophysical and socioeconomic factors also contribute to the yield gap. This complexity has been confirmed by studies showing that factors affecting the yield gap can vary substantially between farms (Kihara et al., 2015; Mueller et al., 2012; Silva et al., 2018). Moreover, a body of work analysing technical efficiency of maize producers in Ghana also points to numerous, and varied factors explaining yield differences among farmers, including seed input, agrochemicals, fertilization, labour, farm experience, age, education and access to credit (Appendix A).

The diversity of smallholder farming systems and households in SSA (e.g. in terms of soils, risk perceptions, wealth) (Affholder et al., 2013; Berre et al., 2017; Tittonell et al., 2010, 2007; Tittonell and Giller, 2013) compel one to dig deeper into yield gap analysis. However, until now, most yield gap analyses of Ghana are based on either surveys (Abdulai et al., 2013; Addai and Owusu, 2014; Kuwornu et al., 2013), modelling (Mueller et al., 2012) or field experiments (Sileshi et al., 2010). Integrated assessments, using multiple methods at multiple levels, might be able to unravel some of the complexity experienced by farmers. Causes of yield gaps have been analysed through models and surveys in different countries (Rattalino Edreira et al., 2017; Silva et al., 2017, 2018), but up to now these approaches were not combined with field experiments. Combining the approaches and different levels of analysis (including field and farm level) is expected to result in relevant insight into the factors explaining yield gaps. Our main objective in this study is therefore to assess the impact of crop management, soil and household factors on maize yields and yield gaps in Ghana by integrating different methods and data sources. Subsequently, we aim to identify options that could be used to mitigate yield gaps. We focus on maize production by smallholder farmers because in Ghana agriculture is mainly carried out by smallholder farmers (Chamberlin, 2008) who widely produce maize, a major food crop in the country (Angelucci et al., 2013; Wood, 2013).

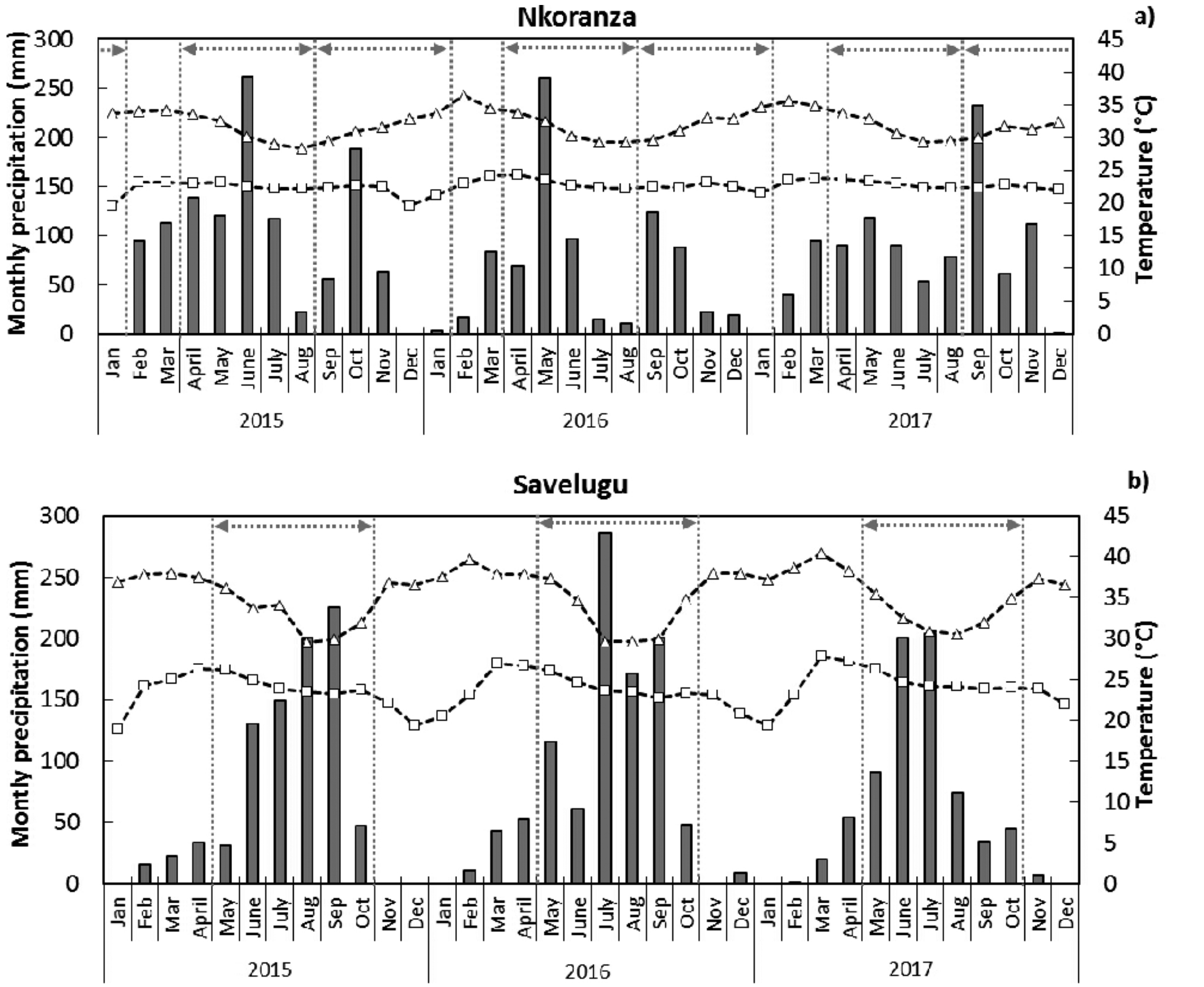

Fig. 2. Monthly precipitation (bars) and average monthly minimum (squares) and maximum (triangles) daily temperatures for 2015 and 2016 in a) Nkoranza (Source: Sunyani weather station) and b) Savelugu (Source: Savelugu weather station). Grey dotted lines and arrows indicate the growing seasons, which last in Nkoranza from September to January (minor season) and from April to August (major season), and in Savelugu from May to October.

2. Material and methods

2.1. Study sites

The study was conducted in 2015, 2016, and 2017 growing seasons in Nkoranza and Savelugu municipalities, located in two different agroecological zones (AEZ) that represent major maize growing regions in Ghana and across large areas of West Africa (Fig. 1). Each AEZ has markedly different agroecological and market conditions.

Nkoranza, located in the Brong Ahafo region of Ghana, is in the forest/savanna transitional AEZ (Fig. 1a). The region experiences a major rainy season commencing in April and a minor rainy season commencing in September (Fig. 2a). This region accounts for the highest proportion of maize production within the country (MOFA, 2015). Data collection in Nkoranza was carried out in three villages, namely, Bibiani (7.55 °N, 1.77 °W), Dandwa (7.52 °N, 1.73 °W), and Broahohuo (7.48 °N, 1.73 °W), which are located eight, five and 12 km away from Nkoranza, the municipal capital, respectively (Fig. 1c).

Savelugu, located in the Northern region, is in the southern Guinea savannah AEZ and has a single rainy season commencing in May and ending in October (Fig. 2b). Data collection was carried out in three villages, namely, Nyatua (9.63 °N, 0.77 °W), Kpendua (9.66 °N, 0.89 °W) and Langa (9.57 °N, 0.89 °W), which are located six, eight and 11 km away from Savelugu, the municipal capital, respectively (Fig. 1b). The villages in both municipalities were selected in consultation with the local agricultural extension agents based on the extent of maize cultivation in the community, proximity to the main capital, i.e. the market, and for representativeness.

2.2. On-farm data

2.2.1. Household survey

Farm household surveys were conducted during the 2015 and 2016 maize growing seasons. The same households were surveyed in both years (as yields and management differ per year), 15 per village and 90 households in total. The selected households represented different wealth statuses within each of the villages. Wealth status was based on, among others, household size, livestock herd size, and farm area. Individuals within the village, with an overview of all households, assisted in categorising the households into low-, medium- and high-wealth categories. Depending on the proportion of households in the three wealth categories in each village, three to eight households within each category were selected to constitute 15 farms per village.

In Nkoranza, each of the selected households were surveyed three times during consecutive maize harvests. Households were visited during the 2015 minor season and both the major and minor seasons in 2016. In Savelugu the survey was conducted during harvest in November in both 2015 and 2016.

The survey included information on the household's socio-economic characteristics, farm characteristics and field-level maize management (Appendices C, D). Questions related to the household included topics on household composition, schooling, farm experience, labour availability, household assets, and off-farm income. Questions related to the farm included farm structure, livestock herd size, and crops grown on each of the plots. Furthermore, questions on management regarding the maize plots included variety, sources of seed, labour, agrochemical inputs and use of maize residues. After the first round of the household survey, the questions related to household characteristics were excluded as we assumed these factors did not change between seasons.

2.2.2. Maize yield measurement

Maize yields were measured in each maize plot belonging to each of the surveyed farmers. In each maize plot, three random areas measuring five by five metres, were selected for sampling. Maize plants were counted to determine plant density at harvest and, cobs were removed, de-husked and marketable cobs counted and weighed. From the marketable cobs, ten were randomly selected, weighed and oven-dried at 70 °C for two days to determine the dry matter content. Maize grain yield data are presented with a correction for moisture content of 12%.

2.2.3. Soil sampling and analysis

Soil was sampled from every maize plot in the household survey. Soil samples were randomly collected at four sites within each field. Samples were taken from 0 to 20 cm depth in a y-shaped manner. These were bulked and a composite sample was taken for analysis. The samples were air dried, sieved with 2 mm mesh and analysed for both physical and chemical properties at the Soil Research Institute of Ghana in Kumasi. The chemical properties analysed were: organic matter content (Walkely Black Procedure), total N (Kjeldahl method), plant available P (Bray-1 method), exchangeable cations (K, Mg, Ca, Na) (1 M NH_4OAc method) and micro-nutrients (Fe, Mn, Cu and Zn; ammonium acetate-EDTA extractable method). During the first round of the survey, soil samples were taken on every maize plot. Given that maize plots were not necessarily the same in every season, soil samples were only taken in the next season if farmers cultivated maize on a different plot, with the assumption that the soil status was unchanged for plots which were the same.

2.2.4. Demonstration experiments

In 2016 and 2017 two demonstration experiments were carried out on four farmers' fields in each of the selected villages, experiments and years (Appendix B). Two villages from each Nkoranza and Savelugu were selected in 2016, and in 2017 again two from Savelugu, but three villages from Nkoranza were selected. In Nkoranza, in 2016 the experiment was conducted in the minor season and in 2017 in the major season. The experiments in 2016 included 16 farmers and those in 2017 included 20 farmers (Appendix B); selection of the farmers was based on accessibility of the plot and willingness of the farmer to donate a plot.

In experiment 1, we tested the effect of recommended and farmers' planting density, at three different fertilizer application rates, on maize yield. The recommended planting density was 5.33 plants m^{-2}, and each of the participating farmers chose their own planting density. For each of the planting densities an N:P:K (23:10:5) fertilizer was applied at rates 0, 250, 375 or 500 kg ha^{-1}. These treatment combinations resulted in a total of eight treatments per farm. A treatment plot measured 10 by 12 m. The hybrids Pannar (variety Pannar 53) and Proseed were used in 2016 and 2017, respectively, on all plots.

In experiment 2, we compared the performance of three improved maize varieties with the local maize variety being cultivated by farmers. The maize varieties used were the farmers' local variety, a drought tolerant maize (open pollinated variety), Obatanpa (the recommended open pollinated variety) and a hybrid (Pannar in 2016 and Proseed in 2017). In total there were four treatments, and a treatment plot measured 10 by 12 m. The recommended planting density of 5.33 plants m^{-2} was used on all plots.

In 2016, there was an outbreak of fall armyworm (*Spodoptera frugiperda*) in both Nkoranza and Savelugu with the incidence being more severe in Nkoranza than in Savelugu. The pest was controlled in Nkoranza using K-Optima EC ® (Acetamiprid, 20 g l^{-1}) and Lambda cyhalothrin (16 g l^{-1}), a systemic insecticide and in Savelugu with Sunpyrifos 48 EC® (Chlorpyrifos ethyl, 480 g l^{-1}). Two different chemicals were used based on their availability. In experiment 1 in both 2016 in Nkoranza and 2017 in Savelugu, yield data from only three farms were obtained, because of the outbreak completely destroyed the maize crop in one of the fields.

For both demonstration experiments maize yields were determined in the same way as during the household survey (Section 2.2.2). Farmers' field days were held in each of the villages where the experiments were running at three different periods during crop growth: first fertilizer application, tasselling, and harvest. During the field days in 2016 there were on average 57 participants per field day, resulting in a total attendance of 680. In 2017, there were on average 47 participants per field day, resulting in a total attendance of 713. During the field day at harvest, group discussions were held to rank the different treatments based on farmers' preferences, and a final ranking was obtained based on a general consensus among the group.

2.3. Yield gap concepts and determination

Since maize production by smallholder farmers in Ghana is mainly under rain fed conditions, we took the water-limited potential yield (Y_w) as a benchmark. The yield gap (Y_g) in this study was thus defined as the difference between Y_w and the farmers' average actual yield (Y_a) (Van Ittersum et al., 2013). We refer to the relative yield gap (%) as equal to $[1\text{-}Y_a/Y_w] * 100$. Next, we defined the highest farmer yield (Y_{hf}), which is the average yield above the 90^{th} percentile (Silva et al., 2017). Farmers' average actual yield (Y_a) and Y_{hf} were based on the measured maize yields from the household survey (section 2.2.2). To estimate Y_w for Nkoranza and Savelugu for the 2015 and 2016 seasons we used the crop growth simulation model Hybrid-Maize (Yang et al., 2004 2006), which has been successful in simulating maize yields under various environmental conditions (Grassini et al., 2015; Meng et al., 2013), including Ghana (Van Ittersum et al., 2016). Details on model calibration and testing can be found in Grassini et al. (2015); Meng et al. (2013); Van Ittersum et al. (2016). The model simulates maize development and growth using a daily time-step, based on temperature driven development, temperature-sensitive maintenance respiration, vertical canopy integration of photosynthesis, and organ specific growth respiration.

Daily weather data for 2015 and 2016 were obtained from the Savelugu weather station and, in the case of Nkoranza, from the Sunyani weather station.

We used the same protocol for determination of the simulated sowing date and the planting density as that published in the Global Yield Gap Atlas (Grassini et al., 2015; GYGA, 2018; van Bussel et al., 2015). For sowing, this means that it was done when cumulative rainfall was > 20 mm within seven consecutive days in the specified sowing window, as defined by the local agronomist from the Global Yield Gap Atlas (Dobor et al., 2016; Wolf et al., 2015). Planting density was obtained from the actual average water deficit in the region and the relation between seasonal water deficit and planting density (Grassini et al., 2009). A generic maize variety was used, with growing degree days specific for the area.

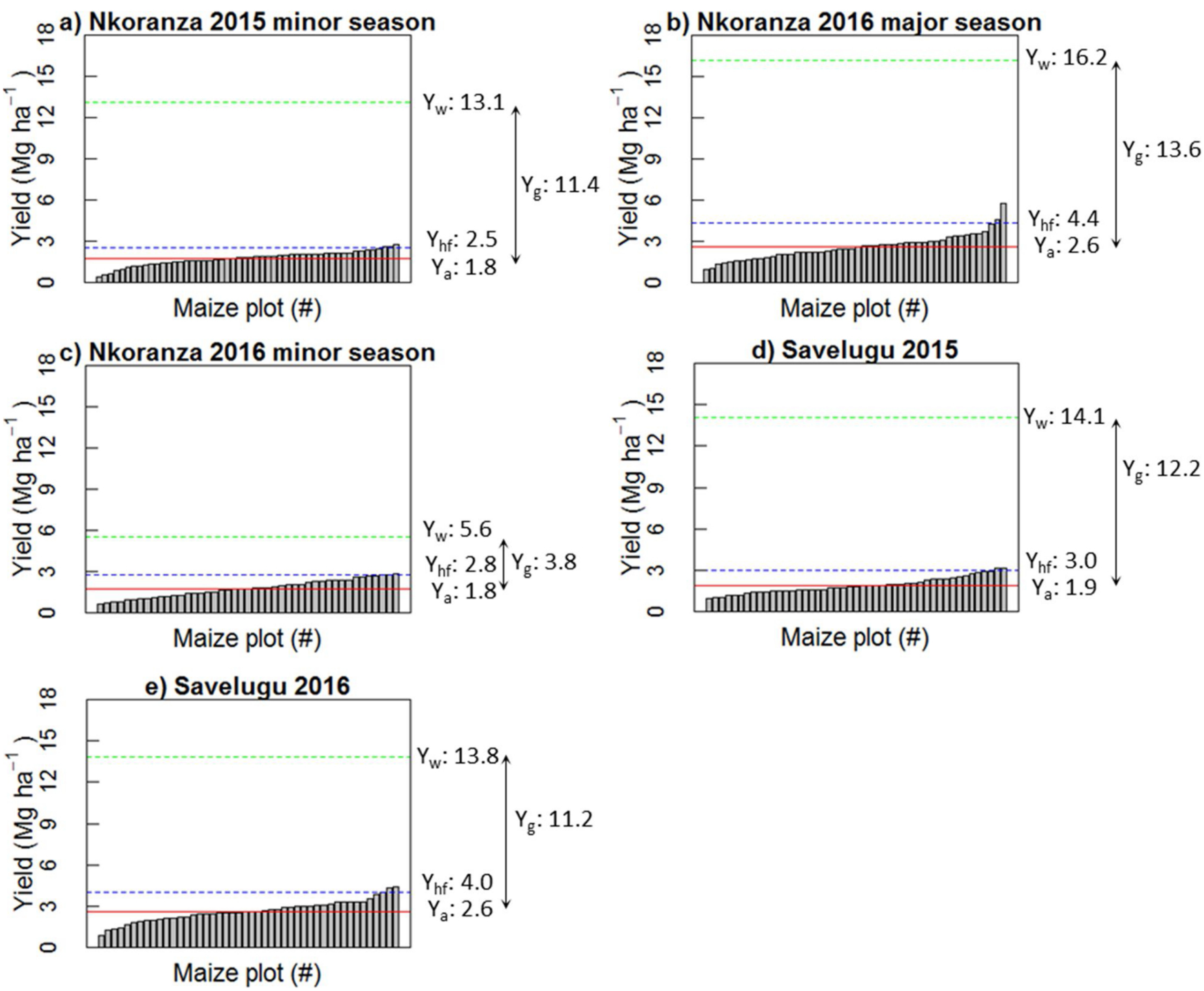

Fig. 3. Actual maize yields of plots for a) 2015 minor season in Nkoranza; b) 2016 major season in Nkoranza; c) 2016 minor season in Nkoranza; d) 2015 main season in Savelugu and; e) 2016 main season in Savelugu. The red continuous line is the average farmers' yield (Y_a), the blue dashed line is the highest farmers' yield (Y_{hf}) as defined by the average yield above the 90th percentile, and the green dashed line is the simulated water-limited potential yield (Y_w). The arrows indicate the yield gaps (Y_g). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2.4. Statistical analysis

Quality control of the data was done in consultation with the persons carrying out the household survey. Suspicious data or outliers were verified at households involved and rectified if needed. If deviations could not be traced back, they were considered an outlier and removed when the value was outside the range of the mean +/- 3 times the standard deviation (McClelland, 2000). Different methods were used to study variance in yield, and crop management, soil and household variables.

First, to test for significant differences between seasons and municipalities in crop management, soil, and household factors, Least Significant Difference (LSD) tests were performed using the agricolae package in R. Correlation analysis was performed on the yield data to test for relationship per plot and per farm (based on average yield) between the different seasons.

Second, to visualise patterns in the data and to explain variance in yield and crop management and soil factors, a Principle Component Analysis (PCA) was performed using the Ade4 package in R. Five PCAs were performed: Nkoranza 2015 (minor season), Nkoranza 2016 (major season), Nkoranza 2016 (minor season), Savelugu 2015 and Savelugu 2016.

Third, to test which factors significantly affected maize yield, multiple linear regression (MLR) was performed using the stats package in R. The MLR models had yield as the response variable and either the crop management, soil, or household factors as predictor variables. As with the PCAs, the MLR analyses were performed for each season and municipality combination and, variables with a large number of missing values were excluded from the analyses. In addition, a model was tested including both nutrient management and soil factors together. Including all factors and interaction was not feasible, because of limited degrees of freedom. Factors which caused collinearity were not included in the MLR model (selection was based on Variance Inflation Factor, using vifstep from the usdm package in R). Both PCA and MLR analyses were performed for each season and municipality combination separately, as the factors which affect maize yield were expected to differ for each of the seasons and municipalities. We also performed pooled analyses using multi-level models, in which both season and municipality were included as random factors. These models did not provide additional insights and results are therefore only presented in Appendix I and not discussed in the paper.

Finally, to test for significant differences between pairs of treatments in the demonstration experiments a LSD test was performed.

3. Results

3.1. Farming system characteristics

In Nkoranza, the households were characterised by their small family size, numbers of livestock and total farm area. This contrasts to Savelugu, where households had significantly more members, owned greater numbers of livestock and had larger total farm areas (Appendix C). In Nkoranza, rental of land for maize cultivation was fairly common, while this was not the case in Savelugu (Appendix D). Both municipalities also had similar characteristics: the use of inputs (fertilizer, manure, seeds, and herbicides) was comparably low (Appendices C, D); next to herbicide no other agrochemicals were used; and the majority of the farmers used their own seeds saved from previous harvests and only a minority used certified improved seeds.

The soil texture of all maize plots in Nkoranza and Savelugu was sandy or sandy loam. The soils in Nkoranza were generally more fertile with more available soil P, and higher percentages of N and organic matter compared to Savelugu (Appendix C).

3.2. Maize yields and maize yield gaps

The simulated Y_w were generally high, reaching 16.2 Mg ha^{-1} in the 2016 major season in Nkoranza (Fig. 3b) and 14.1 Mg ha^{-1} in 2015 in Savelugu (Fig. 3d). A comparison with a previous, long-term modelling study from the same regions confirmed that these values fall at the top of the range of attainable yields (GYGA, 2018). In both municipalities, these high values are largely explained by the high amount of well-distributed rainfall during the season. In the 2016 major season in Nkoranza the total precipitation was 538 mm while estimated reference evapotranspiration was 663 mm. In Savelugu, in both 2015 and 2016, total precipitation (608 mm and 585 mm, respectively) slightly exceeded evapotranspiration.

The yield gap (Y_g) was large in all season and municipality combinations, except for the 2016 minor season in Nkoranza (Fig. 3). Here the relative yield gap was 68%, while for the other season municipality combinations it ranged from 81% to 87%. The low relative yield gap in the 2016 minor season in Nkoranza (Fig. 3c) was the result of a lower Y_w due to water limitation. The water limitation ($[1 - Y_w/Y_p] * 100$) was 60% for the 2016 minor season in Nkoranza, while it was less than 4% in the other season and municipality combinations presented here. For each season municipality combination, the simulated and the actual lengths of the growing seasons were similar. However, in Savelugu the simulated sowing dates were substantially earlier than the farmers actual sowing dates (day of year 152 versus 199 in 2015; day of year 155 versus 182 in 2016). This difference in sowing dates contributed to the large difference between Y_w and Y_a.

Overall, Y_a was similar between the two municipalities (Fig. 3, Appendix C). Within Nkoranza, Y_a was significantly higher in the 2016 major season compared to the minor seasons in 2015 and 2016 ($P < 0.01$). In Savelugu, Y_a in 2016 was significantly higher than that in 2015 ($P < 0.01$).

For both municipalities, there was not a significant relationship between yields from different seasons in the same plots (Fig. 4), and also not between the yield from different seasons when averaged per household (Appendix E). These unexpected results show that farmers obtaining high yields in one season did not necessarily obtain high yields in other seasons.

3.3. Principle component analysis

Maize yield did not make substantial contributions to any of the PCs. Whereas, relations between yield and other variables were detected (Fig. 5, Appendix F, G), there was no consistency across seasons and sites. In the 2015 minor season in Nkoranza, yield was positively correlated with the amount of organic matter in the soil but negatively correlated with nutrient inputs (Fig. 5a). In the 2016 major season in Nkoranza, yield was negatively correlated with cation exchange capacity (Fig. 5b) and in the 2016 minor season, negatively correlated with the amount of organic matter in the soil (Fig. 5c). In 2015 in Savelugu, yield was positively correlated with nutrient inputs and negatively correlated with the percentage of clay in the soil (Fig. 5d), while in 2016 there was a positive correlation between yield and the percentage of clay in the soil (Fig. 5e).

3.4. Factors affecting maize yield

Results from the MLR analysis were not consistent across seasons and municipalities (Table 1 and Appendix H). This is not surprising, because there was no correlation between yields from different seasons on individual fields or farms (Fig. 4, Appendix E).

The MLR models with the most explanatory power in general were those based on the combination of nutrient management and soil factors, where the R^2 values ranged from 0.45 to 0.84 (Table 1). Individual factors that were statistically significant within the models predominantly related to soil variables and these varied between each model.

In general, there was not a strong and positive relationship between N input and yield, except in 2015 in Savelugu (Fig. 6). Likewise, the other crop management variables included in the MLR analysis did not help to explain the variation in yield. Plant density at harvest had a significant effect on yield in three models. With respect to the household factors, the only significant, and consistent result from the MLR was that in Savelugu, for both seasons, there was a positive effect of livestock herd size (TLU) on yields.

3.5. Demonstration experiments

Demonstration experiment 1, to test the effect of planting density at different fertilizer rates, showed fertilizer application resulted in higher maize yields compared to the treatment without fertilizer (Fig. 7; $P < 0.01$). This was not the case for the 2016 minor season in Nkoranza, where no significant differences were found between any of the treatments (Fig. 7a), which was probably due to the severe yield reduction across all plots due to the fall armyworm outbreak. Across all sites, there was no significant difference in yield when comparing application rates of 500 kg ha^{-1} and 375 kg ha^{-1} ($P = 0.65$). During the group discussions of the field days the farmers indicated that 375 kg ha^{-1}, i.e. equivalent to 86.25 kg N ha^{-1}, was their preferred fertilizer application rate (Table 2), which is much higher than the farmers reported average application rate of 27 kg N ha^{-1} (Appendix C).

No clear effect of planting density on yield was found in all municipality and season combinations (Fig. 7). Nevertheless, farmers indicated that they preferred the recommended planting density in Nkoranza in both 2016 and 2017 and in Savelugu in 2016 (Table 2). This preference led to farmers' planting at higher densities in the 2017 round of the experiment, thus potentially impacting the comparison of results for that year. Looking at all factors together, farmers mentioned they preferred the combination of 375 kg ha^{-1} of fertilizer, together with the recommended planting density and the hybrid seed.

Yield was high (up to 9 Mg ha^{-1}) in the 2017 major season in Nkoranza across all treatments compared with the other season municipality combinations and when compared to yield levels found in the survey. This is probably the result of the use of hybrid seeds in 2017. The hybrid was also used in 2017 in Savelugu, but here, most likely due to drought at the end of July and beginning of August, yield levels were similar to those in 2016.

Demonstration experiment 2 showed some differences in yield due to the maize varieties planted (Fig. 8). In the minor season in 2016 in Nkoranza, there was no significant difference among the different varieties (Fig. 8a), while in Savelugu in 2016, the hybrid Pannar had a significantly higher yield than the farmers' variety (Fig. 8b) ($P = 0.04$).

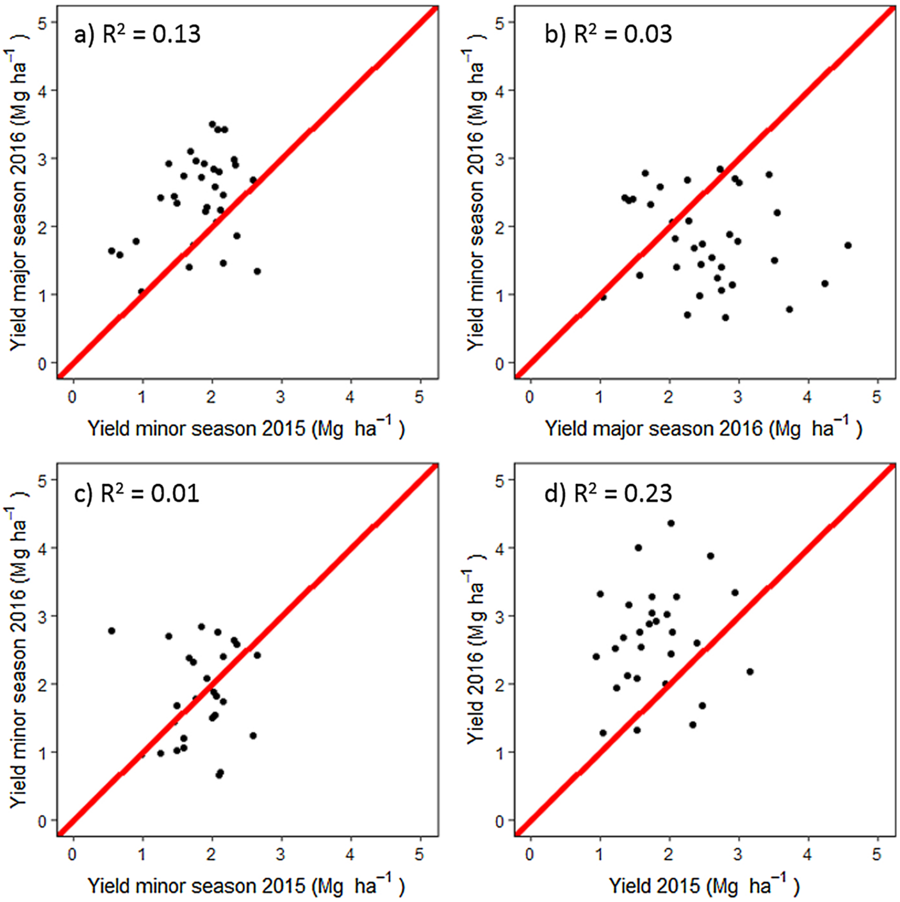

Fig. 4. Comparison between seasonal maize yields per plot in a) Nkoranza – the 2016 major season versus the 2015 minor season (Spearman's rank correlation = 0.27, $P =$ 0.14); b) Nkoranza – the 2016 minor season versus 2016 major season (Spearman's rank correlation = -0.16, $P =$ 0.35); c) Nkoranza – the 2016 minor season versus 2015 minor season (Spearman's rank correlation = 0.17, $P =$ 0.39) and; d) Savelugu – the 2016 versus 2015 main season (Spearman's rank correlation = 0.20, $P =$ 0.29). The continuous lines are the 1:1 lines.

In 2017, in both Nkoranza and Savelugu, the hybrid Proseed resulted in significantly higher yields than the other three varieties in the experiment (Fig. 8) ($P < 0.01$ for both municipalities). Despite the high yield of Pannar in 2016 the farmers indicated during the group discussion at harvest that they preferred the drought tolerant maize because those seeds are less expensive and can be recycled (Table 2). Proseed was preferred in 2017 due to the high yields, but farmers indicated that the price of the seeds is not within their reach (Table 2).

4. Discussion

The large yield gaps observed in this study in Nkoranza (i.e., 69% and 76% in the minor and major season) and Savelugu (Y_g was 75%) municipalities show that there is substantial potential to increase maize yields in the study sites and, more broadly across the forest/savannah transitional and southern Guinea AEZs. This is consistent with what has been found for the whole of Ghana, for which the average yield gap is 80% (GYGA, 2018). However, despite the large potential to increase the maize yield in Nkoranza and Savelugu municipalities in Ghana, we did not find consistency in factors that have impact on maize yields and yield gaps when combining data sources and methods of analyses across sites, seasons and levels of analysis. In a review of yield gap analyses, Beza et al. (2017) showed that, across studies, explanations of the yield gap often differ which can be a result of the factors considered in each study. In discussing our results, we used the framework of van Ittersum and Rabbinge (1997), which groups potential causes of the yield gap into growth-defining, growth-limiting and growth-reducing factors. We also discuss the challenging aspects of the results and the methodological, practical, and policy implications of this study.

4.1. Growth-defining factors

The demonstration experiment showed higher yields could be obtained when improved maize varieties are used (up to 9 Mg ha^{-1}), although this effect was not always observed (Fig. 8, Fig. 7b). Other studies confirm the potential of improved varieties compared to farmer-saved seeds (Asiedu et al., 2008), under favourable production environments, including good management (Adu et al., 2014). Nevertheless, all farmers from the survey used open pollinated varieties and saved their seeds for subsequent seasons. This is attributed to the lack of cash at planting to obtain seeds in combination with the prohibitive cost of hybrid seeds, as they explained during the group discussion.

The demonstration experiments did not confirm that the recommended planting densities out-performed farmers' planting densities in terms of maize yield. However, farmers perceived that increasing planting density did increase yield as they observed more plants per unit area (Table 2). Interestingly, those participating in the experiment changed their behavior and increased their planting density in the second year of experiment 1. From farmers' fields, we do not have precise data on planting densities, which hinders clear conclusions.

4.2. Growth-limiting factors

According to model simulations, water supply was only substantially limiting crop growth during the 2016 minor season in Nkoranza. The favourable conditions are reflected in the high simulated values for Y_w (GYGA, 2018). It is possible that these simulations underestimated water limitations on individual farmers' fields as they were based on precipitation recorded at a single weather station for each municipality.

Analysis of the farm survey data did not clearly show that the use of fertilizer increased maize yields for any of the municipality and season

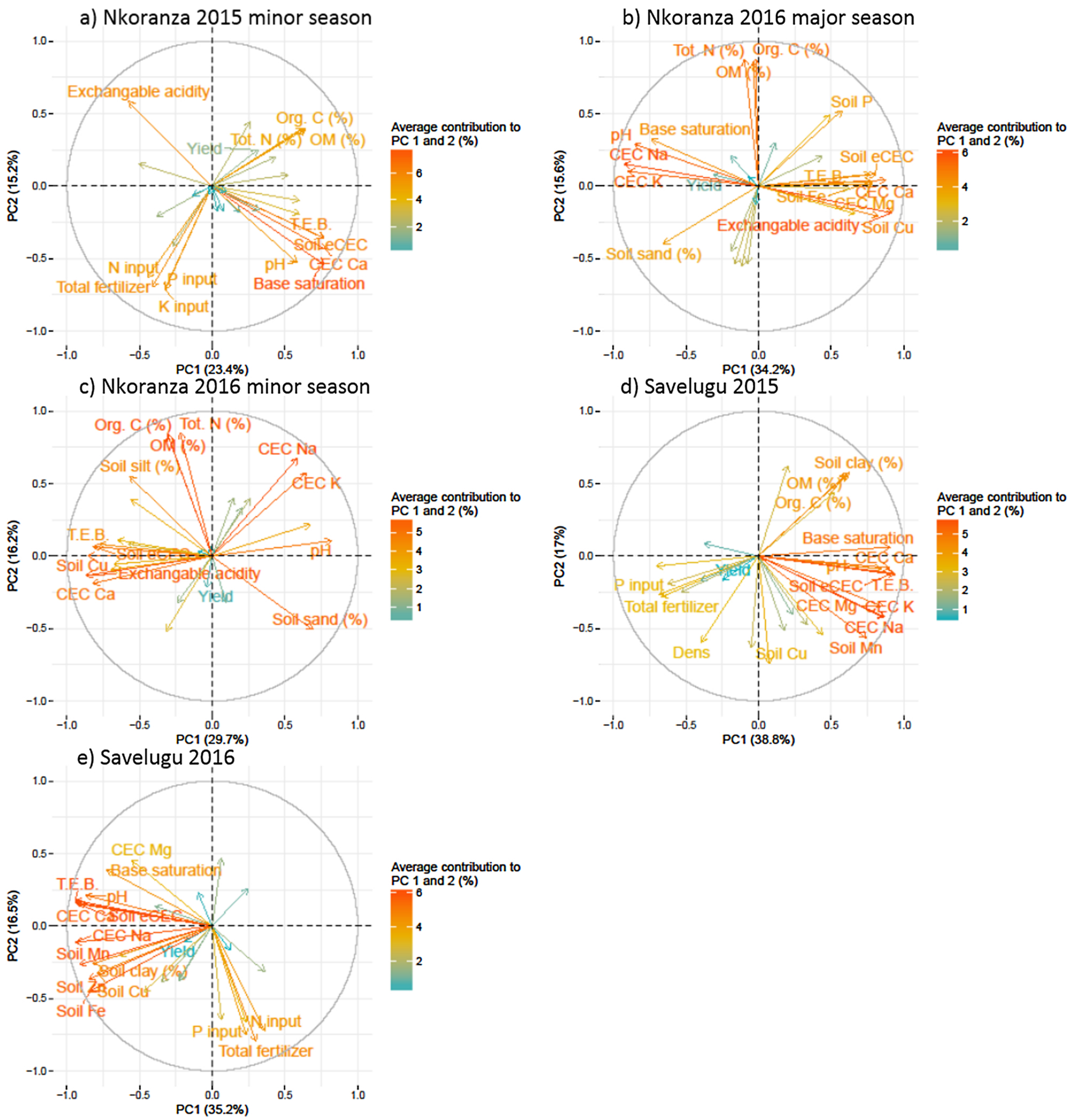

Fig. 5. Plots showing the relation between, and contribution of, different variables to the first two principle components (PC1 and PC2) for a) 2015 minor season in Nkoranza; b) 2016 major season in Nkoranza; c) 2016 minor season in Nkoranza; d) 2015 main season in Savelugu and; e) 2016 main season in Savelugu. Variables with latent vectors less than 0.5 (with the exception of yield) are not labelled (a variable with a latent vector with a value close to one indicates that the variable makes a large contribution to the component axis). The average contribution to PC1 and 2 (%) = [(C1 * Eig1) + (C2 * Eig2)] / (Eig1 + Eig2), where C1 and C2 are the latent vectors and Eig1 and Eig2 are the eigenvalues for PC1 and PC2, respectively. The correlation matrix of latent vectors is provided in Appendix G. The percentage of variance explained by each principle component is presented on the axis labels in brackets (see also Appendix F).

combinations, while in the demonstration experiments fertilizer did increase yields (Fig. 7 versus Fig. 8). A possible explanation for the differences in yield response to fertilizer between the household survey and the demonstration experiment could be the low fertilizer application rates applied on farmers' fields (i.e., on average 27 kg N ha^{-1}; note this is substantially more than the 5 kg N ha^{-1} reported as average N input in Ghana by the FAO (FAO, 2018)) compared to the fertilization rates used in the demonstration experiments (i.e., ranging between 57.5 and 115 kg N ha^{-1}). It is thus not a great surprise to see such low rates having minor effects on yields. Moreover, several management and environmental factors that interact with fertilizer input (Getnet et al., 2016) were controlled for in the demonstration experiment, namely sowing density, time of fertilizer application, crop variety and pest control (Tittonell et al., 2008). Thus, the value of combining these results lies in the implication that at least a minimum rate of fertilizer should be supplied to positively impact yields.

4.3. Growth-reducing factors

Our study lacked sufficient data to analyse the impact of pest

Table 1
Significant factors from the multiple linear regression models of crop management, soil and household factors which affect maize grain yields in Nkoranza and Savelugu for the different seasons. Estimates of each of the factors are given and the significance stated: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, + $P < 0.1$. R^2 of the models and the number of observations (n) are provided below the response variables. An x in the table indicates that the variable was excluded from the analysis due to a large number of missing values. The full regression model can be found in Appendix H.

	Nkoranza			Savelugu	
Crop management	*Minor season - 2015*	*Major season - 2016*	*Minor season - 2016*	*Main season - 2015*	*Main season - 2016*
Plant density (harvest)	−0.14	0.83***	0.77**	0.07	0.54*
N input	−0.08*	0.00	−0.04	0.08**	0.02
Model R^2	0.30	0.36	0.37	0.40	0.38
n	36	46	34	42	40
Soil					
Mn	−0.39*	−0.26+	−0.08	x	x
Percentage silt	0.96	1.30*	−0.95	2.06	−0.66
CEC K x exchange acidity	0.65	1.20	−0.36	0.50	2.54*
Soil P x Cu	−1.36	−0.29	−1.17+	2.44	0.90
CEC Mg	9.53	0.11	1.96	−6.15	0.04
CEC Ca x CEC Mg	−6.28	−0.01	−1.40	3.29	0.45
Model R^2	0.58	0.68	0.49	0.25	0.57
n	51	48	45	47	43
Nutrient management and soil					
N input	−0.04	0.01	−0.02	0.07*	−0.01
Dummy variable no P input	−0.02	0.05	−0.57*	0.11	−0.35
Soil P x Cu	−3.55*	0.50	−0.94+	2.21	1.70
CEC Mg	19.43*	0.55	1.54	−7.75	0.55
CEC Mg x CEC Ca	−12.17*	−0.43	−1.38	5.01	0.18
Mn	−0.16	−0.31*	−0.40	x	x
Percentage silt	0.92	1.53*	0.60	2.34	−0.73+
Model R^2	0.84	0.66	0.56	0.45	0.65
n	40	47	44	46	43
Household					
TLU	0.00	0.01	−0.04	0.17**	0.14*
Family labour available	−0.10	0.12	0.61	−1.66*	−1.38
People in the household	−0.22	−0.40+	0.05	−2.97*	−0.54
Family labour available x people in the household	0.35	0.26	−0.28	0.74*	0.55
Model R^2	0.53	0.57	0.37	0.66	0.64
n	35	33	34	37	36

incidences and diseases. Fall armyworm reduced yields in both demonstration experiments in 2016 and 2017, and probably also the surveyed farmers' yields from the 2016 season, but no reporting was done on actual pest infestations. The farm survey data indicated that no farmers applied pesticides during the 2016 seasons. Day et al. (2017) indicate that maize yields in Ghana were reduced by 45% in 2017 due to fall armyworm attack. Other studies have indicated that agrochemicals can be positive determinant of maize yield (Addai and Owusu, 2014; Awunyo-Vitor et al., 2016; Bempomaa et al., 2014; Oppong et al., 2014) and integrated pest management should be part of sustainable intensification of maize production in our study sites as well.

4.4. Challenging results

A first challenge of our results is that a relatively short term study like this one is not well equipped to capture factors that vary between season, e.g. management decisions, pest and disease outbreaks and weather patterns. This calls for caution in the interpretation of results, and for more long-term studies to better understand relationships and dynamics. In this study, we observed little relation between yield obtained by individual farmers between seasons. This is likely due to the temporal variability in climate, management, and household factors, the impact of which becomes larger with sub-optimal management conditions (Fermont et al., 2009). Another study in Uganda reported that farmers make significant changes to their crop management from season to season (Ronner et al., 2018). Even in long-term studies, correlations between yields of farmers in different years are relatively low (Silva et al., 2018).

Second, all farmers in the study sites achieved yields far below Y_w with relatively small differences between the farms. The uniform and low yields can be explained by the incidence of fall armyworm, but also by the low-input nature of the systems (see relatively large difference between Y_w and Y_{hf} values in Fig. 3) and low soil quality in general (e.g. very low soil Zn). Finally, errors in data collection (e.g. arising from relying on farmer recall) complicate the identification of consistent relationships (Kassie et al., 2013). Compared to the separate models per location and season, no additional insights were obtained by pooling data in the multi-level regression model (Appendix I).

4.5. Methodological, practical and policy implications

The practical aim of this study was to identify options to mitigate yield gaps. However, disentangling spatial and temporal factors in biophysical, social and economic domains that interact and impact crop yields proved to be difficult. Nevertheless, our integrated approach combining different data sources and methods helped to reveal complexity that must not be ignored, but instead be incorporated in yield gap analysis. Employing different methods provided both confounding and complementary results. Therefore, we highlight the danger of drawing over-simplified conclusions based on a single method that in turn may lead to potentially unjustified crop management recommendations.

Smallholder systems are complex and heterogeous and blanket recommendations to increase yields are often irrelevant, infeasible and risky (Berre et al., 2017; Giller et al., 2011). Our results confirm that, in terms of offering recommendations to mitigate yield gaps, a "basket of options" that includes technologies and practices that farmers can choose, try and adapt is more appropriate (Ronner et al., 2018). In this case, the farm-level "basket" may include a selection of adapted varieties, fertilizer rates and pest control methods, i.e. options that all contribute to good agronomy. Further research that investigates how such a "basket" is used over multiple seasons would be extremely

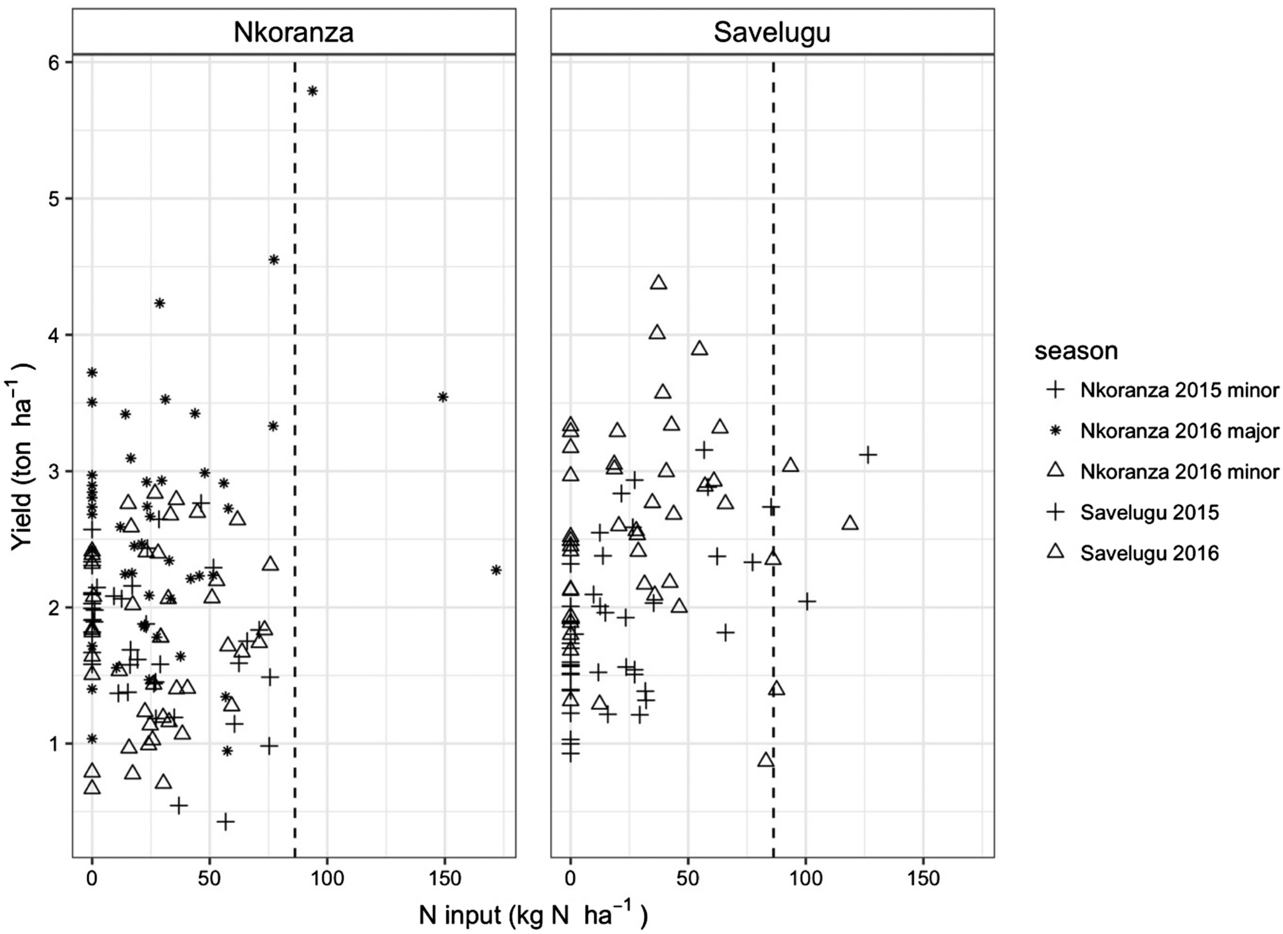

Fig. 6. Yield versus N input for Nkoranza and Savelugu for the 2015 and 2016 seasons. Dashed lines represent the recommended N input.

valuable. Innovative data collection methods including crowdsourcing and sensor technology (Beza et al., 2017), and data science (e.g., Janssen et al., 2017) can contribute to integrated assessments to explain yield gaps. We can nevertheless conclude that given the importance of socioeconomic constraints faced by farmers, policies can contribute to closure of the maize yield gap in Ghana by improving the availability and access of farmers to improved seeds. Next, affordability of fertilizers is likely to contribute to yield improvements. Finally, we

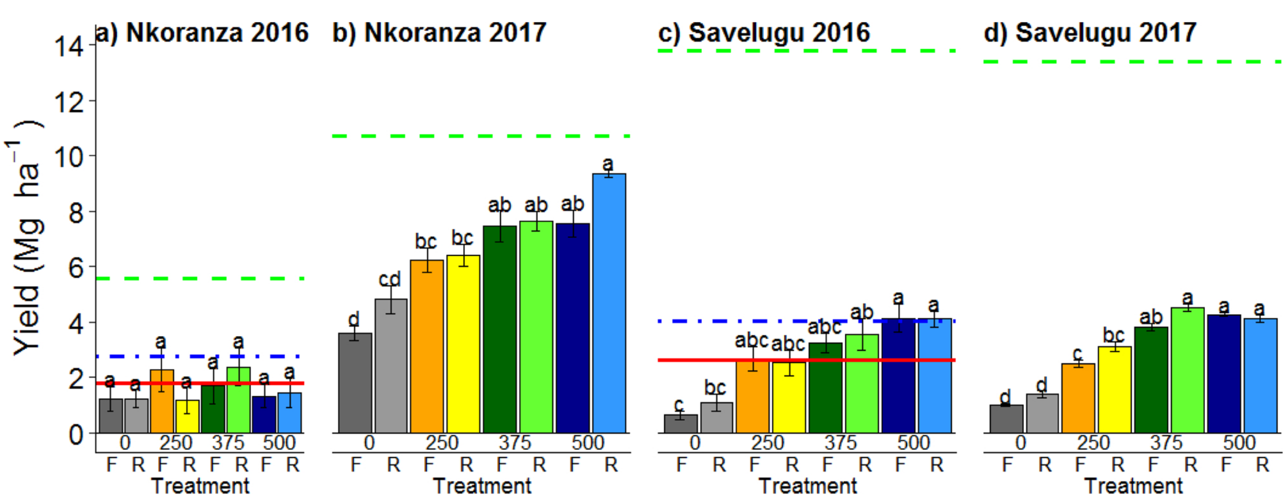

Fig. 7. Average maize yield with standard error from demonstration experiment 1 for farmers' chosen planting densities (F, dark colored bars) and recommended planting density (5.33 plants m^{-2}) (R, light colored bars) at fertilizer application rates (N:P:K 23:10:5) of 0 (grey bars), 250 (yellow bars), 375 (green bars) or 500 (blue bars) kg ha^{-1} for a) 2016 minor season in Nkoranza; b) 2017 major season in Nkoranza; c) 2016 in Savelugu and; d) 2017 in Savelugu. Bars labelled with different letters within each graph indicate significant differences in yield, $P < 0.05$ based on the LSD analysis. The red continuous line is the average actual yield (Y_a) as measured during the household survey, the blue dot dashed line is the highest farmers yield (Y_{hf}) as measured during the household survey, and the green dashed line is the simulated water-limited potential yield (Y_w) (see also Fig. 4). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
Ranking (1 = best, 4 = worst) of varieties, fertilizer application rates and planting densities based on general consensus of farmers' preferences as indicated during farmer field days at harvest of the demonstration experiments in the different seasons and municipalities. Comments regarding preferences are also included.

	Nkoranza		Savelugu		
	2016	2017	2016	2017	Comments
Fertilizer rate (N:P:K, 23:10:5) (kg ha^{-1})					
0	4	4	4	4	In 2016 and 2017 375 kg ha^{-1} of N:P:K fertilizer preferred, because: yield and growth performance was high and was not much different from that of 500 kg ha^{-1}, but was better compared to 0 and 250 kg ha^{-1}; cob sizes were uniform and their weights were close to that of 500 kg ha^{-1}; 375 kg ha^{-1} fertilizer is similar to what is recommended by research and extension; more cost effective to use 375 kg ha^{-1} than 500 kg ha^{-1}; financial constraints to purchase 500 kg ha^{-1} of fertilizer; in 2017 resulted in delayed drying of cobs thus delaying harvesting for this treatment.
250	2	2	2	3	
375	1	1	1	1	
500	3	3	3	2	
Planting density					
Farmers	2	2	2	1	Recommended planting density preferred in Nkoranza 2016, and 2017 and Savelugu 2016 because: higher yields could be achieved with this higher planting density; in Nkoranza farmers noted that it gives more plants per unit area, and they are already used to row planting so increasing the rate may not be too difficult. Farmers planting density preferred in Savelugu 2017 because: recommended planting density involves row planting, which requires more labour due to obstruction by trees in the field
Recommended	1	1	1	2	
Variety					
Drought Tolerant Maize (DTM)	1	3	1	2	In 2016 DTM preferred because: uniform and with filled cobs; yield was high and consistent across all fields; recycling of seeds is possible unlike Pannar seeds; Pannar seeds are expensive. In 2017 Proseed preferred even though the price is not within reach of farmers because: high and consistent yield across most fields; good and uniform germination; well-filled cobs; large grain size.
Farmer variety	4	2	4	4	
Obatanpa	3	4	3	3	
Pannar	2	–	2	–	
Proseed	–	1	–	1	

recommend improving integrated pest management by farmer capacity building and improved information access through extension services.

5. Conclusion

We conclude that there is great potential to increase maize yields within low-input smallholder farming systems in Ghana. However, identifying recommendations to achieve such yield improvements is far less straightforward because farmers' yields are determined by interacting, and often strongly varying, household, soil and management factors. Our study showed that it is often not possible to make sense of these factors on the basis of a single methodological approach. Instead, results obtained through individual methods should be interpreted in light of complementary methods that account for the multiple yield-determining factors acting at different spatial and temporal levels.

The combination of household survey, crop growth simulation modelling, and demonstration experiments with farmers' feedback used in this study adds value to yield gap analysis of maize in Ghana. Demonstration experiments showed that improved varieties and increased fertilizer rates can lead to yields much closer to water-limited yields, whereas farmers' yields differed among plots and seasons, and explaining factors differed per season and site. Nevertheless, the approach can be improved upon with additional data sources and methods that better disentangle variation in space and time.

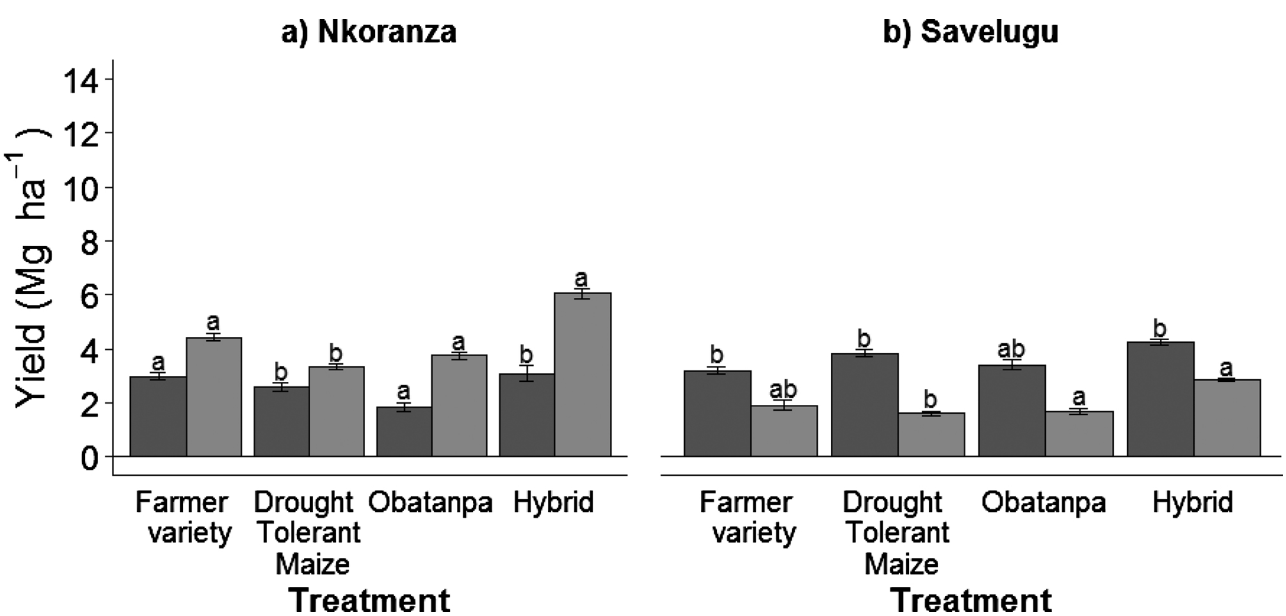

Fig. 8. Average maize yield with standard error for different varieties used in demonstration experiment 2 (note that in 2016 Pannar is used as a hybrid and in 2017 Proseed is used) in a) Nkoranza and b) Savelugu. The dark grey bars show results for 2016 and the light grey bars for 2017. Different letters indicate significant differences in yield, $P < 0.05$, between the different treatments within each season and municipality combination.

Acknowledgements

This research was part of the project Integrated assessment of the determinants of the MAize yield Gap in Sub-Saharan Africa: towards farm INnovation and Enabling policies (IMAGINE), funded by the DEGRP programme, the DFID-ESRC Growth Research Programme. We thank the Ministry of Food and Agriculture of Ghana and farmers in Savelugu and Nkoranza who participated in the project. We also thank Wim Paas and Lenny van Bussel, from Wageningen University, for developing the questionnaires for the household surveys and starting up the data collection, and Kwasi Gyan, from the University of Development Studies at Nyankpala, who assisted in the data collection for both the surveys and the field experiments. In addition we thank Mink Zijlstra for assisting in the data analysis, and finally Madeleine Florin for her great contribution to finalize the writing of the paper.

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