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RESEARCH ARTICLE

Potential contribution of agronomic practices and conservation agriculture towards narrowing smallholders’ yield gaps in Southern Africa: lessons from the field

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Summary

Smallholders in Southern Africa continue to grapple with low maize productivity despite this being the staple food crop. This study sought to analyze and isolate the relative contribution of agronomic practices to maize yields obtained by smallholders in Malawi and Mozambique using data generated from on-farm trials testing the performance of conservation agriculture cropping systems. The trials were implemented in two communities, namely Kasungu district in Malawi and Sussundenga district in Mozambique, and ran for seven consecutive growing seasons starting in 2010–2011. Maize yield was measured annually in the on-farm trials, which included a ‘control treatment’ representing an improved farm practice, and in neighboring fields managed by the same farmers on their own, hence representing a ‘true farm practice’. Results indicated that maize yield increased linearly with increasing plant population at harvest at both sites. On average, an increase in plant population at harvest by 1000 plants ha^{-1} resulted in an increase in maize yield of 90 and 63 kg ha^{-1} at Kasungu and Sussundenga, respectively. The greatest maize yields were obtained when plant population at harvest exceeded 40 000 plants ha^{-1}. Yet, the plant population at harvest was below the generally recommended optimum for most of the cropping systems studied and in most growing seasons. Furthermore, the use of agronomic practices alone without conservation agriculture (i.e., improved varieties, fertilizer management, and timely weed control) resulted in maize yield gains of as much as 54% and 43% relative to the ‘true farm practice’ at Kasungu and Sussundenga, respectively. Overall, the proportion of these yield increases relative to the ‘true farm practice’ accounted for by agronomic practices amounted to 53–70% and 57–85% at Kasungu and Sussundenga for the highest to the lowest-yielding cropping system. Although conservation agriculture significantly improved maize yield at both sites, such increases were smaller in magnitude compared to the yield gains derived from improved agronomic practices. The study suggests that considerable strides toward narrowing maize yield gaps in Southern Africa can be achieved through improvement of current crop management practices, let alone adhering to the conservation agriculture principles of minimum tillage, residue retention, and crop diversification.

Keywords: Maize; plant population; sustainable intensification; crop rotation; crop management

Introduction

Feeding the growing population of sub-Saharan Africa (SSA) without further expansion of current cropland requires considerable increases in crop productivity across smallholder farming systems on the continent. SSA's food supply and demand gap have widened, with demand for cereals estimated to increase by 335% between 2010 and 2050 (Barnes et al., 2019). Yet, crop productivity across the region remains largely stagnant, and well-below its potential, for most crops in many countries (Tittonell and Giller, 2013; Beza et al., 2017). Maize yield in particular remains quite low, averaging between 1.5 and 2.0 t ha^{-1} against a water-limited yield potential above 6.0 t ha^{-1} (van Ittersum et al., 2016; Ligowe et al., 2017). Crop productivity in SSA is largely dependent on climate-sensitive rainfed agriculture and has been negatively impacted by recurrent droughts resulting in maize crop failures (Tesfaye et al., 2017; Thierfelder et al., 2017). Other reasons for low productivity include low uptake of inputs and improved technologies (Silva et al., 2023; Leonardo et al., 2018; Sheahan and Barrett, 2017), agronomic constraints linked to tillage practices, poor soil fertility, and overreliance on cereal monoculture (Mango et al., 2017; Moswetsi et al., 2017; Mupangwa et al., 2021; Thierfelder et al., 2015).

Conservation agriculture (CA) has been widely promoted as an approach to sustainable intensification of crop production given its focus on minimum tillage, soil residue retention, and crop diversification (Pretty and Bharucha, 2014; Steward et al., 2018). With its perceived benefits, there have been concerted efforts to promote CA as a solution to land degradation, climate change adaptation and mitigation, and food security, given its potential to stabilize and increase maize yield in Southern Africa when complementary inputs are provided (Mazvimavi et al., 2010; Mutegi et al., 2018; Nyagumbo et al., 2016; Thierfelder et al., 2015). Furthermore, extensive field experiments in Eastern and Southern Africa between 2010 and 2017 also confirmed the climate resilience superiority of CA cropping systems under low seasonal rainfall conditions ($<$ 700 mm; Nyagumbo et al., 2020). It is also notable, however, that in such studies, CA practices were implemented along with complementary agronomic practices such as improved varieties, application of mineral fertilizers, and recommended plant populations.

Plant stands or populations are well-known components of good agronomic practices (Ali et al., 2017; Mhlanga et al., 2016; Thierfelder et al., 2018). Mineral fertilizers have been promoted for decades in Southern Africa, yet adoption levels remain low alike for many other innovations (Mupangwa et al., 2017; Thierfelder et al., 2018). Yet, there is clear evidence that the use of fertilizer and improved varieties can enhance food security across the region (Silva et al., 2023; Kihara et al., 2016; Vanlauwe et al., 2011). A recent assessment further pointed to the importance of increasing the use of mineral fertilizers in low-input cropping systems across SSA (Falconnier et al., 2023). For instance, yield gains from applied mineral fertilizers as high as 100 and 330% have been reported in Malawi and Mozambique, respectively, with the use of hybrid maize varieties (Jama et al., 2017; Musafiri et al., 2023).

Crop output in SSA remains far below what can be potentially achieved with best agronomic practices, despite an abundance of improved agricultural technologies tested and promoted across the continent (Giller, 2020). The yield gap of rainfed crops is defined as the difference between the water-limited potential yield and the actual farmers' yield, with the former reflecting the maximum yield that can be achieved with the moisture available during the growing season (Van Ittersum and Cassman, 2013). Maize yield gaps as large as 80% of the water-limited yield, corresponding to more than 10 t ha^{-1} in absolute terms, were estimated in Zambia (Silva et al., 2023) and in Ethiopia (Assefa et al., 2020). The same is likely to be true in Malawi and Mozambique, where the difference between maize yield measured on-station and on-farm was reported to exceed 4 t ha^{-1} (Mutegi et al., 2018). Such large yield gaps present an opportunity to increase crop production on existing cropland and call for the identification, promotion, and realization of widespread adoption of agronomic technologies that can deliver sustainable crop intensification across large scales (Arslan et al., 2014).

We define ‘agronomic practices’ in this study as the crop management practices derived from local research and recommended by extension that include improved maize varieties, timely sowing, use of mineral fertilizer, and timely pest, disease, and weed control. Such agronomic practices are also naturally embedded in CA cropping systems and can be considered complementary practices (Thierfelder et al., 2018) to the three CA principles of reduced soil disturbance, provision of permanent soil cover, and crop diversification through cereal-legume rotations or intercrops. From this viewpoint, CA thus entails a much higher level of agronomy than the aforementioned agronomic practices alone. This study sought to analyze and understand the potential contribution of these bundled agronomic practices to maize yields obtained from on-farm trials testing CA cropping systems under smallholder conditions in Malawi and Mozambique, over multiple cropping seasons. In other words, the study sought to understand the extent to which on-farm maize yields could be increased with the use of such agronomic practices, let alone also evaluating the performance of cropping systems including CA principles. The on-farm trials tested different CA-based cropping systems and were conducted under the auspices of the Sustainable Intensification of Maize Legume Systems in Eastern and Southern Africa (SIMLESA, https://simlesa.cimmyt.org/) project over seven consecutive cropping seasons (2010–2011 – 2016–2017). Yield data from the on-farm trials were complemented with yield data from smallholders’ fields adjacent to the trial plots to disentangle the effect of agronomic practices from that derived from the use of CA principles.

Materials and Methods

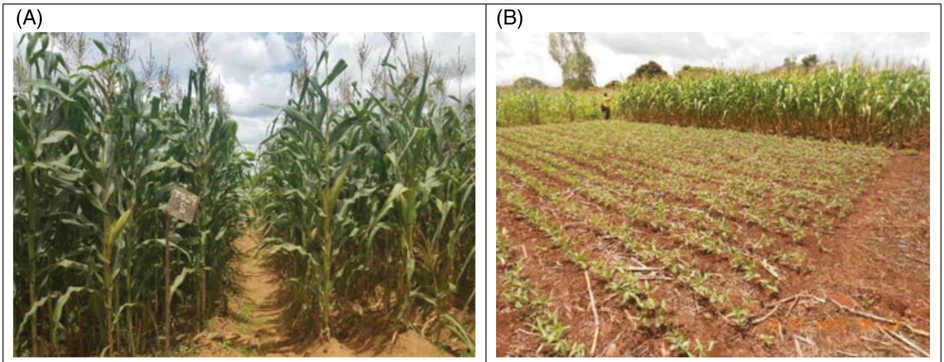
Site description

Maize yields from on-farm trials testing different CA-based cropping systems were assembled from two communities (i.e., rural households located within an approximate radius of 3km), one in Kasungu district (Malawi) and the other in Sussundenga district (Mozambique). Kasungu is located in a mid-altitude agro-ecology of central Malawi, a region with an altitude ranging between 760 and 1300 m above sea level. Average yearly rainfall in Kasungu ranges between 600 and 1000 mm, with the maize growing season spanning between November and April. The main soil types are classified as Lixisols and Luvisols. Ridge and furrow cropping systems are common in this site (Ngwira et al., 2014). Sussundenga is located in Manica province, Central Mozambique, at an elevation ranging between 600 and 700 m above sea level. Average yearly rainfall varies between 800 and 1200 mm (Maria and Yost, 2006), with maize being sown in November and harvested in May. The main soil types are fairly well-drained Haplic Lixisols. Cropping systems in Sussundenga are dominated by manual hoe tillage with maize and cowpea often grown as intercrops.

Both Kasungu and Sussundenga districts were characterized by smallholder farms practicing mixed crop livestock farming with maize being the dominant staple food crop and arable land sizes hardly exceeding 2 ha per household. Furthermore, access to farm inputs is often constrained by lack of collateral for farmers to access credit, meaning most inputs are acquired through subsidized government schemes, such as the Farm Input Supply Program rolled out in Malawi since 2004 (Dorward and Chirwa, 2011). The use of improved hybrid maize varieties and mineral fertilizers is much higher in Malawi than in Mozambique, where subsidies contributed to a 48% increase in maize yield among beneficiaries (Carter et al., 2021).

CA cropping systems tested

On-farm trials testing different CA-based cropping systems were carried out at Kasungu and Sussundenga for seven consecutive seasons, starting in 2010–2011 (Nyagumbo et al., 2016). At Kasungu, four cropping systems involving CA dibble stick for crop establishment, use of



Left: No-till continuous maize cropping system. Right: Conventional ridge and furrow system ('control treatment') as applied in Kasungu, Malawi.

Cowpea under conservation agriculture (left) in rotation with maize (right) at a farm in Sussundenga, Mozambique.

Figure 1. Field view of some of the cropping systems tested on-farm in Kasungu, Malawi, and Sussundenga, Mozambique, over seven consecutive growing seasons starting in 2010/11.

glyphosate herbicide, and maize-soybean rotation were tested relative to the traditional ridge and furrow cropping system (referred to as 'control treatment'), all using improved seed and recommended mineral fertilizer rates (Figure 1A). At Sussundenga, five manual traction systems, involving maize-cowpea rotations (Figure 1B) and intercrops, were compared against the commonly practiced flat hand hoe conventional tillage (referred to as 'control treatment'). At each site, the 'control treatment' was defined in relation to the most common local farmer practice and using locally recommended varieties, mineral fertilizer rates, and other inputs (Table 1). Newly released improved maize and legume varieties were provided by the project and used in all trials. A full description of the CA-based cropping systems tested in each site is provided in Table 1.

Maize yield was also measured in farmers' fields adjacent to the trials, where the farmers hosting the trials used their own inputs and management practices ('true farm practice') as a means of comparing these to the CA-based cropping systems tested in the trials. Average maize yield from both districts was also obtained for each cropping season based on official district extension crop estimates. The difference between the 'true farm practice' and the 'control treatment' constituted what we define in this study as 'agronomic practices' and essentially involved the bundled or separate use of improved crop varieties, timely sowing, recommended rates of mineral fertilizers, and timely pest, disease, and weed control.

Management practices in the on-farm trials

The on-farm trials were researcher-designed and farmer-managed. An open-pollinated maize variety, Tsangano, was used at Sussundenga whereas the maize hybrid, MH26, was used in Kasungu. Sowing was carried out on the same plots every growing season after receiving at least 30 mm of rainfall within 3 consecutive days. MH26 at Kasungu was planted at 75 cm inter-row spacing targeting to achieve a recommended plant population at harvest of 53 333 plants ha^{-1} in all cropping systems. For the CA basins, an inter-row and in-row spacing of 75 cm was also used with 3 maize plants per station, whereas 25 cm in-row and 75 cm inter-row with one plant per station, was used for the dibble stick under maize also to achieve a plant population of 53 000 plants ha^{-1}. Soybean was planted in rotation cropping system at 37.5 cm inter-row spacing using and seed dressed with rhizobium inoculant before planting. The maize variety Tsangano was planted at 90 cm inter-row spacing at Sussundenga and at 25 cm in-row with one plant per station for the jab planter and dibble stick tillage systems while 50 cm in-row spacings with two plants per

Table 1. CA-based cropping systems tested in Kasungu, Malawi, and Sussundenga, Mozambique, over seven consecutive growing seasons

Site	CA-based cropping systems tested and their treatment codes (in brackets)
Kasungu, Malawi Altitude of 760–1300 m.a.s.l. 600–1000 mm of rainfall per year	**True farm practice (TFP):** Sowing crops on ridges in the widely used 'ridge and furrow' system. This is the cropping practice used by farmers on their own plots with their own inputs and crop management practices.
	Control (Control): Sole maize sown in the 'ridge and furrow' system with improved crop management as per the protocol. This refers to the tillage practice as used by farmers but with the use of improved seed, fertilizer, and controlled time of sowing and weeding. Residues were removed prior to sowing.
	CA dibble stick with sole maize and no herbicide (CASoMzNoHb): Sole maize with the use of a dibble stick for planting holes, application of residue cover at 2.5 t ha^{-1}, and a manual shallow hoe weeding. Other crop management as per the control.
	CA dibble stick with sole maize and glyphosate herbicide (CASoMzHb): Sole maize with the use of a dibble stick for planting holes, application of residue cover at 2.5 t ha^{-1}, glyphosate applied at a rate of 3 L ha^{-1}, and a manual shallow hoe weeding. Other crop management as per the control.
	CA dibble stick maize-soybean rotation + glyphosate + residue (CAMzSoyRot): Maize-soybean rotation with the use of a dibble stick for planting holes, application of residue cover at 2.5 t ha^{-1}, glyphosate applied at 3 L ha^{-1}, and a manual shallow hoe weeding. Other crop management as per the control. Two plots are used in each season, one in the legume phase (soybean) and the other in the cereal phase (maize). The two plots alternated crops annually.
Sussundenga, Mozambique Altitude of 600–700 m.a.s.l. 800–1200 mm rainfall per year	**True farm practice (TFP):** Sowing crops with a flat hoe tillage land preparation method. This is the cropping practice used by farmers on their own plots with their own inputs and crop management practices.
	Control (Control): Sole maize sown in flat hand hoe tillage system with improved crop management as per the protocol. This refers to the tillage practice as used by farmers but with the use of improved seed, fertilizer, and controlled time of sowing and weeding. Residues were removed prior to sowing.
	CA basins sole maize and glyphosate herbicide (CABMzS): Sole maize with the use of permanent planting holes (basins) with 15cm diameter by 15cm depth, application of residue cover at 2.5 t ha^{-1}, glyphosate applied at 3 L ha^{-1}. Other crop management as per the control.
	CA jab-planter sole maize and glyphosate herbicide (CAJPMzS): Sole maize with the use of a jab planter for establishing planting stations, application of residue cover at 2.5 t ha^{-1}, glyphosate applied at 3 L ha^{-1}. Other crop management as per the control.
	CA basins maize-cowpea rotation and glyphosate herbicide (CABMzCpRot): Maize-cowpea rotation with the use of hand hoe prepared 15 cm diameter planting stations for crop establishment, application of residue cover at 2.5 t ha^{-1}, glyphosate applied at 3 L ha^{-1}. Other crop management as per the control. Two plots are used in each season. One in the legume phase (cowpea) and the other in the cereal phase (maize). The two plots alternated crops annually.
	CA basins maize-cowpea intercrop and glyphosate herbicide (CABMzCpInt): Maize-cowpea intercrop with the use of hand hoe prepared 15 cm diameter planting stations for crop establishment application of residue cover at 2.5 t ha^{-1}, glyphosate applied at 3 L ha^{-1}. Other crop management as per the control. Cowpea planted at 45 cm between the maize rows.

Note: 'm.a.s.l.' = meters above sea level.

station were employed for the CA basins. All cropping systems in Sussundenga targeted a recommended plant population of 44 444 plants ha^{-1}. For cowpea, 45 cm inter-row was used in the crop rotation and in-between maize rows in the intercrop. The same permanent planting stations were maintained for the CA basins and used repeatedly every growing season. Digging of basins was carried out to approximately 15 cm depth at the same positions annually. Maize stubbles from the previous growing season were used to locate the planting stations annually thereby ensuring permanent planting stations over time.

Local agronomic recommendations were implemented in all cropping systems tested in the trials including the use of basal fertilizer and top-dressing urea (46% N). At Kasungu, basal fertilizer (23N:21P:0K + 4S) was applied at sowing in each planting station of maize and soybean at a rate of 100 kg ha^{-1} and maize was rotated with soybean for the cropping systems comprising cereal-legume rotations. Uniform fertilizer was applied across all cropping systems with urea top dressing to maize at 4–6 weeks after crop emergence as side dressing to each plant at a rate of 150 kg ha^{-1}. No top-dressing fertilizer was applied to legume crops. Similarly, at Sussundenga, basal fertilizer (12N:24P:12K) was applied at sowing on each planting station (for maize and cowpea in rotation) at a rate of 100 kg ha^{-1}. Urea (46% N) was applied as top dressing only to maize plants also at a rate of 100 kg ha^{-1}. Fertilizer basal application and top dressing were done manually, and fertilizer rates were applied and kept constant over the seven growing seasons. Cowpea was the legume included in the trials at Sussundenga as both a rotation crop and as an intercrop with maize. Glyphosate, a nonselective systemic pre-sowing herbicide, was applied at a rate of 3 L ha$^{-1,}$ and Harness, a pre-emergence herbicide, was applied at a rate of 1 L ha^{-1}. Two to three manual shallow hoe weedings were carried out for all cropping systems each growing season depending on the presence of weeds. No systematic control was carried out for pests and diseases, although maize stalk borer (*Busseola fusca* spp.) and soil-borne pests such as white grubs (*Phyllophaga* spp.) were sprayed with agro-chemicals occasionally and whenever infestation levels warranted it.

Crop residue management in the CA-based cropping systems involved farmers applying at least 2.5 t ha^{-1} maize crop residues to each cropping system. Thus, at the start of the first growing season (2010–2011) at both Kasungu and Sussundenga, maize residues had to be imported from neighboring fields when necessary and measured to give an equivalent application rate of 2.5 t ha^{-1}. Crop residues from the previous maize crop were retained thereafter in subsequent seasons and uniformly distributed to all CA plots. Field assessments at the start of the third and fourth growing seasons (October – November) showed that residue cover usually ranged between 30 and 70% at Kasungu and between 10 and 40% at Sussundenga (data not shown). At Sussundenga, termites attacked most of the surface-applied residues during the dry winter period. In the ‘control treatment’ of both sites, crop residues were removed annually following local farmer practices.

Maize yield, biomass, and plant population at harvest

Maize yield, aboveground biomass, and plant population were measured at harvest over the seven consecutive growing seasons. In each on-farm trial, maize grain yield was determined from 3 sub-plots of 5 m × 2 rows from each cropping system at the end of each growing season as well as farmer’s fields adjacent or closest to the trial. The harvested area on each sub-plot equated to approximately 7.5 and 9 m^2 for Kasungu and Sussundenga, respectively. Measured air-dried grain weight from each plot was corrected to 12.5% moisture content after determining its moisture content using a grain moisture meter. Aboveground biomass was measured by weighing the stalks after removing the cobs. A subsample of stalks was then taken, weighed, air-dried, and reweighed after 2 to 3 weeks. The original fresh biomass was then corrected for moisture loss using the ratio obtained from the air-dried sub-samples and then added to the grain weights to get the total aboveground biomass. Finally, the maize plant population at harvest was determined by counting the number of plants in each sub-plot and standardizing this to a hectare basis.

Statistical analyses

Linear mixed models were fitted to the data to test the effect of cropping systems and growing seasons on maize yield, total aboveground biomass, and plant population at harvest. The mixed models comprised the interaction of cropping system and growing season as fixed effects and the identifier of each farm hosting the trials as random effect. Analysis of variance (ANOVA) was used to test the statistically significant effect of the fixed effects on the variables of interest. The two-way interaction between cropping system and growing season was not significant in any of the fitted models (Supplementary Table S1), hence cropping systems and growing seasons were analyzed separately in subsequent analysis. Linear mixed models were fitted with restricted maximum likelihood using the lmer() function of the lmerTest R package (Kuznetsova et al., 2017).

Measured maize plant population at harvest was regressed against measured maize yield to establish the contribution of plant population to maize yield in each site × growing season combination using the *lm()* function in R (Kuznetsova et al., 2017). Measured plant population at harvest was further subdivided into four categories (10 000 – 30 000, 30 000 – 40 000, 40 000 – 50 000, and > 50 000 plants ha^{-1}), and an ANOVA was conducted on the pooled data to test the effect of plant population on maize yield at each site. Maize yield data measured from trial host farmers' own fields (i.e., 'true farm practice') and district average maize yield reported by government officials could not be subjected to formal statistical analysis, unlike the data from the on-farm trials. The district average maize yield per site refers to one value per growing season and the absence of replicates did not allow for statistical testing as conducted for the on-farm trial data. Mean maize yields in the 'true farm practice' were missing for two growing seasons in either site and thus were not included in the statistical analysis. Maize yield differences between the on-farm trials and the 'true farm practice' were calculated from the predicted means of the fitted linear mixed models in both absolute and relative terms.

Results

Maize yield response to plant population at harvest

Statistical analysis showed no significant interaction between cropping systems and growing season at both sites (Supplementary Table S1). However, in terms of the main effects, there was a statistically significant effect ($p < 0.05$) of growing season on plant population at harvest at both Kasungu and Sussundenga, whereas the effect of cropping system on plant population at harvest was not significant at either site. This means the tested cropping systems did not influence the maize plant population at harvest, justifying the analysis of the maize yield response to plant population at harvest using data for each growing season, pooled across cropping systems.

Plant populations at harvest that were lower than the recommended 53 333 plants ha^{-1} were observed at Kasungu in most growing seasons (Figure 2). The mean plant population at harvest at this site ranged between 28 000 plants ha^{-1} in the 2010–2011 growing season and 53 000 plants ha^{-1} in the 2016–2017 growing season (as indicated by the vertical lines in Figure 2). The mean plant population at harvest for the 2016–2017 growing season was indeed significantly higher ($p < 0.05$) than the mean plant population at harvest observed in all other growing seasons. For instance, mean plant population at harvest was 47 648, 47 109, 45 629, and 45 057 plants ha^{-1} for the 2015–2016, 2013–2014, 2012–2013, and 2011–2012 growing seasons, respectively, with no statistically significant differences observed between these growing seasons. Significantly ($p < 0.05$) lower plant populations at harvest were observed in the 2014–2015 growing season (41 299 plants ha^{-1}) and in the 2010–2011 growing season (28 216 plants ha^{-1}). Similarly, plant population at harvest was also lower than the recommended 44 444 plants ha^{-1} for most plots and growing seasons at Sussundenga (Figure 2). Mean plant population at harvest was significantly ($p < 0.05$) higher in the 2010–2011 growing season (39 247 plants ha^{-1}) and lower in the 2015–2016 (33 000 plants ha^{-1}) and 2014–2015 (32 416 plants ha^{-1}) growing seasons

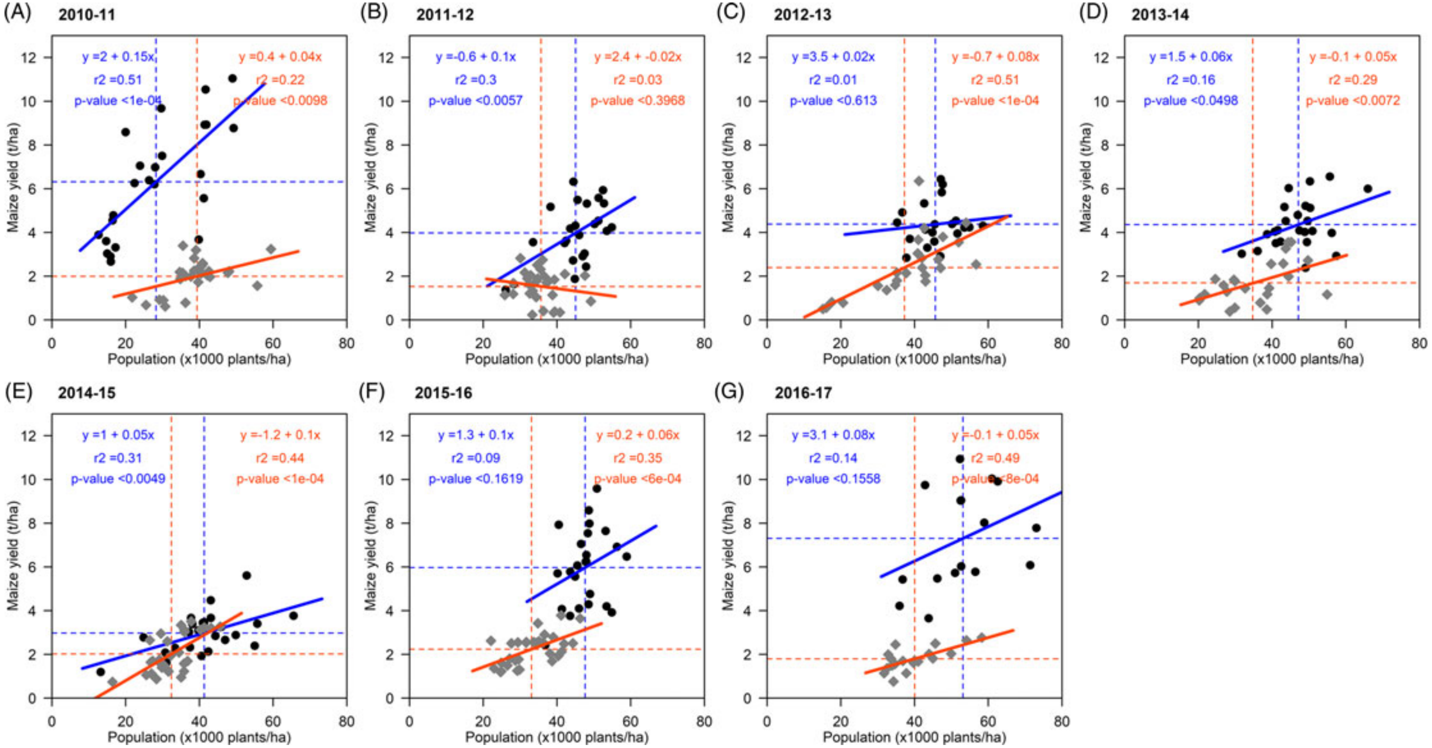


Figure 2. Maize yield response to plant population at harvest across the seven growing seasons when the on-farm trials were conducted in Kasungu, Malawi (black dots and blue lines), and Sussundenga, Mozambique (gray diamonds, and orange lines). The seven growing seasons spanned over the period 2010/11 and 2016/17. Regression equations, goodness-of-fit, and significance of linear regressions are provided in each panel. Vertical dashed lines show the mean plant population at harvest in each growing season pooled across cropping systems, whereas horizontal dashed lines show the average maize yield in each growing season pooled across cropping systems. Growing season rainfall amounts at Kasungu were as follows: 839, 750, 623, 809, 631, 635, and 759 mm ordered from the first (2010–2011) to the last (2016–2017) growing season. Growing season rainfall amounts at Sussundenga were as follows: 750, 700, 627, 1127, 1198, 1387, and 1279 mm ordered from the first (2010–2011) to the last (2016–2017) growing season.

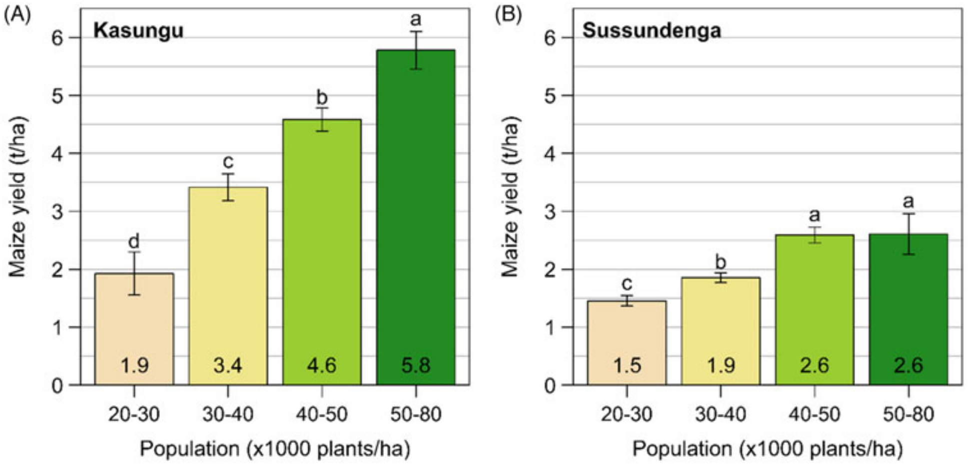


Figure 3. Maize yield across different classes of plant population at harvest at Kasungu, Malawi, and Sussundenga, Mozambique, averaged over seven consecutive growing seasons (2010/11 – 2016/17). Data from the 2010–2011 growing season were excluded for Kasungu in this analysis due to abnormally high maize yields at low plant population in this growing season (cf. Figure 2A). Different letters above each bar denote significant differences in maize yield across planting density categories for each site considering a significance level of 5% ($p < 0.05$).

compared to the other growing seasons for which it ranged between 34 066 and 38 135 plants ha^{-1} (as indicated by the vertical lines in Figure 2).

The linear relationship between plant population at harvest and maize grain yield was statistically significant at 5% significance level in four and six out of seven growing seasons at Kasungu and Sussundenga, respectively (Figure 2). The slope of the statistically significant linear regressions for the Kasungu data indicated that increasing the plant population at harvest by 1000 plants ha^{-1} resulted in an increase in maize yield of 150, 100, 60, and 50 kg ha^{-1} for the 2010–2011 (Figure 2A), 2011–2012 (Figure 2B), 2013–2014 (Figure 2D), and 2014–2015 (Figure 2E) growing seasons, respectively. The R^2 of the aforementioned linear regressions ($p < 0.05$) ranged between 16% in the 2013–2014 growing season and 51% in the 2010–2011 growing season (Figure 2). At Sussundenga, maize yield response to plant population at harvest was highest in the 2014–2015 growing season (100 kg maize ha^{-1} per 1000 plants ha^{-1} at harvest, Figure 2E) and lowest in the 2010–2011 growing season (40 kg maize ha^{-1} per 1000 plants ha^{-1} at harvest, Figure 2A). The R^2 of the linear regressions ($p < 0.05$) fitted for the Sussundenga data ranged between 22% in the 2010–2011 growing season and 51% in the 2012–2013 growing season (Figure 2).

Maize yield responded positively ($p < 0.01$) to increasing plant population at harvest at both sites (Figure 3). For Kasungu, the lowest plant population class of 20 000–30 000 plants ha^{-1} at harvest yielded 1.9 t ha^{-1} compared to 5.8 t ha^{-1} obtained in the highest plant population class of 50–80 000 plants ha^{-1} (Figure 3A). Intermediate plant population classes of 30–40 000 and 40–50 000 plants ha^{-1} at harvest yielded 3.4 and 4.6 t ha^{-1}, respectively (Figure 3A). This corresponds to a relative increase in maize yield from each class to the next of 79%, 35%, and 26% from 20–30 000 to 30–40 000, 40–50 000, and 50–80 000 plants ha^{-1} at harvest, respectively. However, increases in maize yield across plant population classes were more modest at Sussundenga due to lower maize yields at this site (Figure 3B). Maize yield was on average 1.5, 1.9, and 2.6 t ha^{-1} for plant population between 20–30 000, 30–40 000, and above 40 000 plants ha^{-1} at harvest, respectively. This corresponded to a relative increase in maize yield of 27% and 39% from 20–30 000 to 30–40 000 and from 30–40 000 to 40–50 000 plants ha^{-1} at harvest, respectively. Unlike Kasungu, where increases in maize yield beyond 50 000 plants ha^{-1} at harvest were observed (Figure 3A), plant population at harvest beyond 50 000 plants ha^{-1} did not increase maize yield further at Sussundenga, indicating that 40–50 000 plants ha^{-1} at harvest is the optimum range to achieve high

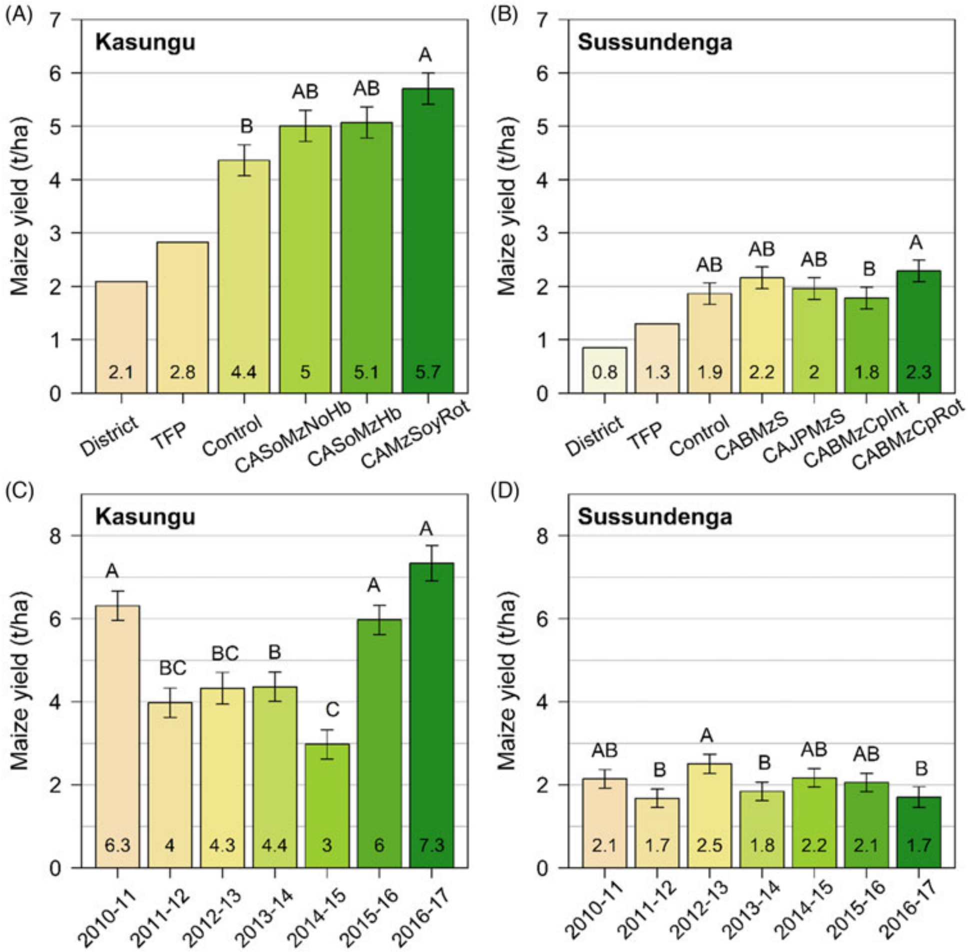


Figure 4. Maize yield across the tested cropping systems (A-B) and the growing seasons in which the on-farm trials were conducted (C-D) at Kasungu, Malawi, and Sussundenga, Mozambique. The district average and 'true farm practice' for each site across growing seasons is displayed for comparative purposes (please note data on the 'true farm practice' were not recorded in the 2010–2011 and 2015–2016 growing seasons at Kasungu nor in the 2010–2011 and 2013–2014 growing seasons at Sussundenga). Different letters above each bar denote significant differences in maize yield across cropping systems and growing seasons for each site considering a significance level of 5% ($p < 0.05$). Growing season rainfall amounts at Kasungu were as follows: 839, 750, 623, 809, 631, 635, and 759 mm ordered from the first (2010–2011) to the last growing season (2016–2017). Growing season rainfall amounts at Sussundenga were as follows: 750, 700, 627, 1127, 1198, 1387, and 1279 mm ordered from the first (2010–2011) to the last growing season (2016–2017). 'TFP' = 'true farm practice'. Please refer to Table 1 for a description of the cropping systems tested in each site.

maize yields at this site. Narrowing maize yield gaps at both sites thus requires that farmers manage to maintain high plant populations throughout the growing season.

Maize yield variability across cropping systems and growing seasons

The two-way interaction between cropping system and growing season was not statistically significant (Supplementary Table S1), indicating that cropping system performance was consistent across growing seasons. Moving onto main effects, there was a statistically significant ($p < 0.05$) effect of both cropping system and growing season on maize yield at both Kasungu and Sussundenga (Figure 4). Irrespective of the cropping system, maize yields at Sussundenga were generally much lower than at Kasungu (Figure 4). Aboveground biomass was also not statistically affected by the two-way interaction between cropping system and growing season (Supplementary Table S1). First-order cropping system and growing season effects were both statistically significant ($p < 0.05$) for aboveground biomass at Kasungu, whereas first-order growing season effects, not cropping systems, were statistically significant ($p < 0.05$) at Sussundenga (see Supplementary Figure S1 for further details).

Mean maize yield was greatest for the maize-soybean rotation (CAMzSoyRot, 5.7 t ha^{-1}) intermediate for the sole maize cropping systems with (CASoMzHb, 5.1 t ha^{-1}) and without herbicide (CASoMzNoHb, 5.0 t ha^{-1}), and lowest for the 'control treatment' (4.4 t ha^{-1}, Figure 4A). Yet, statistically significant yield differences ($p < 0.05$) were only observed between the maize-soybean rotation and the 'control treatment'. At Sussundenga, mean maize yield was greatest in the maize-cowpea rotation (2.3 t ha^{-1}), intermediate in the sole maize with basins (2.2 t ha^{-1}), sole maize with jab planter (2.0 t ha^{-1}), and 'control treatment' (1.9 t ha^{-1}), and lowest in the maize-cowpea intercrop (1.8 t ha^{-1}, Figure 4B). Statistically significant differences ($p < 0.05$) in mean maize yield between cropping systems in this site were only observed between the maize-cowpea rotation and maize-cowpea intercrop, with sole maize cropping systems not showing any statistically significant yield differences between themselves and the maize-legume cropping systems. These results indicate that minimum tillage and diversification with legumes (rotations or intercrops) were not effective in increasing maize productivity at Sussundenga. The opposite was true at Kasungu, where maize-soybean rotations and the use of herbicides provided considerable increases in maize productivity.

Maize yield at Kasungu was greatest in the first and last two growing seasons with a mean value of 6.3, 6.0, and 7.3 t ha^{-1}, respectively (Figure 4C). Intermediate mean maize yields were observed in 2013–2014 (4.4 t ha^{-1}), 2012–2013 (4.3 t ha^{-1}), and 2011–2012 (4.0 t ha^{-1}) growing seasons, and finally the lowest mean maize yield of 3.0 t ha^{-1} was observed in the 2014–2015 growing season (Figure 4C) that was characterized by low rainfall and long dry spells. Statistically significant differences ($p < 0.05$) in maize yield were observed between the 2010–2011, 2015–2016, and 2016–2017 growing seasons and the other growing seasons, and between the 2013–2014 and the 2014–2015 growing seasons (Figure 4C).

At Sussundenga, mean maize yield was greatest in the 2012–2013 growing season (2.5 t ha^{-1}), intermediate in the 2014–2015 (2.2 t ha^{-1}), 2015–2016 (2.1 t ha^{-1}), and 2010–2011 (2.1 t ha^{-1}) growing seasons, and lowest in the 2013–2014 (1.8 t ha^{-1}), 2011–2012 (1.7 t ha^{-1}) and 2016–2017 (1.7 t ha^{-1}) growing seasons (Figure 4D). Statistically significant differences ($p < 0.05$) in maize yield, at the same site, were observed between the 2012–2013 growing season and the 2011–2012, 2013–2014, and 2016–2017 growing seasons only (Figure 4D).

Potential contribution of agronomic and CA practices to maize yield

Mean maize yield at Kasungu (district average) ranged between 1.1 t ha^{-1} in the 2014–2015 growing season and 2.8 t ha^{-1} in the 2010–2011 growing season, with an average of 2.1 t ha^{-1} across growing seasons (Figure 4A). District average maize yield across growing seasons at Sussundenga was only 0.9 t ha^{-1} (Figure 4B), with a maximum and minimum value of 1.2 and 0.7 t ha^{-1} in the 2010–2011 and 2012–2013 growing seasons, respectively. The average 'true farm practice' across growing seasons at Kasungu was slightly above the district average, i.e., 2.8 t ha^{-1} (note data for two growing seasons were not recorded), and the same was true at Sussundenga, 1.3 t ha^{-1} (Figures 4A and 4B). Maize yield in the 'control treatment' of the on-farm trials was therefore considerably larger than the district average maize yield or the measured maize yield in fields managed by farmers on their own, and this was true at both Kasungu and Sussundenga (Figure 4). Such large differences between maize yields measured under farm conditions and maize yields under on-farm trials indicate that improving basic agronomic practices, such as those

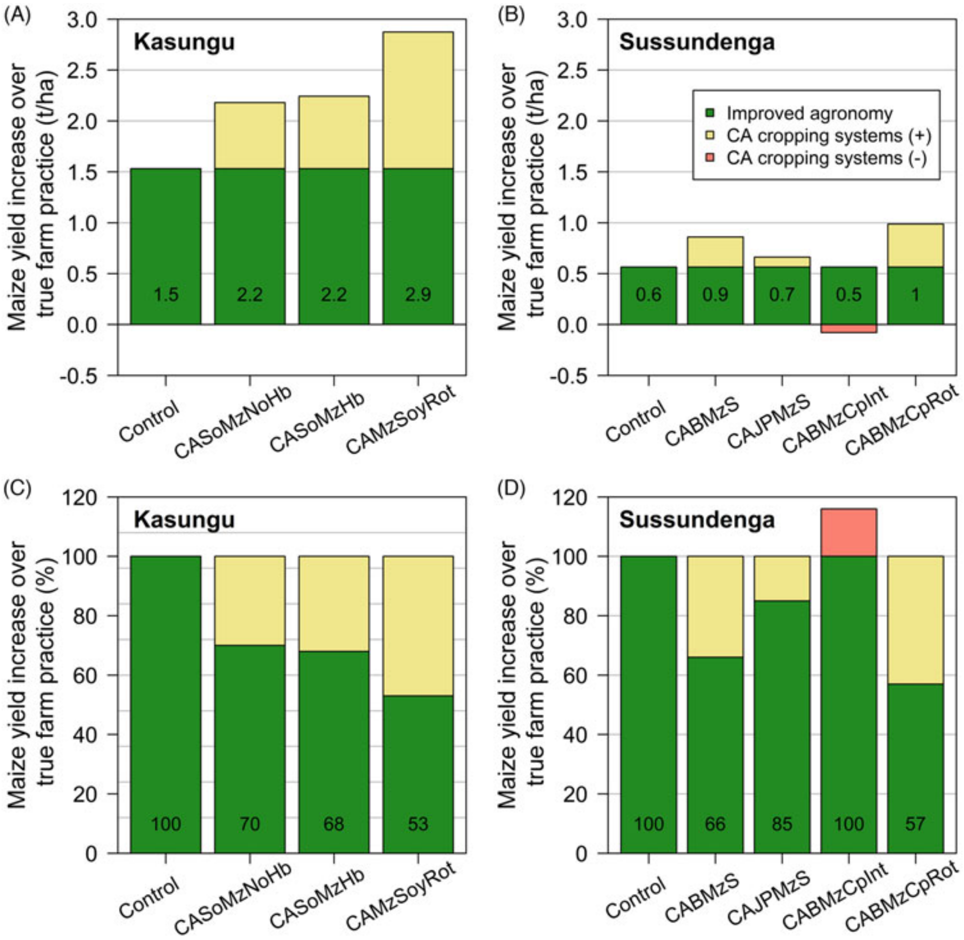


Figure 5. Absolute and relative maize yield increase due to improved agronomy and conservation agriculture cropping systems relative to the 'true farmer practice' at Kasungu, Malawi (A-B), and Sussundenga, Mozambique (C-D). Calculations were done using the predicted means across seven growing seasons estimated using linear mixed models (cf. Figure 4). Please refer to Table 1 for the full definition of the codes used for the different cropping systems and to Supplementary Table S1 for background data.

used in the 'control treatment', can have a significant contribution to increase farmers' yields, which was true across growing seasons.

At Kasungu, the 7-year mean maize yield amounted to 2.1 t ha^{-1} for the district average, 2.8 t ha^{-1} for the 'true farmer practice', and 4.4 t ha^{-1} for the 'control treatment' in the on-farm trials (Figure 4). The 'control treatment' thus resulted in a yield increase of 1.5 t ha^{-1}, equivalent to 54% more than the 'true farm practice' (Figures 5A and 5C). For the CA sole maize cropping system with no herbicide applied, the overall mean yield increase over the 'true farm practice' amounted to 2.2 t ha^{-1}, corresponding to an increase of 77% over the 'true farm practice' (Figures 5A and 5C). Out of this, 70% of the yield increase, equivalent to 1.5 t ha^{-1}, was attributable to agronomic practices while the remaining 30%, equivalent to 0.7 t ha^{-1}, was attributed to the cropping system tested (see Table 1). For the CA sole maize cropping system with herbicide, the overall maize yield increase was 2.2 t ha^{-1} and equivalent to 79% of the maize yield of the 'true farm practice' (Figures 5A and 5C, Supplementary Table S2). Of this overall yield increase, 68% was attributable to agronomy practices, and 32%, corresponding to 0.7 t ha^{-1}, was attributable to use of reduced soil disturbance, soil cover, and chemical weed control. In the best case (CA maize-soybean rotation), in which all CA principles (reduced soil disturbance, provision of soil cover, and crop rotations) were applied, the overall maize yield increase relative to the 'true farm practice' was 2.9 t ha^{-1}, and of this, 53% was attributable to agronomic practices while the remaining 47% was attributable to the CA components of the tested cropping system and the use of herbicide (Figures 5A and 5C). Thus, for all three CA cropping systems tested at Kasungu, agronomic practices alone accounted for 50 to 70% of the observed yield increases while CA-related practices accounted for 30 and 50% of the observed yield increases over the 'true farm practice' (Figures 5A and 5C).

The 7-yr mean maize yield at Sussundenga was 0.9 t ha^{-1} for the district average, 1.3 t ha^{-1} for the 'true farm practice' and 1.9 t ha^{-1} for the 'control treatment' in the on-farm trials (Figure 4). The maize yield increase due to agronomic practices in the 'control treatment' relative to the 'true farm practice' thus amounted to 0.6 t ha^{-1}, equivalent to 43% of the maize yield in the 'true farm practice' (Figures 5B and 5D). The highest overall maize yield increase relative to the maize yield of the 'true farm practice' was 1.0 t $ha^{-1,}$ corresponding to 74%, and was observed for the CA maize-cowpea rotation (Figures 5B and 5D). In total, 57% and 43% of this increase in maize yield was attributable to agronomic practices and CA practices, respectively (Figures 5C and 5D, Supplementary Table S2). For the CA jab-planter sole maize cropping system, the maize yield increase relative to the 'true farm practice' was 0.7 t ha^{-1} and 85% of this increase (amounting to 0.6 t ha^{-1}) was attributable to agronomic practices while the remaining 15% (equivalent to 0.1 t ha^{-1}) was attributable to the CA practices (Figures 5B and 5D). Finally, the CA basin sole maize cropping system increased maize yield by 0.9 t ha^{-1} over the 'true farm practice', and 66% (or 0.6 t ha^{-1}) of this increase was attributable to agronomic practices. The remaining 34% (or 0.3 t ha^{-1}) was attributed to the CA practices (Figures 5B and 5D). Thus, excluding the CA maize-cowpea intercropping system, which reduced maize yield compared to the 'control treatment', the tested CA cropping systems increased maize yield by 57 to 85% relative to the 'true farm practice' (Figures 5B and 5D).

Discussion

The importance of plant population for maize yield in Southern Africa

The positive maize yield response to increased plant population at harvest at Kasungu and Sussundenga (Figures 2 and 3) confirms that plant population is a key factor driving maize productivity in Southern Africa. Theoretically, maize yield increases with increasing plant population following a quadratic functional form, whose maximum yield and optimal plant population are site-specific (Greveniotis et al., 2019). For instance, a maximum plant population of about 90 000 plants ha^{-1} is deemed optimal in high-yielding environments of the USA (Assefa et al., 2016), which is considerably more than the 53 333 and 44 444 plants ha^{-1} recommended for maize growing environments of Malawi and Mozambique, respectively. In this study, plant populations at harvest were below the levels recommended at both sites for a large number of field-year combinations, which explains the positive relationship between maize yield and plant population at harvest observed in most growing seasons (Figure 2). These findings confirm that failure to reach optimum plant populations at harvest contributes to considerable yield losses both in on-farm trials and farmers' fields. The results reconfirm that plant population at harvest has a strong influence on maize productivity (van Roekel and Coulter, 2011; Dawadi et al., 2012), thus being a key agronomic step toward increasing maize yield (Farnham, 2001, 1998) in smallholder farming systems of Southern Africa.

Low maize plant population at harvest in rainfed cropping systems of Southern Africa are often caused by poor seed quality (especially in Mozambique), sowing when conditions are not conducive for good crop establishment (arising from labor constraints and poor timeliness of planting; Nyagumbo et al., 2017) or simply poor soil fertility (Rurinda et al., 2014). Farmers in Southern Africa typically use poor-quality seed from previous harvests, which often results in poor germination and non-uniform crop stands (Mazvimbakupa et al., 2015). Seed treatment with chemicals often helps to preserve seed from weevils and attack by soil-borne pests when planted. Yet, in this study, the seed that was used in the on-farm trials was improved quality seed that was supplied from local commercial suppliers who, in some cases, failed to treat the seed properly. In such rainfed cropping systems, the early and subsequent stages of crop development are often negatively affected when poor-quality seed is employed (Mazvimbakupa et al., 2015; Khodarahmpour, 2012). The distribution of rainfall, i.e., its variability at crop establishment and long dry spells soon after planting, in each season at each site, possibly also influenced the strength of the linear relations between maize yield and plant population (Figure 2). This could explain why nonsignificant linear relationships were obtained, for instance, at Kasungu in the 2012–2013 growing season and at Sussundenga in the 2011–2012 growing season (Figure 2). Given the importance of plant population at harvest for maize-based cropping systems in Southern Africa, we recommend future studies to consider this factor in yield gap assessments in the region and to better understand the factors driving poor crop establishment and reductions in plant population during the growing season (see also An et al., 2021). Delayed responses by farmers to activate pest control (cutworms, fall army worm, stalkborer, rodents) and late weeding in some instances, may have also contributed to variability in plant populations measured at harvest. Yet, this did not advantage or disadvantage a particular cropping system.

CA cropping systems and their potential to increase maize yield

Temporal trends observed for maize yields in the on-farm trials revealed that CA has an advantage over the ‘control treatment’, particularly when maize-legume rotations are practiced as found for the maize-soybean rotation at Kasungu, Malawi (Nyagumbo et al., 2016). The maize yield obtained in the CA maize-cowpea rotation at Sussundenga was also slightly higher than the maize yield in the ‘control treatment’, with such difference being as high as 87% in one growing season (data not shown). These results validate earlier conclusions regarding the potential of maize-legume rotations for sustainable intensification of maize-based cropping systems in sub-Saharan Africa (Nyagumbo et al., 2020; Franke et al., 2018). It is also worth noting that the contribution of other CA practices, namely minimum tillage, residue retention, and use of herbicides, contributed to increases in maize productivity at Kasungu but did not prove effective in intensifying maize production at Sussundenga (Figure 4). Possible causes for the latter could be the erratic rainfall patterns, a build-up of pests and diseases, or poor crop management. For example in Barue district of Mozambique, white grubs (larvae of *Phyllophaga* ssp. and *Heteronychus* spp.) were observed as being more problematic in CA cropping systems (Thierfelder et al., 2014). Diseases such as gray leaf spot were found to be prevalent in CA cropping systems due to the carry-over of residues from one growing season to the next, particularly when humid conditions prevail for a period of 2 weeks or more (Cairns et al., 2012).

A recent synthesis of CA studies in Eastern and Southern Africa established that cereal-legume rotations can increase maize yield by as much as 41% over continuous maize monocropping (Nyagumbo et al., 2020). In another study in Mozambique, intercropping of maize with pigeonpea resulted in maize yield increases of up to 4.8 t ha^{-1} relative to conventional plowing (Rusinamhodzi et al., 2012). Yet, in this study, the intercropping of maize and cowpea tended to depress maize yield (Figures 4 and 5), an effect attributed to competition for soil moisture. The incorporation of legumes in maize-based cropping systems, as rotations or intercrops, increases nitrogen availability through biological nitrogen fixation (Franke et al., 2018). For example, soybean can fix up to 53–82 kg N ha^{-1} yr^{-1} (Giller, 2001) and cowpea can fix up to 337 kg N ha^{-1} yr^{-1} (Yahaya et al., 2019). The inclusion of legumes in a rotation-based cropping system also helps to prevent the carry-over of pests and diseases (Mango et al., 2017).

Therefore, diversification and intensification through rotation of legumes in cereal-based cropping systems is an effective option for sustainable maize intensification in sub-Saharan Africa (Vanlauwe et al., 2019). Yet, such legume rotations can be unattractive to land-constrained farmers who tend to focus on producing the staple food crop (maize) before allocating land to alternative legume crops. It may thus be important to identify conditions or niches (e.g., Baudron et al., 2015) where maize yield increases due to legume diversification are likely to be realized.

Maize yield response to agronomic and CA practices

After seven consecutive growing seasons, the on-farm trial results at Kasungu, Malawi, and Sussundenga, Mozambique, indicated that agronomic practices, not direct investments in the CA principles, were responsible for the largest maize yield increases observed at each site (Figures 4 and 5). Agronomic practices as applied here involved the use of improved crop varieties, use of recommended rates of mineral fertilizers, and timely crop management practices particularly sowing and weeding. Investments in these agronomic practices should thus be prioritized for maize yield improvements at least in the short-term (Figures 4 and 5). These results support recent findings that increasing input use, more timely planting and efficient crop management is needed to narrow maize yield gaps in Eastern and Southern Africa (Assefa et al., 2020; Silva et al., 2023). They also highlight the need for timely planting and efficient crop establishment (Nyagumbo et al., 2017), in addition to investments in soil fertility management (Vanlauwe et al., 2015) toward increasing maize productivity in the region. Although agronomic practices and CA principles can both contribute to improve maize productivity of smallholder cropping systems in Southern Africa, our results indicate that agronomic practices such as improved seed, use of mineral fertilizer, correct plant populations, and timely sowing and weeding were responsible for more than 50% of the observed yield increases in CA cropping systems tested on-farm, and therefore need not be ignored in future agricultural research and development programs.

At both Kasungu and Sussundenga, the largest yield gain relative to the ‘true farm practice’ was generated from CA cropping systems involving the three CA principles (Mwansa et al., 2017; Thierfelder et al., 2014; Wall et al., 2014), i.e., reduced soil disturbance, application of soil cover, and maize-legume rotations. For these cropping systems, the use of all three CA principles accounted for 47% and 43% of the maize yield increase over the ‘true farm practice’ at Kasungu and Sussundenga, respectively (Figure 5). At Kasungu, the overall yield gain of the sole maize CA cropping system (in which no herbicide was applied and only two of the CA principles, i.e., reduced soil disturbance and provision of soil cover, were applied) relative to the ‘true farm practice’ was 77% with the CA practices accounting for only 30% of that yield increase and agronomic practices accounting for as much as 70% of that yield increase (Figure 5). Similarly, at Sussundenga, the use of CA basins with a continuous maize monocrop, in which the diversification CA principle was not implemented, resulted in an overall yield gain relative to the ‘true farm practice’ of 66%, and out of this, 66% and 34% of that yield increase was attributed to agronomic and CA practices, respectively (Figure 5). The results from this study show that huge strides from a yield standpoint can be achieved by simply addressing basic agronomic management practices including, e.g., variety choice, fertilization, timely planting, and weeding, even without the three CA principles as evidenced by the 54% and 43% maize yield increases of the ‘control treatment’ used in the on-farm trials relative to ‘true farm practice’ at Kasungu and Sussundenga, respectively (Figure 5). It is clear, therefore, that maize yield gaps in farmers’ fields in Southern Africa could be considerably reduced by applying available production technologies more effectively as a first step, let alone applying CA principles. These outcomes confirm that Southern Africa smallholders’ low productivity is to a large extent attributable to poor agronomy, insufficient and inappropriate fertilizer application, lack of use of improved cultivars, and in some instances inappropriate tillage practices (Jama et al., 2017; Kihara et al., 2014; Mhlanga et al., 2015; Morris et al., 2007).

Our results also indicate that the generally resource-constrained farmers in Southern Africa can yield 45 to 55% more without CA principles if improved crop varieties, herbicides, and fertilizers are used according to the recommendations. Measurement of maize yields in farmers' fields not targeted by research for development programs testing improved technologies on-farm is thus critical to contextualize the yield responses of technologies tested in those trials. Moreover, governments in Southern Africa should develop policy strategies that ensure smallholders are capacitated to address basic agronomic factors as a first step towards improved food security in the region. The application of CA principles has its payoffs as yield benefits from cereal-legume rotation, minimum tillage, and residue retention become increasingly larger and more conspicuous over time (e.g., Nyagumbo et al., 2016). Previous economic analyses revealed that CA, improved varieties, and associations of cereal-legume crops were economically viable for risk-averse smallholders (Mutenje et al., 2019; Nyagumbo et al., 2021). Moreover, the evaluated CA technologies had payback periods of at least 2 years due to the extra investments that were needed for their effective implementation, yet the use of mineral fertilizer and crop diversification were also considered important risk aversion strategies (Mutenje et al., 2019). Despite the agronomic and economic benefits of CA, we note that agronomic practices can also make significant contributions to maize yield increases. This is important because smallholders who fail to adopt CA can still realize significant yield gains through recommended agronomic practices. Although this study disentangled the yield gains due to CA from those due to agronomic practices, it still did not effectively isolate which agronomic practices were limiting maize productivity as such effects were bundled in the 'control treatment', which could be done along two complementary avenues of future research. First, future on-farm trials will need to evaluate the interaction between agronomic practices and CA cropping systems to unpack the contribution of individual agronomic practices to crop yield and resource-use efficiency under CA. Second, decomposing yield gaps using farm field data (Silva et al., 2017) would be invaluable to identify and help target the agronomic practices with the highest leveraging effects on food security.

Conclusion

Results of this study highlight a strong linear and positive relationship between maize yield and planting population at harvest in four out of seven growing seasons at Kasungu, Malawi, and six out of seven growing seasons at Sussundenga, Mozambique. On average, maize yield increased by 90 and 63 kg ha^{-1} for every 1000 plants ha^{-1} increase in plant population at harvest at Kasungu and Sussundenga, respectively. These results indicate that maize yields are largely compromised by low plant populations, which often fall below optimum levels in smallholder farming systems. Paying due attention to attaining optimum recommended plant populations at harvest could thus go a long way toward improving maize productivity in Southern Africa. Ensuring high plant population throughout the growing season requires a combination of high-quality treated seed, timely sowing when conditions are conducive for crop establishment, and improvements in soil fertility, among other factors.

The use of good agronomic practices alone, and without implementing CA principles, resulted in maize yield gains of as much as 54 and 43% relative to the 'true farm practice' at Kasungu and Sussundenga, respectively. The results also indicate that the largest yield gains in the tested cropping systems were derived from investments in agronomic practices, i.e., the use of improved seeds, fertilizer, and timely crop management, rather than from CA-related practices. Good agronomic practices alone accounted for between 53 and 70% of the observed yield increases relative to the 'true farm practice' from the tested CA cropping systems at Kasungu and between 57 and 85% at Sussundenga. It remains critical to disentangle the relative contribution of the different agronomic practices to identify the limiting factors to maize production under smallholder farming in Southern Africa.

Although CA cropping systems significantly improved maize yield at Kasungu, and much less so in Sussundenga, such increases were smaller in magnitude compared to the yield gains due to agronomic practices. Yet, returns to CA investments became relatively larger when all three CA principles were applied together. Although the study did not isolate the different components constituting good agronomic practices, it still points to the need for policy makers to invest in strategies enabling access to improved seeds and fertilizer, and timely crop management as a key to increase smallholder maize productivity in the region.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0014479724000012

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Key points.

- Increasing plant population at harvest by 1000 plants ha^{-1} increased maize yield by about 60–90 kg ha^{-1} on average.
- Improved seed and high planting population at harvest, together with proper fertilizer and weed management, boosted maize yield by more than 40%.
- In the lowest-yielding conservation agriculture plots, 70% of the observed maize yield increase was attributed to agronomic practices alone.
- Conservation agriculture comprising cereal-legume rotation systems resulted in the highest maize yields in both sites.
- Access to improved seed, fertilizer, and crop management practices is required to increase smallholder maize productivity in Southern Africa.

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