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Incorporating male sterility increases hybrid maize yield in low input African farming systems

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Abstract

Maize is a staple crop in sub-Saharan Africa, but yields remain sub-optimal. Improved breeding and seed systems are vital to increase productivity. We describe a novel hybrid seed production technology that will benefit seed companies and farmers. This technology reduces the cost of seed production by preventing the need for detasseling. The resulting hybrids segregate 1:1 for pollen production, conserving resources for grain production and conferring a 200 kg ha^{-1} benefit across a range of yield levels. This represents a 10% increase for farmers operating at national average yield levels in sub-Saharan Africa. The yield benefit of fifty-percent non-pollen producing hybrids is equivalent to approximately six years of progress in plant breeding. Benefits to seed companies in the form of reduced production cost and improved seed purity will provide incentives to improve smallholder farmer access to higher quality seed of climate-smart hybrids. Demonstrated farmer preference for these hybrids will help drive their adoption.

Introduction

Increasing productivity of smallholder farmers in sub-Saharan Africa (SSA) is an important step towards improving livelihoods and reducing risk (Hansen et al. 2018). Maize yields in SSA remain the lowest in the world, with historical production increases are associated with an unsustainable increase in maize area. At current yield levels, the area under maize cultivation must increase by 184% to meet future food security needs (van Ittersum et al. 2016). Obsolete varieties that were developed for climate conditions which have subsequently changed are still widely grown. Rapid-cycle breeding and faster varietal replacement are essential to increasing yields under changing climates (Atlin et al. 2017). Progress in SSA has been made through modernizing breeding programs, engagement with seed companies, and development and delivery of elite, stress-tolerant varieties (Cairns and Prasanna, 2018). Improved maize production in Ethiopia, through improved maize genetics and other agronomic inputs (Abate et al. 2015), has helped lift an estimated 788,000 people out of poverty annually (Kassie et al. 2018). There is increasing focus on improving the efficiency of public sector maize breeding (Cobb et al. 2019) but seed production remains a key bottleneck in SSA (Prasanna et al. 2021).

Hybrids are maize varieties in which the seed is produced by two different parent lines, increasing the yield through heterosis. Detasseling in hybrid seed production in SSA is manual, unlike other regions of the world, leading to higher cost of the seed and issues with quality (Eritro et al. 2017; Gaffney et al. 2016).

Most commercially available hybrids in SSA are three-way hybrids which are formed by crossing two lines together to form a single cross female parent and then crossing the single cross female to a third inbred to produce commercial seed. Three-way cross hybrids are common in SSA since the cost of goods sold (COGS) is lower due to the higher seed yield of single cross females compared with inbred lines. Technologies to reduce both COGS and the complexity of producing high quality hybrids would offer smaller seed companies greater opportunities to provide new hybrids to smallholder farmers. Seed Production Technology (SPT) is a process previously used by Corteva Agriscience to produce commercial hybrid maize seed in the United States. The original SPT system was based on a recessive male sterility gene, Ms45, and utilized a transgenic maintainer cassette containing a gene to restore fertility to ms45 homozygous plants, an α-amylase gene to render transgenic pollen non-viable, and a seed color marker gene (Wu et al. 2016). SPT enables the production of homozygous male sterile non-transgenic seed.

Subsequent development of an SPT system based on the dominant male sterility gene, Ms44, (Fox et al. 2017), enables seed increase of homozygous dominant NPP inbred and heterozygous NPP female single-cross parent plants. The Ms44-SPT system is well suited for three way hybrid production as it eliminates the need for detasseling maize hybrid production fields during both hybridization steps. Three-way hybrids produced using heterozygous NPP female parents segregate 1:1 pollen-producing (PP) and non-pollen-producing (NPP) and have been shown to increase yield by 4% when nitrogen was applied at only 66-112 kg ha^{-1} (compared to 224 kg N ha^{-1}) in the US (Fox et al. 2017). Such hybrids are designated fifty-percent non-pollen-producing (FNP). Low fertilizer use (<17 kg ha-1) is a major factor contributing to the yield gap in SSA (Leitner et al. 2020), particularly in female-managed plots (Farnworth et al. 2017) and is exacerbated by low and variable returns on investment (Jayne et al. 2018). Here was investigate the potential of FNP hybrids to increase maize yields under a range of conditions including low input and drought stressed conditions commonly encountered by small holder farmers in SSA. Most agricultural research only involves researchers, without any participation from farmers (Stathers et al. 2020). Working with the primary beneficiaries is essential to ensure an understanding of what the user needs or wants in order to facilitate adoption (Gaffney et al. 2016). For this reason, trials were conducted largely on-farm with primary beneficiaries and farmer perceptions of FNP hybrids were evaluated. Finally we investigate the mechanisms for the yield increase associated with the FNP trait.

Results

FNP hybrids have increased yield relative to PP hybrids

Multiple hybrids were grown in both on-station trials (OST) and on-farm field trials (OFT) across Kenya, South Africa and Zimbabwe, from 2016-2019. The FNP trait was evaluated in 26 different hybrid backgrounds. Trials were conducted in 112 locations. FNP hybrids produced using SPT increase yield over a broad range of environments. When averaged across all hybrids within a location, the grain yield of FNP hybrids, relative to their PP controls, was consistently higher across yield levels (Fig 1A). FNP hybrids significantly out-yielded the PP controls in 75% of the locations tested, with an overall average yield increase of 202 kg ha^{-1}. Absolute yield improvement was consistent across yield levels (Fig 1A). Predicted yield improvement is 192 kg ha^{-1} (9.6 %) at the low end (2000 kg ha^{-1}) and 229 kg ha^{-1} (2.4 %) at the high end (8000 kg ha^{-1}) (Fig 1B).

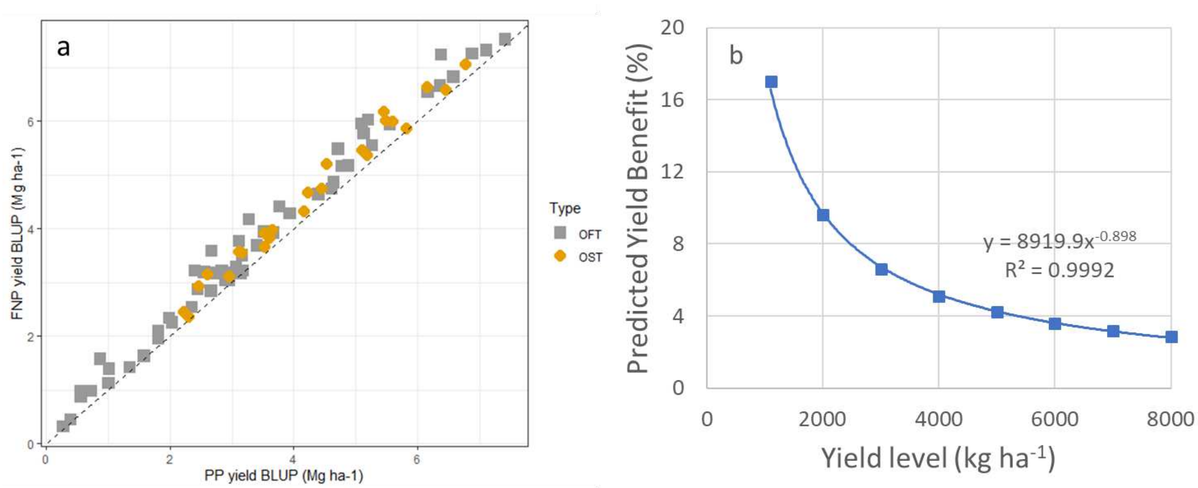

Figure 1. Yield of fifty-percent non-pollen producing (FNP) hybrids compared with conventional PP hybrids. A. FNP hybrids yield (y axis) plotted against the yield of pollen producing (PP) conventional hybrids (x axis). Each point represents the mean of four to nine hybrid backgrounds for on-farm trials (OFT) (grey square) and 4-15 hybrid backgrounds for on-station trial (OST) (yellow diamond). The dotted grey line represents the 1:1 line. B. Percent yield increase predicted by growing FNP hybrids (y axis) plotted against location mean yield (x axis). Yield increase was projected using the fitted linear regression in Fig 1A to predict yield of FNP hybrids.

The yield benefit of FNP was consistent across 19 hybrid backgrounds with more than 22 locations of data (Figure 2). Seven hybrids were not included as they were grown in 12 or fewer locations. From these 19 hybrids, the average yield advantage of FNP in single cross hybrids was 178 kg ha^{-1} and for three-way crosses the benefit was 264 kg ha^{-1}.

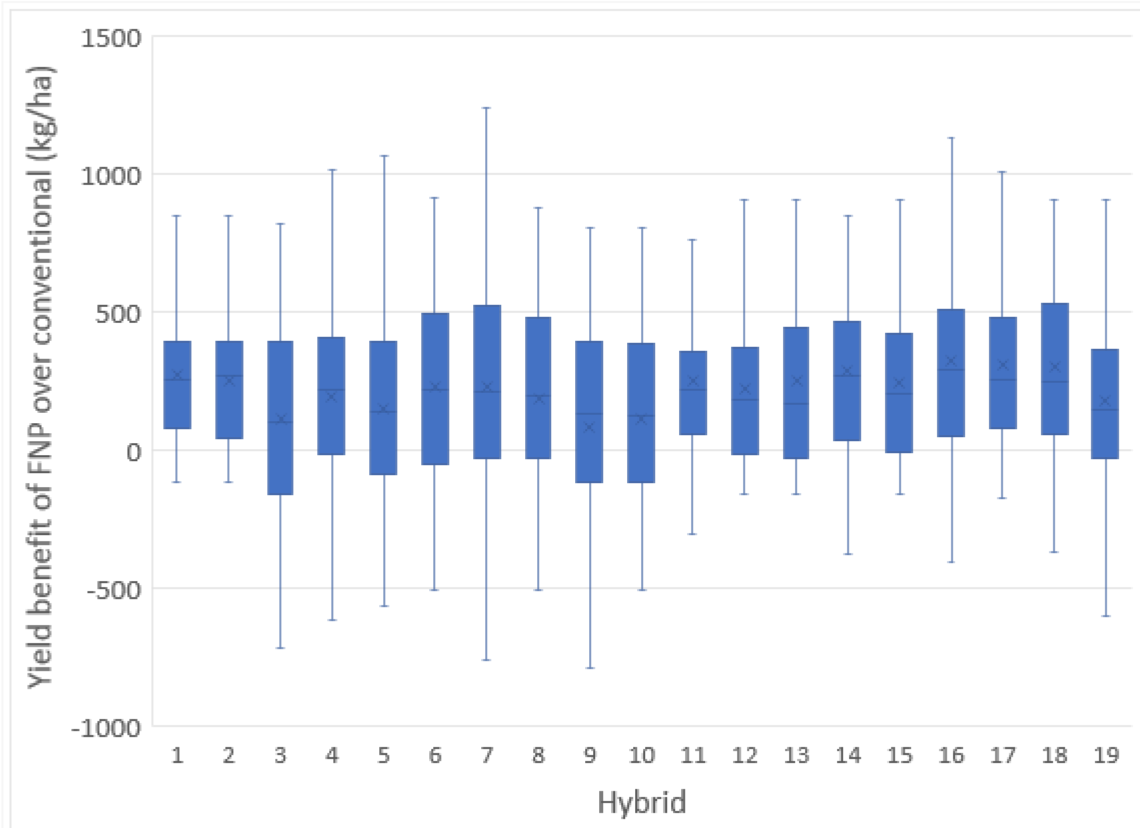

Figure 2. Box and whisker plots indicating the range in yield benefit (kg ha-1) for FNP hybrid compared with conventional control for 19 hybrids, each grown in at least 20 locations. Hybrids 1-11 are single crosses, 12-19 are three-way crosses. Seven hybrids were removed as they were grown in 12 or fewer locations. X represents the mean, the solid box represents 25th to 75th percentile and the whiskers represent the minimum and maximum of the distribution. Outliers (greater than 1.5 outside the outer quartile) were removed.

Secondary trait differences between PP and NPP plants

Across all trials, the yield of FNP hybrids increased significantly by 202 kg ha^{-1} or 5.2%, compared with conventional PP controls (Table 1A). There was no difference in grain moisture. In a subset of OST in Zimbabwe, individual plants were tagged and identified as either PP or NPP at flowering. NPP plants are significantly shorter (3-4%) and have significantly lower ear height (1.1%) than PP plants (Table 1B). NPP plants have a significant 8.7% increase in grain dry weight per plant, and a significant decrease in tassel branch number (8.5%) and tassel dry weight at flowering (6.7%).

Table 1. (A) Grain yield (Mg ha-1) and grain moisture (%) (mean ± se) across all on-farm and on station trials for fifty-percent non-pollen producing (FNP) and pollen producing (PP) control hybrids. The difference between FNP and PP mean values, % change, probability and N (number of data points) are

also presented. (B) Measurements recorded on individual non-pollen producing (NPP) or PP plants tagged within an FNP hybrid plot for a subset of on-station locations. Values presented are the mean ± se for each trait, the difference between FNP and PP values, % change, probability and N (number of data points) are also presented. (C) Ear component traits estimated from image analysis of NPP and PP ears taken from tagged plants within an FNP hybrid plot. Values presented are the mean ± se for each trait, the difference between FNP and PP values, % change, probability and N (number of data points) are also presented. Samples were taken from a subset of on-station locations.

Trait	Pollen Producing (PP)	Fifty-percent non-pollen producing (FNP)	Difference	Change (%)	Pvalue	Number
A						
Yield (Mg ha-1)	3916.5 ± 73.2	4118.6 ± 73.3	202.1	5.2	<0.0001	4585
MST (%)	18.18 ± 0.25	18.22 ± 0.25	0.03	0.20	0.62	3923
B						
Ear height (m)	1.01 ± 0.01	1.00 ± 0.01	-0.01	-1.1	<0.01	708
Plant height (m)	1.93 ± 0.01	1.86 ± 0.01	-0.07	-3.8	<0.0001	708
Grain weight (g)	87.6 ± 3.7	95.2 ± 3.7	7.6	8.7	<0.0001	698
Tassel branch number	16.7 ± 0.18	15.3 ± 0.18	-1.4	-8.5	<0.0001	713
Tassel weight (g)	4.0 ± 0.09	3.73 ± 0.09	-0.27	-6.7	<0.001	714
C						
Kernel number	281.3 ± 3.7	297.9 ± 3.7	16.6	5.9	<0.001	464
Grain weight (g)	89.6 ± 1.4	95.1 ± 1.4	5.6	6.2	<0.001	464
100 kernel weight (g)	31.7 ± 0.34	32.0 ± 0.34	0.3	0.9	<0.01	469
Cob length (cm)	13.2 ± 0.18	13.9 ± 0.18	0.64	4.9	<0.0001	469

In these same trials, photos of all the ears harvested from NPP and PP plants were taken at harvest and image analysis used to estimate ear parameters (Makanza et al. 2018). Table 1C indicates that NPP plants had a significant 5.9% increase in the number of kernels per plant, and a small but significant increase in 100 kernel weight of 0.9%. Cob length was increased significantly (4.9%), reflecting the larger number of kernels for NPP plants.

Farmer Participatory Evaluation

In Kenya, 2697 farmers (62% women) visited the trials to evaluate the FNP technology at eight different sites in 2017 and 2018. When participants were first asked to score the importance of the different criteria on a scale of 0 (not important) to 3 (very important), they gave high scores to most of the criteria. During the mid-season evaluation, the criteria with highest scores were yield, early maturity, cob size and number of cobs, which all received an average score between 2.5 and 2.7. When farmers were asked if tassel formation was important during the mid-season evaluation, they scored the trait very high (2.68) second only to yield (2.69) (out of a maximum of 3). Similarly, amount of pollen shed received an importance score of 2.6.

During the mid-season evaluation in 2017, farmers scored the conventional PP hybrids significantly higher for tassel formation and pollen shed than the FNP hybrids, indicating they can clearly distinguish the two types (Figure 3a). In the mid-season, both the yield score and the overall score of the FNP hybrids were significantly higher than that of the conventional, PP hybrids. Otherwise, there were few differences between the scores for the individual criteria. At the end-season (harvest) evaluation, there was no difference between scores for tassel formation of PP and FNP hybrids, indicating that participants could no longer tell the difference. At harvest, FNP hybrids generally scored better on several criteria, including significant differences for cob size and yield, and for the overall evaluation. At the mid-season evaluation in 2018, scores for amount of pollen shed were similar between PP and FNP hybrids, the latter even getting slightly higher scores for tassel formation. During group discussions after the (individual) evaluations, farmers explained they now understood the trait and did not give FNP hybrids lower scores, even though they recognized the morphological differences. The results at harvest in 2018 were similar to those in 2017: there was no difference between the two hybrid types for tassel formation, but FNP hybrids scored higher on yield and overall evaluation compared to conventional hybrids. The results indicate that farmers can distinguish FNP from PP hybrids and identify them as higher yielding and better overall (Figure 3b).

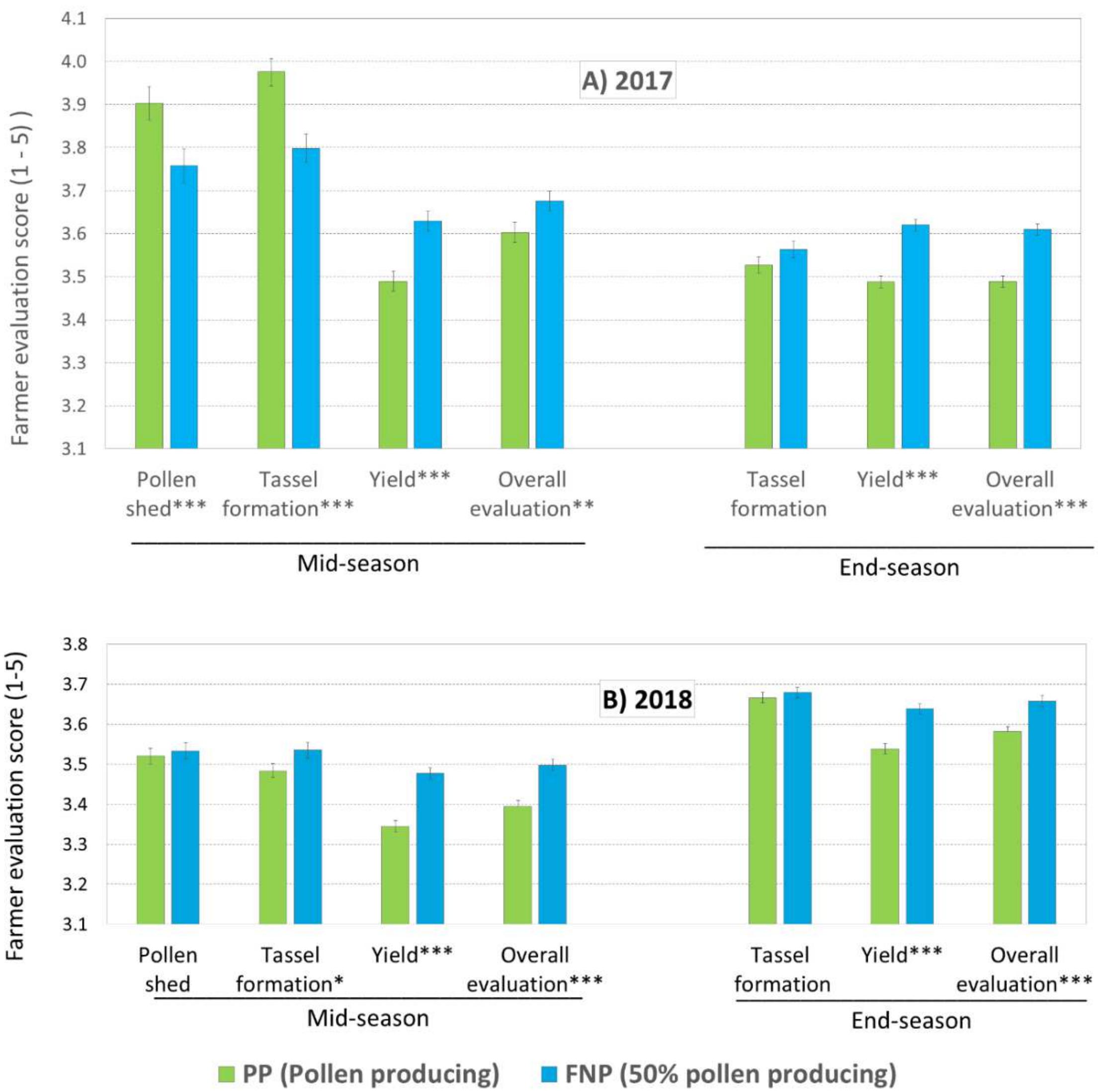

Figure 3. Farmer evaluations of pollen producing (PP) and fifty-percent non-pollen producing (FNP) hybrids in A. 2017 and B. 2018, on a 5-point hedonic scale (1 = dislike very much, 2 = like, 3 = neither like nor dislike, 4 = like, 5 = like very much) in mid-season and end-season for different criteria and overall. Bars present average scores, error bars present standard errors, asterisks represent significance of the difference in pairwise t-tests.

Impact Assessment

At this stage, technology adoption rates are unknown, but based on preliminary discussions with seed companies two scenarios can be considered. An adoption rate of FNP of 10% of the current area in maize hybrids seems a reasonable low-end scenario, while 25% would be an optimistic scenario. Based on FAO statistics and the adoption literature, the maize area in the top 25 maize producing countries is estimated at 36.6 M ha, of which 34.2% or 12.6 M ha is planted to hybrids. The total seed needed for the low scenario (10% adoption by hybrid users) is calculated at 31,390 tonnes, and 78,000 tonnes at the high scenario (25% adoption). At an adoption rate of 10%, only 11 countries have a demand of more than 1000 tonnes (and 17 a demand of > 100 tonnes). The total demand for FNP seed for these 11 countries adds up to 27,906 tonnes, 93% of the total.

To compare the benefits to the cost, we use net present value (NPV), internal rate of return (IRR) and benefit cost ratio (BCR) (Gitner, 1982) (Table S5). Based on the current cost of the development of the technology, from 1 to 1.6 million $/year, the discounted cost comes to 28.9 million. For the benefits, we assume the technology to be on the market in 2023, and to take 10 years to reach the target 10% adoption (market penetration of FNP hybrids as a percentage of hybrid seed), keeping maize production constant. Under this basic scenario, maize production is expected to increase by 244,204 tonnes per year at the target adoption rate, valued at $40 million. The discounted benefits, up to 2040, are estimated at 180 M$. The NPV is calculated at 152 M$, the BCR at 6.25, and the IRR at 24%. Under the optimistic scenario, the adoption rate of FNP reaches 25% of total hybrid use, and the extra production is estimated at 610,511 tonnes annually, valued at $100 million. Under this scenario, the discounted benefits up to 2040 are estimated at $452 million, the NPV at $423 million, the BCR at 16 and the IRR at 32%.

Discussion

In farmers' fields across hybrid backgrounds in Africa, we demonstrate that FNP hybrids, segregating for Ms44, increase yield by approximately 200 kg ha^{-1} at current SSA yield levels. There is an urgent need to increase genetic gain for yield under low fertility conditions; observed rates of genetic gain under drought are 23-32 kg ha^{-1} yr^{-1} and low nitrogen 21 kg ha^{-1} yr^{-1} (Masuka et al. 2017). The yield benefit of FNP hybrids under stress conditions represents at least six years of progress in plant breeding. This study demonstrates the ability of FNP hybrids to deliver 10-20% yield increase under extremely stressful growing conditions faced by millions of small holder maize farmers. The stability of the yield benefit across genetic backgrounds indicates that FNP can be successfully deployed across an array of hybrids to meet the needs of farmers in various agroecological zones throughout SSA.

On-farm trials are being increasingly scrutinized due to high input and yield levels that are not representative of the actual realities of the farmers testing the technologies (e.g. de Roo et al. 2017; Laajaj et al. 2020). Our aim was to evaluate yield benefits at close to national average yield levels by targeting farmer managed on-farm trials with minimal nitrogen inputs, typical of many smallholder farmers. Participatory research was a key component given the visual differences of FNP hybrids compared to conventional hybrids. Kenyan farmers interviewed during participatory evaluation of these trials could observe the differences in tassel and pollen formation but favored FNP hybrids overall due to the improved ear size and increased yield. As the technology broadens to other African countries it will be important to continue to seek farmer feedback on FNP hybrids.

Yield improvement was correlated with reduced tassel size prior to anthesis and lack of production of pollen, as formation of tassel structure and pollen competes for resources with grain production. Reducing this competition also reduces anthesis silking interval (ASI) under stress (Duvick, 1999). Reduced ASI has also occurred during selection for yield in SSA (Masuka et al. 2017). In FNP hybrids, 50% of the plants do not produce pollen and partitioning of resources within the plant early on in development is shifted from the tassel in favor of the ear, leading to earlier silk protrusion and reducing ASI under stress. This change in partitioning results in more efficient use of nitrogen, a scarce resource for many smallholder farmers. Therefore, an added benefit of FNP hybrids is that they do not increase total N uptake but improve nitrogen utilization efficiency by reducing partitioning from the tassel in favor of the ear, increasing kernels per ear and kernel weight (Fox et al. 2017). The adoption of modern FNP hybrids and the realization of associated yield benefits will still require nutrient inputs, given that current production largely relies on mining of nutrients which is unsustainable (ten Berge et al. 2019; Pasley el al. 2020).

Widespread acceptance of FNP hybrids will be dependent on adoption by both farmers and seed companies. In this paper we have described yield benefits to the farmer (about 200 kg per ha) and highlighted farmer acceptance, indicating the hybrids are likely to be adopted quickly. Under the conservative scenario (adoption of FNP in 10% of current maize hybrid area), we estimate that FNP would increase maize production in Africa by 0.245 Mt per year, valued at $40M. While this increase is relatively modest, for example when compared to the benefits of *Bt* maize (De Groote et al. 2011), the benefits would still outweigh the cost by more than 6:1, indicating a good return to the research investment.

Apart from benefits to farmers, the technology also provides benefits to seed companies. These include: no detasseling costs, as the NPP females will not require detasseling during seed production; improved seed purity, as there is no self-pollination during seed production; and increased kernel numbers, leading to reduced seed production costs. Kernel number was increased by 6% in NPP plants under low N in these studies, but was not measured under favorable conditions more typical of seed production. In US trials, kernel number was increased by 9.6% in plants with NPP tassels compared with wild type controls under optimum conditions (Fox et al. 2017). This will be evaluated in African germplasm under seed production practices in SSA, but the expected increase in seed production of about 10% is an additional anticipated benefit to seed companies. The benefits to seed companies are also expected to help catalyse a shift towards more modern hybrids, improving the selection and purity of climate smart hybrids available to smallholder farmers by providing incentives for seed companies to replace older, lower-yielding varieties with more recent higher-yielding ones.

The replacement of older hybrids in the market will have added benefits for farmers, on top of those predicted from the ~200 kg ha^{-1} benefit of growing FNP hybrids. We plan to collect additional data on the average age of hybrids that will be replaced, but assuming the average age of replacement is 10 years, this would reflect an additional 275 kg ha^{-1} benefit to the farmer using conservative estimates of genetic gain. Therefore, the adoption of FNP hybrids would benefit farmers growing at the 2 Mg ha^{-1} yield level by almost 25%, or 0.5 Mg ha^{-1}, approximately \$76 ha^{-1} in added income.

In conclusion, the Ms44-SPT system provides a unique opportunity to transform the maize hybrid seed industry in Africa, providing recognizable benefits to both seed companies and farmers. The FNP trait delivered using the Ms44-SPT system can deliver economic benefit in the form of improved input use efficiency to small holder maize farmers faced both with limited ability to purchase recommended quantity of fertilizer and the uncertainty of drought stress.

Materials and Methods

Germplasm and incorporation of Ms44

The dominant male-sterile allele Ms44 was backcrossed into five inbred maize lines. Two were dose 6 (BC5) and two were dose 4 (BC3) for the numbers of crosses to the recurrent parent. Four to five ear sources were selected for increase based upon positive marker calls for a donor insertion site and decreased insertion size. The five converted Ms44 female inbred parental lines were each crossed to 3-4 male inbred parental lines to produce 18 hybrids. In the nursery, plants were tagged pollen-producing

(PP) and non-pollen producing (NPP) based on phenotype at flowering. Ears were harvested separately for PP and NPP plants. The F1 hybrid seed harvested from NPP plants segregated 1:1 for pollen producing (PP) and non-pollen producing (NPP) and was used for yield trials. These hybrids will be referred to as FNP, or fifty percent non-pollen-producing. The F1 hybrid seed harvested from PP plants was used as 100% PP controls to compare in yield trials. Eight three-way cross hybrids were produced by planting F1 seed harvested from NPP plants and crossing these to inbred PP males, resulting in three-way crosses segregating 1:1 PP and NPP plus the 100% PP controls.

Yield testing

From 2017-2019, yield trials were planted both on-station (OST) and researcher-managed on-farm (OFT) in Kenya, South Africa and Zimbabwe (Figure S1 and Table S1). Trials at experimental stations (OST) were conducted under optimal, low-N, heat and drought stress. Optimal, heat and drought stress sites were optimally fertilized based on local recommendations and received recommended weed and insect control measures. Optimal trials were planted during the main maize growing seasons, irrigated twice at planting and emergence, and supplemental irrigation was applied as needed to avoid drought stress. Managed drought trials were planted in the dry season and irrigation was withheld approximately 2 weeks prior to mid-anthesis. Delayed planting in the dry season allowed for high temperatures at reproductive stage for heat stress trials. In low-N, fields had been depleted of nitrogen for at least 4-seasons. Rescue irrigation was only applied to avoid total crop loss when required. Depletion was achieved by applying no N fertiliser to plots and removing stover from the field after grain was harvested.

Experiments were in a randomized complete block with a split plot design, with main plot as hybrid pedigree and sub-plot as trait (PP or FNP). Different hybrid combinations were grown in different years and locations depending on seed availability. On-station trials were 2-4 row plots of 5 m length and 0.75 cm between rows. There were 4-6 reps per location and usually more hybrid pedigrees planted across fewer locations.

At selected OST locations, plants in the middle two rows were tagged at flowering according to phenotype: NPP for non-pollen-producing and PP for pollen producing. When all PP plants shed, the tassels from two PP and two NPP tagged plants in each plot were removed and the number of tassel branches recorded. The tassel was cut at one inch above the flag leaf, oven dried to zero moisture and dry weight recorded.

At 2-3 weeks after flowering, ear height (from ground surface to the highest ear node) and plant height (to the tip of the tassel) were recorded for 4 PP and 4 NPP plants per plot.

At OST locations in Zimbabwe, ear photos were taken and images analyzed (Makanza et al. 2018) to estimate cob length, kernel number, 100 kernel weight and grain weight per plant. Photos were taken using a tripod with the camera fixed at least 50 cm above the ears. Dehusked ears were placed on a black background, with 15-20 ears per photo. A 30 cm ruler was placed in the same orientation as the ears to be used as a reference.

For on-farm trials, smallholder farmers were identified by agricultural extension agents in each country. Extension agents were given a small monetary amount to cover all expenses related to trials. In Zimbabwe, additional seed and inputs were given as compensation to farmers. On-farm trials were 2-4 row plots, 5 m rows with 0.75 m between rows. Plots were double planted and thinned, leaving an intra-row spacing of 25 cm. There were 2 reps per location and multiple locations per year (Fig. 5?). In each country, project partners worked alongside extension agents and directly with farmers. Researcher-managed trials implemented by farmers are often higher yielding than farmers' own fields (de Roos et al. 2017), thus farmers were asked to use appropriate pest and weed management, but not to apply N fertiliser. Target yields were less than 4 t ha^{-1}, based on the average yield of target farmers. Harvesting was conducted by hand, ears were shelled and grain weight and moisture recorded. Yield on an area basis was calculated and adjusted to 155 g kg^{-1} moisture.

Statistical analysis

Analysis was conducted using ASREML (VSN International Ltd). In the analysis for grain yield, main effect of trait is considered as fixed effects and hybrid background and interaction between trait and hybrid background are treated as random effects. Location and interaction between location and trait are considered fixed. The blocking factors such as replicates, as random. Yield for trait within hybrid was predicted using best linear unbiased predictor (BLUP), as hybrid effect was treated as random. Yield for trait across hybrids was predicted using best linear unbiased estimates (BLUE), trait is considered a fixed effect. Differences between the 100% PP and the FNP trait were considered significant at the 5% confidence level.

Farmer evaluations

Farmer evaluations were organized in eight trial sites in Kenya in the main season of 2017 and 2018. The original sites were randomly selected from the trial sites in 2017. In 2018, two of the sites were dropped from the trials, so for farmer evaluations they were replaced by nearby suitable sites. The evaluations were conducted twice in each year/season, mid-season (June - July) and end season (July - August). While breeders observed yield and other traits in the field, social scientists invited farmers to come and evaluate the entries in a subset of trials. The evaluations were double blind: plots were identified by number and neither farmers nor facilitators/enumerators knew the treatments. For the participatory evaluations in 2017, 8 OFT sites were randomly selected from the trial sites, 4 in Central Kenya and 4 in Western Kenya in 2017. In 2018, 2 sites in Central Kenya were replaced, the other six maintained.

In each site, neighboring farmers were identified through farmer groups, local administration and extension officers, and invited to come and see the trials. In Kenya, women often tend to the farms while men are more likely to look for employment elsewhere, and it is common to have more female farmers participate (Worku et al. 2020). The participants, 2697 in total, of which 62% women, were adults from all ages (from 17 to 88). Most participants were experienced farmers, with an average of 17 years of farming experience. Most had also finished primary education, with on average eight years of formal education. Most participants owned their farm, with an average size of almost one ha (0.85), more than half of which (0.5 ha) was planted in maize. Most participants practice a mixed crop/livestock system, with about two thirds owning cattle, and a quarter oxen. Average cash income over the previous year was KES 92,617 (almost $1000), of which about half came from agriculture.

Procedure

Farmers' evaluation of new technologies, including varieties, is a two-step procedure, where first the selection criteria or traits important to farmers are identified, followed by an evaluation of the new technologies or varieties on those criteria. Criteria during the first year were set and, based on discussions with farmers, four more criteria were added in 2018 (Table S3) (De Groote et al. 2005). To confirm the importance of these criteria to the participants of this study, we asked them, individually, to give these a score for importance (0 = not important, 1 = somewhat important, 2 = important, 3 = very important) (Table S3).

Participants were asked to evaluate the different entries on these criteria. In 2017, they evaluated the eight entries and two reps, so all 16 plots in total. In 2018 there were 16 entries and the participants only evaluated one of the two reps each, randomly assigned. To score the entries, they used a 5-point hedonic scale, following previous experience (De Groote et al. 2010). Experience has shown that using numbers for the scores can be confusing, as “1” can indicate both a very good or a very poor score. Therefore, letter scores were used, which correspond to the Kenyan school system and hence are easy for farmers to understand. The options were A (like very much), B (like), C (neither like nor dislike), D (dislike), E (dislike very much) (Worku et al. 2020). In 2017, farmers were randomly assigned to the control (without evaluations of tassel or pollen), treatment 1 (including the criterion "good tassel formation"), or treatment 2 (including both the tassel criterion and the criterion "amount of pollen shed"). As the results of 2017 indicated treatments 1 and 2 were very similar, they were merged in 2018, with only one treatment group, whose members evaluated the entries on tassel and pollen. All criteria were expressed in both English and Kiswahili on the questionnaire, the national languages in Kenya. In the different counties, depending on the situation, the criteria were translated into local languages.

To analyze the scores, the alphabetical scores were converted to numerical scores (from A = 5 to E = 1), mean scores were calculated for all criteria and the mean scores for FNP and PP hybrids compared through pairwise t-test.

Impact assessment

To estimate maize area and production in SSA we used the FAOSTAT data from 2018 which include 50 countries) with an area of 37.55 M ha a production of 70.51 M tonnes and an average yield of 1.92 tonnes t/ha [1]. For levels of adoption of improved maize varieties and hybrids we searched the literature and found data from the top 25 countries (De Groote et al. 2015; Hassan et al. 2001; Abate et al. 2017; Dao et al. 2017; Feed the Future, 2016; Smale et al. 2011; Timothy et al. 1988). These 25 countries, including all countries with a maize area of more than 100 kha (except for Burundi and South Sudan) (Table S4 in supplementary material) plant 36.6 M ha (97.4% of maize area in SSA) with a production of 70.4 M t. Multiplying adoption rates of improved maize varieties by country with their 2018 maize area [1], resulted in an estimated total area in improved maize varieties of 19.3 M ha (52.6%). Similarly, multiplying the % in hybrids for each country with the maize area lead to an estimated area planted in hybrids in these countries at 12.6 M ha (34%). The yield benefit for each country was estimated using the regression from

Figure 1 (Δy=0.006x + 180.2). The weighted average (for the 25 countries with adoption figures, and area in hybrids used as weight) comes to 193 kg ha^{-1}.

To compare the benefits to the cost, we use the following project performance parameters: net present value (NPV), internal rate of return (IRR) and benefit cost ratio (BCR) (Gittner, 1982) (Table S5). The cost of the development of the technology is estimated by the annual cost of the FNP project, US$ 1million per year from 2010 to 2016 and US$ 1.6 million from 2017 to 2020. For the future, we expect the further development cost to be about $1.25 million per year from 2021 to 2024, after which the cost will gradually reduce from $0.8 million in 2025 to 0.1 in 2028. For the benefits, we assume the technology to be on the market in 2023, and to take 10 years to reach the target 10% adoption (market penetration of FNP hybrids as a percentage of hybrid seed), keeping maize production constant.

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Author Contributions

MO led and conceptualised the study with inputs from SC, JEC and MA. EH, JEC, DL, KM led the field trials. HDG and MN led the farmer preference study. All authors contributed to interpretation of the results and manuscript revisions.

Competing Interests

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

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Supplementary Figures and Tables

Figure S1. Map designating on-farm and on-station yield trial locations.

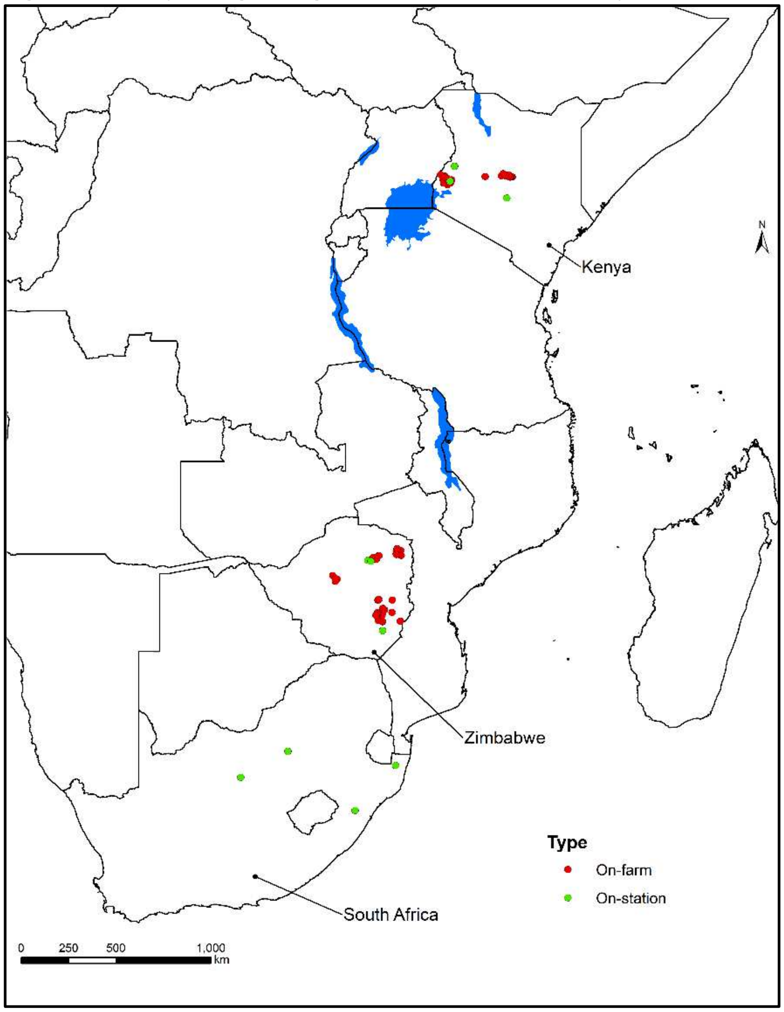

Table S1. Number of replicates, hybrid backgrounds and locations in yield trials conducted on-farm (OFT) and on-station (OST) for each country and year.

Country	Year	Type	Locations	Pedigrees	Reps
Kenya	2017	Onfarm	24	4	2
		Onstation	6	4	4
	2018	Onfarm	20	8	2
		Onstation	6	11	4
South Africa	2017-18	Onstation	8	15	4
Zimbabwe	2017-18	Onfarm	17	6	2
		Onstation	7	12	12
	2018-19	Onfarm	18	6	2
		Onstation	6	15	12

Table S2. Overview of participants in farmer evaluations

Year	Region	Mid-season Number of participants			End-season Number of participants			Overall Number of participants		
		Women	Men	Total	Women	Men	Total	Women	Men	Total
2017	Central	86	46	132	131	45	176	217	91	308
	Western	64	73	137	300	261	561	364	334	698
	Total	150	119	269	431	306	737	581	425	1006
	%	56	44	100	58	42	100	58	42	100
2018	Central	275	127	402	295	113	408	570	240	810
	Western	227	193	420	289	172	461	516	365	881
	Total	502	320	822	584	285	869	1086	605	1691
	%	61	39	100	67	33	100	64	36	100
Overall	Total	652	439	1091	1015	591	1606	1667	1030	2697
	%	60	40		63	37		62	38	

Table S3. Study design for the participatory evaluations.

Criteria No.	Treatment group	Year	Criteria	How important is this criterion? [a]	For each plot, please evaluate the variety for this criterion on a scale of A to E [b] .		
					Plot 1	Plot 2	…
1	All	2017 and 2018	Germination/Crop stand				
2	All	2017 and 2018	Height				
3	All	2017 and 2018	Stalk thickness				
4	All	2017 and 2018	Number of cobs per plant				
5	All	2017 and 2018	Cob size				
6	All	2017 and 2018	Barrenness level				
7	All	2017 and 2018	Yield				
8	All	2017 and 2018	Biomass (for fodder)				
9	All	2017 and 2018	Resistance to stalk borer				
10	All	2017 and 2018	Drought resistance				
11	All	2017 and 2018	Foliar disease resistant				
12	All	2017 and 2018	Tillers development				
13	All	2017 and 2018	Early maturing				
14	All	2018 only	Husk cover				
15	All	2018 only	Drooping of the ear				
16	All	2018 only	Cob rot resistance				
17	All	2018 only	Lodging resistance				
14	Treatment 1 and 2 [c]	2017 and 2018	Good tassel formation				
15	Treatment 2 only	2017 and 2018	Amount of pollen shed (good pollination)				
20	All	2017 and 2018	Overall evaluation (note: not an average)				

[a] Codes: 0 = not important, 1 = somewhat important, 2 = important, 3 = very important

[b] Codes: A = like very much, B = like, C = neither like nor dislike, D = dislike, E = dislike very much.

[c] In 2108, four criteria were added.

[c] Note: In the mid-season of 2017, farmers were randomly assigned to three groups: control, treatment 1 and treatment 2; all participants evaluated the varieties on criteria 1 to 13 and 16, both treatment groups also on criterion 14, only those in treatment 2 on criterion 15. In 2018, treatment groups 1 and 2 were merged.

Table S4. Expected benefits of fifty-percent non-pollen producing (FNP) in terms of yield, production and economic gain (25 top producing maize countries, including all with 128,000 ha or above). Benefits estimated using a 10% adoption rate of FNP hybrids.

Country	Area harvested (1000 ha)	Yield (kg ha^{-1})	Hybrid adoption rate (% rea)	Yield gain (kg ha-1)	Area in FNP (ha)	Production gain (tonnes)	Economic gain (US$ 1000)	FNP seed needed (tonnes)
Nigeria	4,853	10,155	11.6	192.8	56,299	10,852	1,784	1,407
United Republic of Tanzania	4,101	5,987	40.2	189	164,843	31,149	5,121	4,121
Democratic Republic of Congo	2,680	2,078	9.6	184.9	25,611	4,734	778	640
Angola	2,655	2,271	4.1	185.3	10,884	2,017	332	272
South Africa	2,319	12,510	87.5	212.6	202,899	43,130	7,091	5,072
Ethiopia	2,236	7,360	66	200	147,568	29,506	4,851	3,689
Kenya	2,142	4,014	65	191.4	139,213	26,652	4,382	3,480
Mozambique	1,827	1,654	24.9	185.6	45,484	8,442	1,388	1,137
Malawi	1,685	2,698	65.7	189.8	110,727	21,017	3,455	2,768
Cameroon	1,316	2,345	52.2	190.9	68,737	13,121	2,157	1,718
Zimbabwe	1,191	730	95.4	183.9	113,662	20,900	3,436	2,842
Ghana	1,184	2,306	3.1	191.9	3,672	705	116	92
Benin	1,158	1,510	0	188				
Uganda	1,131	2,964	37.6	195.9	42,524	8,332	1,370	1,063
Mali	1,129	3,625	0	199.5				
Zamboa	1,086	2,395	61.5	193.4	66,789	12,919	2,124	1,670
Burkina Faso	1,019	1,700	3.8	190.2	38,76	737	121	97
Togo	715	887	0.5	187.6	368	69	11	9
Guinea	611	819	6.9	188.2	4,211	793	130	105
Cote d'Ivoire	473	1,006	34.4	193	16,275	3,140	516	407
Chad	342	438	44.6	187.9	15,244	2,864	471	381
Rwanda	296	410	22.4	188.5	6,625	1,249	205	166
Senegal	180	264	10	189	1,791	338	56	45
Madagascar	129	215	0	190.2				
Lesotho	128	100	65.1	184.9	8,313	1,537	253	208
Total top 25		70,441	34.3	191.8	1,255,614	244,204	40,147	31,390
Total sub-Saharan Africa		71,430						

Table S5. Benefit to cost ratio for Seed Production Technology for Africa investment assuming 10% adoption rate in 10 years.

Year	Year	Cost (1000 USD)	Benefit (1000 USD)	Present value (2020 1000 USD)	Costs discounted (2020 1000 USD)	Benefits discounted (2020 1000 USD)
2010	-11	1000		-2853	2853.1	
2011	-10	1000		-2594	2593.7	
2012	-9	1000		-2358	2357.9	
2013	-8	1000		-2144	2143.6	
2014	-7	1000		-1949	1948.7	
2015	-6	1000		-1772	1771.6	
2016	-5	1000		-1611	1610.5	
2017	-4	1600		-2343	2342.6	
2018	-3	1600		-2130	2129.6	
2019	-2	1600		-1936	1936	
2020	-1	1600		-1760	1760	
2021	0	1250		-1250	1250	
2022	1	1250		-1136	1136.4	
2023	2	1250	4005	2277	1033.1	3310
2024	3	1250	8010	5079	989.1	6018
2025	4	800	12015	7660	546.4	8206
2026	5	500	16020	9637	310.5	9947
2027	6	300	20025	11134	169.3	11303
2028	7	100	24030	12280	51.3	12331
2029	8		28035	13078		13078
2030	9		32040	13588		13588
2031	10		36045	13897		13897
2032	11		40050	14037		14037
2033	12		40050	12761		12761
2034	13		40050	11601		11601
2035	14		40050	10546		10546
2036	15		40050	9588		9588
2037	16		40050	8716		8716
2038	17		40050	7924		7924
2039	18		40050	7203		7203
2040	19		40050	6548		6548
Net present value (NPV)				151719	28883	180603
Internal rate of return (IRR)				0.24		
Benefits				180603		
Costs				28883		
BCR				6.25		