Received: 10 March 2024 | Revised: 12 September 2024 | Accepted: 13 September 2024
DOI: 10.1002/ppp3.10590

RESEARCH ARTICLE

Plants People Planet PPP Open Access

Validating a novel genetic technology for hybrid maize seed production under management practices associated with resource-poor farmers in Zimbabwe

Esnath Tatenda Hamadziripi[1] | **Sarah Collinson**[2] | **Rachel C. Voss**[3] | **Frédéric Baudron**[1,4,5] | **Maryke T. Labuschagne**[6] | **Angelinus C. Franke**[7] | **Mainassara Zaman-Allah**[1] | **Mike S. Olsen**[3] | **Juan Burgueño**[8] | **Jill E. Cairns**[1]

[1]International Maize and Wheat Improvement Center (CIMMYT), Harare, Zimbabwe
[2]Corteva, Johnston, Iowa, USA
[3]CIMMYT, Nairobi, Kenya
[4]CIRAD, UPR AIDA, Montpellier, France
[5]AIDA, Université de Montpellier, CIRAD, Montpellier, France
[6]Plant Sciences Department, University of the Free State, Bloemfontein, South Africa
[7]Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa
[8]CIMMYT, Mexico CDMX, Mexico

Correspondence
Jill E. Cairns, International Maize and Wheat Improvement Center (CIMMYT), Harare, Zimbabwe.
Email: j.cairns@cgiar.org

Funding information
Biotechnology and Biological Sciences Research Council, Grant/Award Number: GB-GOV-13-FUND-GCRF-BB_T009047_1; Bill and Melinda Gates Foundation, Grant/Award Numbers: INV-004985, INV-018951

Societal Impact Statement

A hybrid maize seed production technology has the potential to reduce the complexity of hybrid seed production and increase seed quality. Here, we investigate the potential impact of this technology on yields when hybrid maize is recycled. Hybrid maize recycling is a practice used by resource-poor farmers as a coping mechanism during drought years. Recycling hybrid maize produced using this technology could provide a small yet significant yield benefit to resource-poor farmers when they chose to recycle. This study provides an example of how social considerations can be incorporated into testing strategies of new technologies to ensure equitable benefits.

Summary

- Understanding the performance of new genetic technologies in farmers' real-world realities, especially those relevant to resource-poor farmers, is often overlooked but is essential to ensure equitable benefits. A new genetic technology was developed to simplify hybrid maize seed production in sub-Saharan Africa, thereby improving farmers' access to high-quality hybrid seed. Hybrids produced with this technology segregate 50:50 for pollen-producing and non-pollen producing and are designated 50% non-pollen producing (FNP). FNP maize has higher yields in low-input environments. As recycling hybrid maize seed remains a common practice in Zimbabwe, including among resource-poor households, it is important to understand the impact of recycling FNP seed on the yield gains from the FNP technology.
- The potential impact of recycling FNP hybrid seed was assessed by testing three seed recycling scenarios on-station and on-farm. The extent of hybrid seed recycling and the types of households recycling hybrid maize seed over a 3-year period were also investigated.
- Hybrid maize seed recycling was associated with resource-poor farmers, although it was not continually practiced across years. Yield gains associated with FNP were retained under recycling practices, albeit reduced. The greatest yield benefit was

when seed from only non-pollen-producing plants was used. Yield gains were associated with longer ears and more kernels per ear.

- While recycling hybrid maize seed reduces potential yields due to inbreeding depression, in the years when farmers cannot afford to plant hybrid maize only, recycling non-pollen-producing hybrid maize seed conferred a yield benefit of 116 kg ha^{-1}.

KEYWORDS

farmer heterogeneity, gender-responsive breeding, hybrid maize seed recycling, smallholder farmers, social inclusion

1 | INTRODUCTION

Improving the production capacity, food security, and livelihoods of smallholder farmers in sub-Saharan Africa (SSA), particularly resource-constrained farmers, is a development priority (Quisumbing et al., 2015; FAO, 2023; FAO et al., 2023). Ensuring that marginalized groups benefit equally from new technologies, including improved varieties, requires first acknowledging that smallholder farmers are highly diverse in terms of resource and input access, capabilities, and aspirations. Resource-constrained farmers often have less access to land, limited financial resources for inputs, fewer assets and animals, and labor constraints (Peterman et al., 2014; Thuijsman et al., 2022; Zingore et al., 2007). Women are often a priority group among marginalized farmers in part because they are frequently resource-constrained and face productivity gaps related to their differential access to resources including land, inputs, labor, agricultural extension, and information (Doss, 2001; Teeken et al., 2021; Tufan et al., 2018; van Etten et al., 2023).

Recognizing these gaps in achieving equitable benefits from new technologies, socially inclusive breeding strategies must scrutinize how variety evaluations are approached to ensure they capture the real-world conditions that a diverse range of farmers face, including poorer farmers and women (Voss, Cairns, et al., 2023). This includes, for instance, verifying variety performance under low-input conditions or other practices that breeders and agronomists do not consider “standard” but may be disproportionately relevant for poorer and women farmers, such as intercropping. Similarly, as new genetic technologies are developed, it is important that they are also considered within the realities of their target beneficiaries.

Over the past two decades, there has been extensive investment toward increasing the efficiency of maize breeding pipelines within SSA, including strengthening partnerships between national and international breeding programs, increasing human capital, and facilitating the deployment of new tools and technology in breeding pipelines (Cairns & Prasanna, 2018; Prasanna et al., 2021). However, seed systems' delivery of new genetics to farmers' fields in SSA remains a bottleneck (Chivasa et al., 2022) and seed production a specific challenge in the maize seed value chain (Langyintuo et al., 2010). Hybrid maize seed is produced by crossing two genetically different parent lines, increasing yield through heterosis (Gaffney et al., 2016). Heterosis or hybrid vigor is the improved performance of F_1 hybrid compared to either of its parents. If seed produced from hybrid maize is planted (recycled), yields are lower because of inbreeding depression or reduced biological fitness. Thus, to achieve the yield benefits associated with heterosis, farmers should buy hybrid seed every year. In hybrid maize seed production, timely detasseling of female parent plants is undertaken to avoid self-pollination and a loss in hybrid vigor of the resultant hybrid seed. Unlike in other regions of the world, detasseling in hybrid maize seed production fields is manual in SSA (Collinson et al., 2022). Manual detasseling is slow, labor intensive and can be prone to human error, leading to issues in seed quality. Male sterility has been exploited in many regions of the world to simplify hybrid maize seed production, removing the need to detassel female seed parents while enabling seed companies to produce high-quality seed more efficiently (Wan et al., 2021). Cytoplasmic male sterility (CMS) and genetic male sterility are both used in commercial hybrid maize seed production (Andorf et al., 2019; Kim & Zhang, 2018).

A Seed Production Technology for Africa (SPTA) system using a naturally occurring dominant male sterility gene, *Ms44*, has been developed to eliminate the need for detasseling in hybrid maize seed production fields (Collinson et al., 2022). Maize hybrids produced using *Ms44* segregate 1:1 for pollen-producing (PP) and non-pollen-producing (NPP) plants and are referred to as 50% non-pollen-producing (FNP). NPP plants divert resources from the tassel to the ear, increasing grain yield, such that FNP maize has a yield advantage of 200 kg ha^{-1} across yield levels compared to conventional varieties (Collinson et al., 2022). Thus, the use of SPTA in hybrid maize seed production in SSA has the potential to both increase demand by seed companies to update their product portfolios and increase farmers' yields. Furthermore, maize hybrids developed using *Ms44* were also shown to have an increased yield benefit under sub-optimal nitrogen (N) fertilization (Fox et al., 2017). Low fertilizer use is a major biophysical constraint to maize production in SSA, particularly for resource-constrained (Zingore et al., 2007) and women farmers who often apply less inputs than men (Adam et al., 2021; Burke et al., 2018; Burke & Jayne, 2021; Djurfeldt et al., 2019; Gebre et al., 2019). As such, women and other resource-poor farmers have been identified as beneficiary targets for this technology.

Ensuring that FNP hybrids meet the needs, priorities, and constraints of resource-poor and women farmers is therefore a priority, which means validating its performance under ~~these~~ farmers' real-world constraints and growing conditions (Khaipho-Burch et al., 2023). Recycling maize hybrid seed is not recommended due to inbreeding depression; however, it remains a practice used by farmers in SSA (Heisey et al., 1997). In official crop estimates, recycled hybrids are not considered improved varieties, and the area planted to recycled hybrids is often reported along with the area planted to landraces, hindering the accurate estimation of the area under recycled seed. However, evidence suggests hybrid maize seed recycling is common. In Zambia, 13% of farmers grow recycled seed (Audet-Bélanger et al., 2016). Zambezi et al. (1997) estimated that in Malawi 40% of households grow recycled hybrid seed as one of the varieties, although this figure may have reduced now with the Farm Input Subsidy Program (FISP) (Hoogendoorn et al., 2018). Smale et al. (1998) estimated that the proportion of farmers using recycled hybrid seed varied from 22% to 38% over a 7-year period. In the eastern highlands of Zimbabwe, Baudron et al. (2019) found that the use of recycled seed ranged from 5% to 7%. Although the subject has not been extensively researched, several studies indicate that women farmers are more likely to recycle hybrid seed. Audet-Bélanger et al. (2016) found that women were more likely to use recycled maize hybrid seed in Zambia. Similarly, Cairns et al. (2022) showed that the gender of the household head was a significant predictor of maize variety choice in Zimbabwe, with recycled seed use associated with female household heads. In the Eastern Cape of South Africa, widowed female farmers were found to grow the most recycled hybrid maize seed (Chimonyo et al., 2020).

The primary aim of this study was to evaluate if the FNP trait retains a yield benefit when FNP hybrid maize seed is recycled. Given the yield benefit of NPP plants, the yield of recycled FNP hybrid maize seed is likely to vary depending on what plants the farmer chose to recycle. As such, a second aim of this study was to assess if any of the hybrid recycling scenarios had higher yields. A final aim of this study was to understand the types of farmers and households that plant recycled hybrid maize seed in Zimbabwe.

2 | MATERIALS AND METHODS

2.1 | Survey to establish the extent and drivers of hybrid seed recycling

Zimbabwe is divided into 10 administrative provinces, which are separated into 64 districts and subsequently divided into 1970 municipal wards. Two surveys (Data S1 and Data S2) were conducted in municipal Wards 4 and 27 of Murehwa District, Mashonaland East, Zimbabwe (Figure 1). Murehwa District was selected as almost 90% of households grow maize (ZimVAC, 2020). The two wards in Murehwa were chosen based on their relatively uniform soil texture and elevation, working knowledge of extension agents in these wards, and that they were not located along the main road. The primary aim of these surveys was to construct typologies to summarize the

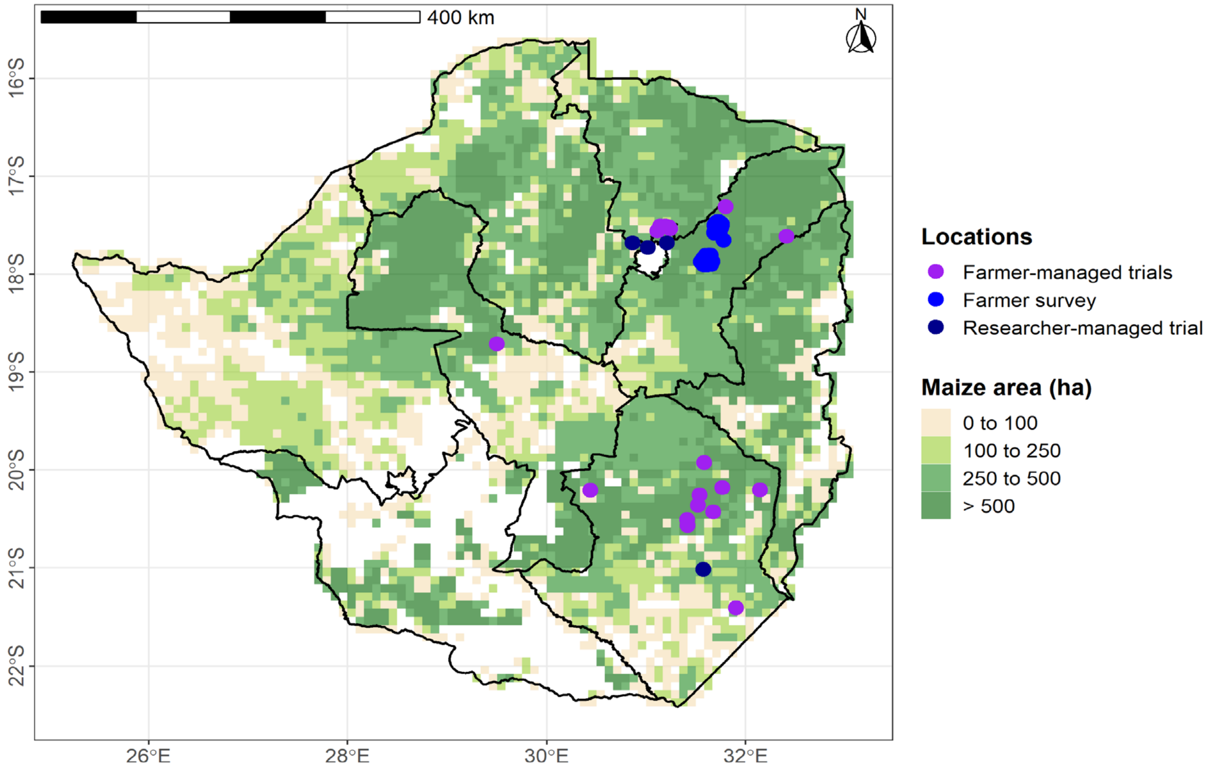

FIGURE 1 Location of surveys, on-station (researcher-managed), andon-farm (farmer-managed) trials in Zimbabwe used in this study.

large heterogeneity of smallholder farming systems and populations (Hassall et al., 2023). The first survey (Data S1) was conducted in 2020 and the second in 2023 (Data S2) on the same farms. Details of the first survey can be found in Cairns et al. (2022). Briefly, 306 farming household heads were randomly selected and asked to complete a survey in KoboCollect, assisted by 10 trained enumerators. All questions were directed to the household head. Questions included age, gender and education of household head, family size, number of cattle and small ruminants, income source, food sources, dietary diversity, cultivated area, total maize produced, total fertilizer and manure used in maize production, gender of plot manager, soil type, method of land preparation, date of planting, use of intercropping in maize fields, pesticide use, and weeding frequency. For this study, the 2020 data were leveraged to help understand key household or plot manager characteristics associated with recycled maize hybrid use and the extent of recycling hybrid seed over time.

An additional survey (Data S2) was conducted in the same 306 households in 2022; however, questions related to plot-level management were directed to the plot managers. Recognizing that there is a relatively high degree of joint management of maize plots in dual-adult households, joint plot management was included in the study, and questions related to plot-level management were directed to joint managers simultaneously. This survey also included questions related to maize varieties used in the preceding year (2021). From both surveys, 3 years data (2020–2022) was extracted on maize varieties planted in all fields to determine temporal variations in the seed recycling practice. International Maize and Wheat Improvement Center (CIMMYT) internal ethics review board provided required approvals (IREC 2020.016, IREC 2023.008). The full questionnaires for both surveys are provided as Data S1 and Data S2.

2.2 | Field trials

In this study, on-farm and on-station trials of recycled FNP hybrids were used to assess the potential yield benefit for farmers practicing hybrid seed recycling. Incorporating primary beneficiaries (the farmers) into the research and development process is important for ensuring accurate real-world data (Cash et al., 2003). Therefore, this study was primarily conducted on-farm in trials managed by extension officers and farmers in Zimbabwe.

2.3 | Germplasm

Lines were converted with *Ms44* using traditional plant breeding methods, that is, backcrossing *Ms44* into each female used as the female of the single cross within a three-way hybrid. The lines were the first to be backcrossed with *Ms44* and were chosen primarily for their abiotic and biotic stress tolerance. Five three-way maize hybrids were formed using key lines from CIMMYTs maize breeding pipeline. These hybrids were neither commercial nor advanced candidate hybrids but were used to assess the impact of *Ms44* on yield.

2.4 | Treatments

FNP hybrids segregate 1:1 for PP and NPP plants. The phenotype of PP plants is visibly different to NPP plants. NPP plants have smaller tassels with fewer branches that do not exert anthers nor produce pollen (Collinson et al., 2022). Resource partitioning within NPP plants shifts nitrogen from the tassel to the ear, resulting in significantly longer ears and higher kernel number, hundred kernel weight, and grain yield (Collinson et al., 2022; Fox et al., 2017). Farmer preference studies have shown farmers can distinguish between NPP and PP plants and prefer NPP plants due to their visibly higher yield (Collinson et al., 2022). Considering these visual differences, three seed recycling scenarios formed the basis of the treatments in this study (Figure 2):

1. PP scenario: The farmer selects ears from PP plants only, and all progeny grown from this recycled seed will be 100% PP.
2. Blend scenario: The farmer randomly selects ears in the field and saves seed from both NPP and PP plants; progeny will subsequently segregate approximately 75% PP and 25% NPP.
3. FNP scenario: The farmer select ears from only NPP plants (based on ear length and grain yield); recycled hybrid seed from NPP will segregate 1:1 PP:NPP, and progeny will therefore be 50% NPP.

The selection of ears from PP plants produces the same progeny as would recycled seed from the same hybrid developed without *Ms44* and was therefore considered to be the control. To simulate these scenarios, entries were planted in a nursery and sibmated. At

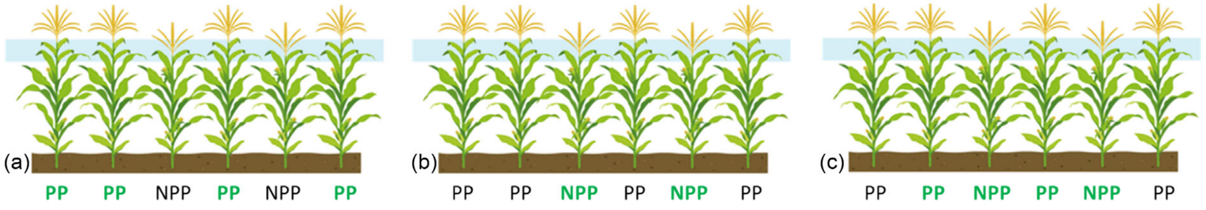

FIGURE 2 Visual representation of the three seed recycling scenarios of 50% non-pollen-producing (FNP) hybrid maize used in this study. Farmers select (a) ears for recycling from pollen-producing (PP) hybrid plants only, (b) ears for recycling from only non-pollen-producing (NPP) plants, or (c) ears for recycling from PP and NPP plants. Selected plants are visually represented in green text.

flowering, PP plants were tagged to differentiate them from NPP. Tagged plants were harvested separately from those without tags to produce the seed compositions as described above.

2.5 | On-station trial management

On-station trials were conducted at three experimental research stations in Zimbabwe; the CIMMYT experimental research station, Harare (−17.77, 31.05, 1480 masl); Rattray Arnold Research Station (RARS), Harare (−17.68, 21.21, 1369, 1369 masl); and Chiredzi Lowveld Research Institute, Masvingo Province (−21.02, 31.58, 433 masl). Four treatments were used on-station—optimal, rainfed, drought stress and nitrogen (N) stress. Drought and N stress are the major abiotic stresses commonly experienced by smallholder farmers in Zimbabwe. Over the past decade in Southern Africa, six growing seasons have had below average rainfall (Frischen et al., 2020), while fertilizer use in maize production is generally sub-optimal in SSA and particularly within resource-constrained farms (Zingore et al., 2007) and female-managed plots (Cairns et al., 2021). To understand the yield of recycled hybrid seed under experimental conditions related to stresses smallholder farmers frequently experience, drought and N stress were therefore included as treatments. To control both the timing and severity of drought stress, drought trials were conducted in the off (dry) season. Trials were irrigated until 2 weeks before flowering to ensure plants experienced drought stress at flowering, the most sensitive stage to drought stress. In N stress trials, fields that had been depleted of N over the last 10 years were used. The rainfed trial was conducted in an experimental station location in agroecological zone two (700–1050 mm per annum).

Optimum and N stress trials were conducted at the CIMMYT experimental research station in 2019/2020 and 2020/2021. The rainfed trial was conducted at RARS in 2020/2021 and managed drought trials were conducted in Chiredzi in 2020 and 2021. Experiments were planted in two row plots (4 m length with 0.75 m between rows and 0.25 m between plants). A nested design was used, where hybrids were nested by the recycled *Ms44* seed blends, replicated four times. All trials received optimal fertilization, except for the N stress trials. Basal fertilizer (compound D, with NPK ratio 7:14:7, was applied at a rate of 400 kg ha^{-1}). Top-dressing using ammonium nitrate (containing 34.5% N) was applied at a rate of 400 kg ha^{-1} at V6 and VT growth stages. Recommended pest and weed control measures were used. In N stress trials, muriate of potash (60% K_2O potassium) and single super phosphate (19.5% P_2O_5 phosphorus) fertilizer were applied at a rate of 200 kg ha^{-1}. Recommended plant and weed control were used at all locations.

2.6 | On-farm trial management

On-farm trials were carried out in 20 farms over five districts in Zimbabwe (Figure 1) in 2019/2020. Forty-eight percent of trials were managed by female plot managers, 44% by male plot managers, and 8% were jointly managed. Smallholder farmers with poor soils, and/or in drought prone environments were purposively targeted by local agriculture research and extension officers to host trials. Two row plots were planted for each experimental hybrid with plot size of 7.5 m^2. A nested design was used, where hybrids were nested by the recycled *Ms44* seed blends, replicated twice.

Land preparation was conducted following the farmer's normal practices. Plant density was the same as in on-station trials. Basal fertilizer compound D with NPK ratio of 7:14:7 was provided, as well as fertilizer cups to ensure farmers apply a uniform rate of 250 kg ha^{-1} across all sites at planting, no further inputs were applied. Pesticides and protective gear to handle them were provided to farmers to control fall army worm. Farmers were responsible to ensure plots were kept weed free. To compensate for the efforts of the farmer to maintain the trial, packs of seed, basal compound D and ammonium nitrate fertilizers were distributed for free for use on their own fields outside the trial. Due to restrictions to reduce the spread of COVID-19, trials were monitored by researchers remotely (cell phones) where extension agents and farmers provided all feedback including pictures of the trials at various growth stages.

2.7 | Field measurements

At harvest, border plants at the beginning and end of each row were discarded in on-station trials under N stress and drought stress conditions. In CIMMYT on-station trials, recycled FNP maize hybrids were tagged at flowering based on their phenotype (NPP or PP). At harvest, plants were individually hand-harvested as NPP and PP. The number of ears per plot showing visible signs of ear rots was counted. Ears were subsequently arranged on a flat, dark nonreflective surface and photos taken with a tripod for subsequent image analysis. The Ear analyzer, a digital application supported by ImageJ software (Schneider et al., 2012), was used to estimate ear length and width, kernel length, and width and kernel weight (Makanza et al., 2018). Ears of each plot were shelled, and grain weight and moisture measured. In on-farm trials, border rows were discarded prior to harvest, and all ears were harvested from each plot, manually shelled, and grain weight and moisture content were measured. Grain yields were adjusted to 12.5% moisture content.

2.8 | Statistical analysis

To enable the prediction of maize seed recycling practice at farm and plot level, two logit models were used with data from the first survey (2020). To assess farm-level variables associated with the use of recycled hybrid maize seed, the following 15 response variables were used: age, gender and education level of household head, family size, number of cattle, number of small ruminants, total cultivated area, area under maize production, total amount of fertilizer used, total amount of manure used, total amount of maize produced, food security status, food sources, household dietary diversity score, and income source. Plot-level assessment used a total of 12 variables encompassing the field management of maize plots (gender of plot manager, maize planting time, soil type, area under maize production, N mineral fertilizer application, P mineral fertilizer application, use of manure, use of compost, pesticide use, weeding method, slope of land, land preparation method, and use of intercropping).

Data were delineated from the survey as described by Cairns et al. (2022). All analyses were conducted in R (version 4.2.2.). As described by Cairns et al. (2022) at both the farm and plot level, all variables were initially included. Models were subsequently reduced using a stepwise backwards elimination model to obtain the lowest Akaike Information Criterion (AIC). Models were then confirmed using the genetic algorithm of glmulti (Calcagno et al., 2020). To understand the relationship between gender of the household head and household-level characteristics, two further analyses were conducted. For categorical data, a chi-square test of independence was used to analyze the frequency table of categorical variables formed by gender of the household head. For continuous data, an unpaired two-samples Wilcoxon nonparametric test was used analyze the relationship of the gender of household head on-farm characteristics. Both the Wilcoxon rank test and chi-squared test were conducted using the Base R function (R Core Team, 2024).

For the field data, three on-farm sites were removed from the combined analysis based on high coefficients of variation (CV) (<50%) and normality of residuals were used to identify outliers for removal in the combined analysis. Two on-farm sites with a CV above 50% and one outlier site yielding 3.41 t ha^{-1} were removed from the analysis. The ASREML package in R (Version 4.1.2) was used to analyze grain yield from on-station and on-farm trials, and yield components derived from image analysis. Linear models were used, with *Ms44* seed blend level as the main effect nested in random effects of hybrid, replication, and block (Equation 1)

$$Y_{ijkl} = \mu + S_i + R(S)_{ij} + H_k + S^* H_{ik} + \varepsilon^a{}_{ijk} + T_l + S^*\, T_{il} + H^* T_{kl} + S^* H^* T_{ikl} + \varepsilon^b{}_{ijk} \tag{1}$$

where Y_{ijkl}: is the response variable, μ: is the overall mean, S_i: is the fixed effect of the ith site, $R(S)_{ij}$: is the random effect of the jth block nested in the ith site, H_k: is the random effect of the kth hybrid, T_l: is the fixed effect of the lth technology, S^*H_{ik}, $S^*\, T_{il}$, H^*T_{kl}, $S^*H^*T_{ikl}$ are the random interaction effects between the respective effects, except $S^*\, T_{il}$, which was considered as a fixed effect *and* $\varepsilon^a{}_{ijk}$ *and* $\varepsilon^b{}_{ijk}$, are the random experimental error associated with the whole (a) and the subplot (b). All random effects follow a normal distribution with zero mean and homogeneous variance and pairwise independent. The whole plot residual was considered homoscedastic, while for the subplot, we considered the autoregressive model of order one in row and column direction for each site $\text{AR1}_{\text{row}} \otimes \text{ARI}_{\text{column}}$ When an autoregressive term was negative or not significant, it was removed from the model. The combined model across all management practices included the same effects for the model above plus a main fixed effect of management plus the interaction effects of management with the other effects in the model. Management interaction effects with another fixed effect (site and technology) were considered fixed effects, while the interaction effects with the hybrid random effect were considered as a random effect.

3 | RESULTS

3.1 | Characteristics of male- and female-headed households

Household characteristics of farms in 2020 are presented in Table 1. The proportion of female-headed households participating in the survey was 43% in 2020 and 44% in 2022. Both male- and female-headed households grew an average of two maize varieties on the homefield (fields closest to the farmers' homestead). The relationship between gender of the household head and household characteristics in 2020 are presented in Figure 3 and Table 2. Female-headed households had significantly less cattle than male-headed households ($p < 0.01$), with female-headed households owning an average of two cattle and male-headed households owning an average of 3.58 (Figure 2b). The total area under cultivation was significantly smaller in female-headed households (3.17 ha) compared to male-headed households (4.18 ha) (Figure 2d). Female-headed households produced significantly less maize (456 kg) compared to male-headed households (670 kg) (Figure 2e); however, there was no significant difference in the area under maize production between female (0.70 ha's) and male-headed households (0.78 ha's) (Figure 2f). While the average 24-h dietary diversity score was generally low, it was significantly less in female-headed households (3.91) compared to male-headed households (4.38) (Figure 2i). Similarly, the percentage of months households self-reported to be food secure was significantly lower in female-headed households (55.3%) compared to male-headed households (68.9%) (Figure 2j). Significantly less female household heads completed secondary education compared to male-household heads (Table 2). Almost 11% of male-headed households used conservation agriculture compared to almost 6% of female-headed households.

3.2 | Recycling practices

Over the course of the 3-year period 85% of male-headed households grew only hybrid maize, compared to 72% of female-headed households. On average 6%, 3%, and 2% of female-headed households used recycled hybrid seed in 2020, 2021, and 2022, respectively. While, on average 3%, 3%, and 6% of male-headed households used recycled hybrid seed in 2020, 2021, and 2022, respectively (Figure 3). Notably, many households switched between only maize hybrids to recycling hybrid maize seed (while also using hybrid maize seed) from year to year. The majority of farms who planted recycled hybrid maize seed planted it only once over the 3-year period of the study, with no specific farm type that consistently recycled across years (Figure 4).

TABLE 1 Characteristics of households recycling hybrid seed and those who did not plant recycled hybrid seed in 2020.

	Households recycling hybrid seed ($n = 52$)	Households not recycling hybrid seed ($n = 254$)
Household characteristics		
Women headed households (%)	59.3	40.6
Age of household head (years)	56.6	53.5
Household head with secondary education (%)	37.0	61.0
Family size	4.89	5.78
Number of cattle	2.20	2.59
Number of small ruminants	2.27	2.04
Total cultivated area (ha)	1.06	1.51
Area under maize production (ha)	0.61	0.66
Total maize production (kg)	486	436
Fertilizer used in maize production (kg)	102	151
Manure used in maize production (kg)	599	1,123
No. of months food secure	5.13	6.52
24H dietary diversity score (0–12)	4.07	4.20
Farming as the main source of income (%)	46.3	48.1
Plot-level characteristics		
Female managed (%)	22.2	29.7
Male managed (%)	25.9	36.5
Joint management (%)	51.9	33.8
Applied manure (%)	40.7	47.4
Applied compost (%)	18.5	15.0
High weeding frequency (%)	27.8	21.2
Applied pesticides (%)	11.1	15.0
Practiced conservation agriculture (%)	12.9	17.4
Used animal or tractor in land preparation (%)	40.7	56.9
Flat slope (%)	7.4	13.9
Steep slope (%)	11.1	4.1
Mineral N applied (kg)	54.2	56.2
Mineral P applied (kg)	15.7	15.0

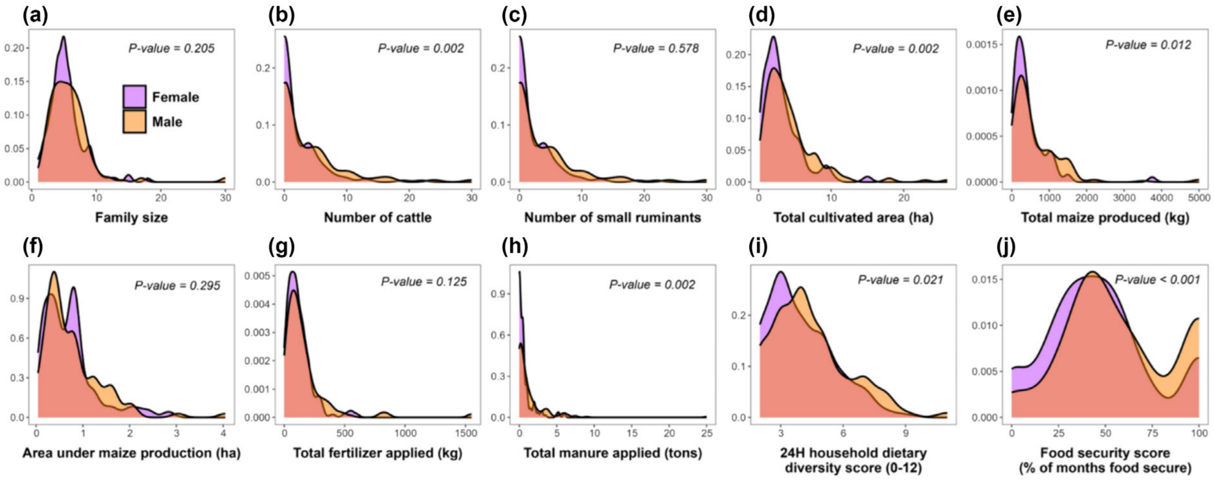

FIGURE 3 Density plots of (a) family size, (b) number of cattle, (c) number of small ruminants, (d) total cultivated area, (e) total maize produced, (f) area under maize production, (g) total fertilizer applied on maize, (h) total manure applied on maize, (i) 24-h dietary diversity score, and (j) food security score in 2020 ($n = 306$ farms). Wilcoxon test for independent samples was used to compare gender differences.

TABLE 2 Chi-square test of independence on the relationship between gender of the household head on household and farm characteristics.

Variable	Description	Female (%)	Male (%)	X^2 value	*p*-Value
Education level of household head	Primary	25.36	17.29	25.57	<0.001
	Secondary	18.16	39.19		
Method of land preparation for maize	Tractor/animal plow	21.61	32.85	9.40	<0.01
	Hand hoe	16.14	12.68		
	Conservation agriculture	5.76	10.95		
Field gradient	Flat	3.17	2.02	2.93	0.282
	Gentle slope	35.16	46.69		
	Steep slope	5.19	7.78		
Manure application	Yes	17.58	28.82	3.46	0.063
	No	25.94	27.67		
Compost application	Yes	7.20	8.36	0.09	0.765
	No	36.31	48.13		
Primary source of income	Crop sales	20.46	27.38	0.03	0.873
	Other	23.05	29.11		

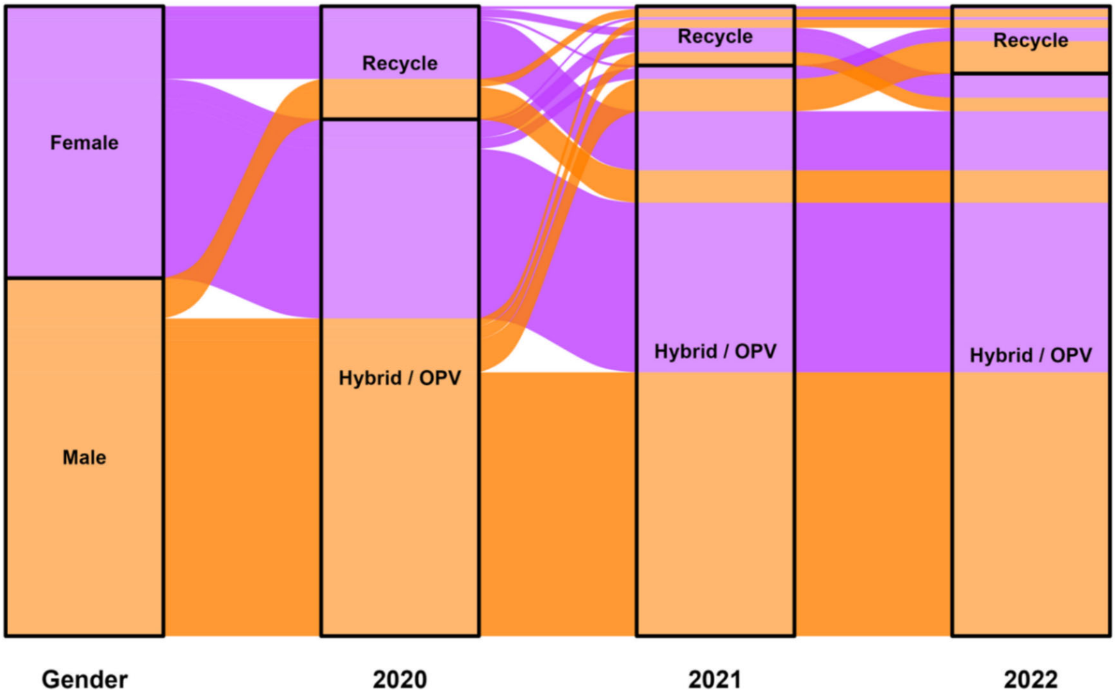

FIGURE 4 Dynamics of recycled hybrid seed use in Murehwa, Zimbabwe. Variation in recycled hybrid seed use across 234 farms between 2020 and 2022. The height of the block is proportional to the number of farms, which grew hybrids/OPVs or recycled seed. The width of stream connecting the years represents the number of farmers who maintained hybrid/OPV production or migrated to recycled seed and vice versa. The gender disaggregation shows the proportion of male and female household heads who grew hybrid/OPV and/or recycled seed from 2020 to 2022.

In 2020, 59% of households using recycled seed were female-headed compared to 41% of the households who did not plant recycled hybrid seed. Within households using recycled hybrid seed, only 37% of household heads had secondary level education, while over 60% of household heads had secondary level education within households who did not recycle hybrid maize seed. Households planting recycling hybrid seed had an average of 2.20 cattle, compared to an average of 2.59 cattle in households not planting recycled hybrid seed.

At the farm level, education of the household head was one of the variables that significantly predicted recycling practice (Table 3). Farmers with secondary education or higher were less likely to recycle maize seed ($p < 0.01$). Total maize produced at the farm level was positively associated with maize seed recycling ($p < 0.01$), while farms

TABLE 3 Summary of the estimates for logit models run after model reduction with of the farm-scale model with the use of recycled hybrid seed as the response variable to explain the variability of recycling in Murehwa District, Zimbabwe.

Variable	Estimate	*p*-Value
Head of the household with secondary education or higher	−0.957	0.003
Family size	−0.122	0.063
Number of small ruminants	0.083	0.140
Cultivated area (ha)	−0.137	0.072
Total maize produced (kg)	0.001	0.009
Fertilizer application (kg)	−0.005	0.043
Manure application (kg)	−0.001	0.123
Number of months food secure	−0.107	0.035

TABLE 4 Summary of the estimates for logit models run after model reduction with of the plot-scale model with the use of recycled hybrid seed as the response variable to explain the variability of recycling in Murehwa District, Zimbabwe.

Variable	Estimate	*p*-Value
Jointly managed plot	2.104	0.049
Female-managed plot	0.663	0.547
Male-managed plot	0.788	0.465
Plot on flat land	−0.522	0.356
Plot on steep slope	1.386	0.015
Land preparation through conservation agriculture	−0.056	0.907
Land preparation through hand hoe	0.799	0.020
Jointly managed plot within male-household head	−2.170	0.067
Female-managed plot within male household head	−0.977	0.475

that applied more fertilizer were less likely to recycle maize seed ($p < 0.05$). Food security was negatively associated with seed recycling ($p < 0.05$). At plot level, jointly managed plots were more likely to be planted with recycled maize seed ($p < 0.05$) (Table 4). Recycled maize seed was also more likely to be planted on plots with steep slopes ($p < 0.05$). Finally, the use of maize recycled seeds was more likely on plots prepared manually using hand hoes ($p < 0.05$).

3.3 | Recycled FNP seed yielded more than recycled blend and recycled PP seed under nitrogen stress

Spatial analysis was used in the grain yield analysis of all trials (on-station and on-farm) but was more important in adjusting means in on-farm trials where CVs were high. In the analyses of grain yield, spatial adjustment improved on-farm data quality and precision of field results by reducing the average standard error of difference of the nest factor (technology) by 72% and the main plot factor (hybrid) in 94% of the trials. The log likelihood of the model increased by 94% of the trials where spatial adjustment was used (Table 5). In on-station trials, the mean grain yield ranged from 6.5 to 9.5 t ha^{-1} under optimal conditions, from 2.6 to 3.5 t ha^{-1} under managed drought stress and 1.6 to 3.7 t ha^{-1} under N stress (Figure 5). In on-farm trials, the mean grain yield ranged from 0.18 to 3.3 t ha^{-1}, with over 80% of the trials yielding less than 2 t ha^{-1}.

Under N stress conditions on-station, recycled FNP yielded significantly more than the recycled blend and recycled PP ($p < 0.05$). FNP yielded 2.64 t ha^{-1}, while the blend and PP yielded 2.49 and 2.32 t ha^{-1}, respectively (Figure 5b). Similar trends were observed in the rainfed trial on-station and on-farm trials; however, the differences in grain yield between FNP, blend, and PP were not significant. There was also no significant difference in yields between FNP, blend, and PP under managed drought, rainfed, and optimal conditions on-station. The combined analysis of grain yield across all on-station and on-farm trials showed that yields differed significantly ($p < 0.001$) between recycling treatments (Figure 5f). Overall, in the combined analysis, pairwise comparison of treatments showed that when the PP is compared to the FNP and blend, there were significant differences at $p < 0.001$ and $p < 0.05$, respectively, while no significant difference was observed between the blend and FNP. The overall estimated yield advantage of FNP compared to the PP was 116 kg ha^{-1}, and the difference between blend and PP was 62 kg ha^{-1} (Table 6).

While the presence of ear rots was generally low, ear rot in NPP plants was less than half that of PP plants under both N stress and optimal conditions ($p < 0.001$) (Table 7). Ears of NPP plants were significantly wider than those of PP plants under N stress and optimal conditions ($p < 0.001$), while FNP hybrids had significantly longer kernels ($p < 0.001$). Under N stress conditions, hundred kernel weight of NPP plants was 6.1% higher than that of PP plants. Under optimal conditions, there was a small (1.3%) yet significant increase in hundred kernel weight in NPP plants compared to PP plants. Significant interactions between management and recycling treatment were observed for kernel number and ear length due to the difference in trend under optimum conditions where NPP ears were shorter (−0.3%) and had a lower kernel number (−3.5%). However, NPP plants also had more kernels than PP plants under N stress (17.6%) and longer ears in NPP plants relative to PP plants under N stress (5.1%). No significant difference in kernel width between PP and NPP plants was observed.

4 | DISCUSSION

These results suggest that the practice of recycling hybrid seed is associated with resource-constrained farmers. At the household level, the use of recycled hybrid seed was associated with food insecurity, lower levels of education of the household head, lower fertilizer use, and higher total maize production. At the plot level, the use of recycled hybrid seed was associated with jointly managed plots,

TABLE 5 Effect of spatial adjustment in on-farm trials on the average standard error, log likelihood ratio, and Bayesian information criterion (BIC). Hybrid denotes the genetic background of 50% non-pollen-producing (FNP) hybrid was evaluated.

	Average standard error difference									
	Ms44		Hybrid		Hybrid*Ms44		Log likelihood		BIC	
Farm	No-spatial	Spatial	No-spatial	Spatial	No-spatial	Spatial	No-spatial	Spatial	No-spatial	Spatial
1	0.463	0.438	0.249	0.235	0.099	0.089	12.353	12.495	−11.673	−8.699
3	0.266	0.265	0.217	0.201	0.073	0.050	−18.631	−18.305	50.295	52.900
4	0.168	0.162	0.189	0.166	0.090	0.078	12.864	15.764	−12.695	−11.979
6	0.214	0.288	0.315	0.252	0.182	0.135	0.382	1.682	12.269	16.184
7	0.136	0.134	0.219	0.160	0.137	0.129	9.674	10.261	−6.472	−1.208
12	0.001	0.001	0.163	0.192	0.113	0.092	−3.118	−1.887	19.269	20.065
16	0.415	0.370	0.277	0.265	0.108	0.100	3.915	6.761	4.882	2.369
17	0.296	0.230	0.205	0.154	0.057	0.057	−2.506	0.876	18.045	17.797
18	0.137	0.091	0.217	0.001	0.081	0.104	4.533	7.408	3.966	4.732
19	0.147	0.002	0.195	0.190	0.065	0.059	15.009	18.656	−16.985	−21.022
20	0.142	0.137	0.249	0.244	0.129	0.115	8.081	8.139	−3.286	3.036
21	0.167	0.140	0.251	0.176	0.152	0.146	28.764	29.709	−44.496	−39.868
22	0.171	0.141	0.274	0.135	0.138	0.145	−9.118	−7.098	31.269	30.487
23	0.397	0.194	0.280	0.219	0.069	0.069	0.984	3.062	11.065	13.424
24	0.305	0.380	0.128	0.001	0.052	0.051	−1.163	1.351	15.358	16.846
25	0.145	---	0.193	---	0.115	---	40.784	---	−68.535	---
27	0.282	0.001	0.217	0.190	0.042	0.042	−10.193	−9.160	33.418	37.869
28	0.361	0.443	0.218	0.169	0.078	0.064	29.058	35.838	−45.084	−52.127

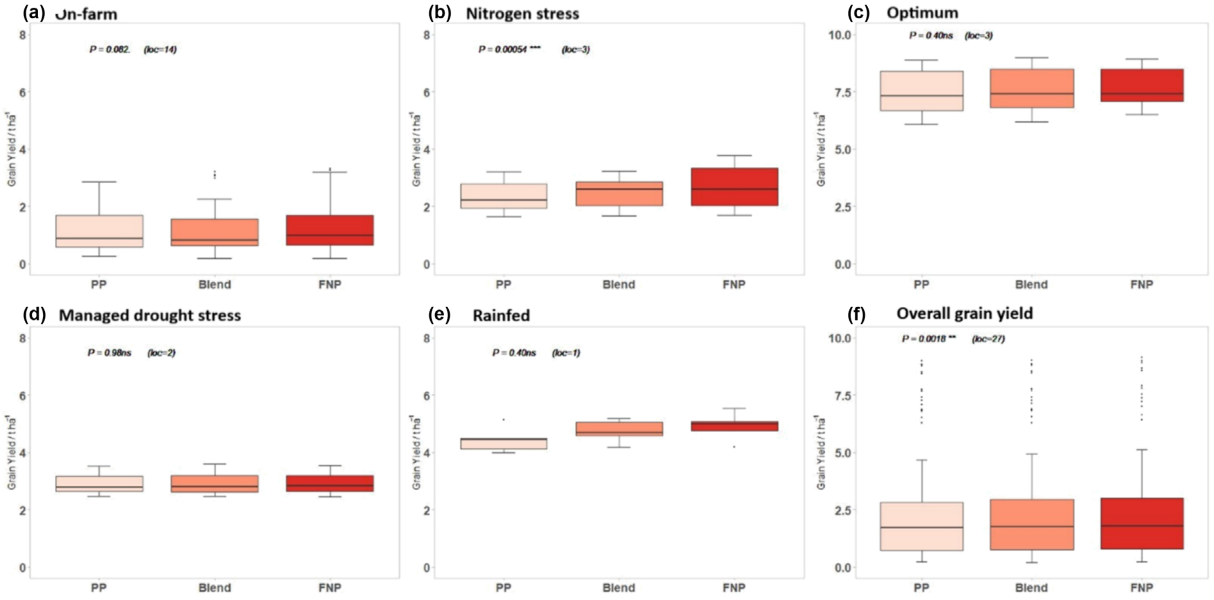

FIGURE 5 Grain yield of recycled seed saved from non-pollen-producing (NPP) plants (and progeny were therefore 50% non-pollen producing (FNP)), pollen-producing (PP) plants, and a blend of NPP and PP plants under (a) on-farm, (b) nitrogen stress, (c) optimum, (d) managed drought stress, (e) rainfed, and (f) overall grain yield. *P* indicates significance at 0.05 level, and loc indicates number of locations.

manual land preparation, and steeper slopes. The majority of households who used recycled hybrid maize seed on their farms only planted recycled hybrid seed once over the 3-year study period. The results suggest that the practice of recycling hybrid seed was associated with resource-constrained farmers. It is likely to be a coping mechanism to increase total maize production at the household level when the household was unable to plant the entire area with hybrid maize. The lower yield potential of recycled hybrid maize

(Pixley & Banziger, 2004) is likely to account, in part, for the practice of recycling to be associated with lower total fertilizer use at the household level. Similarly, fields, which have steeper slopes, are likely to be less fertile and productive due to greater fertility gradients.

Notably, the gender of the household head and plot manager did not emerge as significant predictors of hybrid recycling, although the results suggest significant gender-based disparities in access to some key resources. These findings contrast with an earlier study using the same 2020 survey (Cairns et al., 2022), in which gender of the household head *was* significantly associated with the use of recycling hybrid maize seed. In the earlier study, Cairns et al. (2022) treated gender as the sole explanatory variable and did not include any additional socio-economic variables. Similarly, using gender as the sole explanatory variable, Audet-Bélanger et al. (2016) and Chimonyo et al. (2020) found female farmers in southern Africa more likely to practice hybrid recycling. In this study, the inclusion of additional socio-economic variables at the household level resulted in gender of the household head no longer being a significant predictor of the use of hybrid seed recycling. This finding suggests that gender per se is not the primary factor associated with hybrid maize seed recycling, but rather variables related to household capabilities and resource access, several of which are correlated with gender of the household head. Female-headed households in this study had less area under cultivation, less cattle (a key indicator of wealth in Zimbabwe), lower household food security, and lower dietary diversity. This concurs with earlier studies, which highlighted that gender differences in technology use and productivity are often associated with gender-linked differences in key variables such as access to inputs, level of education, farm size, and access to credit (Doss & Morris, 2001; Ndiritu et al., 2014; Peterman et al., 2014).

TABLE 6 Pairwise comparison of grain yield of recycled maize seed from non-pollen-producing (NPP) plants, pollen-producing (PP) plants, and a blend of NPP and PP plants.

	Estimated yield difference (t ha^{-1})	*p*-Value
NPP—blend	0.053	0.07
Blend—PP	0.062	0.03
NPP—PP	0.116	<.001

Significant temporal variation was found in farms using the practice of recycling hybrid seed over the 3-year period between male-headed and female-headed households. The overall extent of hybrid maize recycling declined during the course of this study, although there was an increase within male-headed households. This may be related to several factors, including seasonal rainfall forecasts, methodological differences between surveys, and national input provision programs. In the first year, the season was predicted to have below average rainfall (Cairns et al., 2022). The following 2 years were forecasted to have average or above average (Tsiko, 2021, 2022). Rainfall projections are widely shared in national media, through social media, extension agents, and agro-dealers; thus, most farmers would have been aware of rainfall projections. Given the use of recycling maize hybrid seed was highest in the season forecasted to have below average rainfall, it is likely this information informed farmers' choices related to the amount of hybrid maize seed they purchased, particularly resource-poor farmers. Farmers are less likely to invest in improved maize in seasons perceived as drought due to the high risk of crop failure (Almekinders et al., 2021; Shiferaw et al., 2011). In both 2021 and 2022, rainfall was forecasted to be average or above average for the season. Additionally, in the first study (2020), survey questions were directed to the household head only and did not consider joint decision-making. In the 2023 survey, questions related to varietal use and agronomic management practices were directed to plot managers, and joint decision-making was included at the plot manager level (Voss, Gitonga, et al., 2023). The Government of Zimbabwe has also been running an input support scheme (Pfumvudza) that included maize seed to increase national maize yields. The households receiving support from Pfumvudza varied slightly between 2020 and 2023. Interestingly, jointly managed plots were associated with the practice of hybrid maize seed recycling, validating the incorporation of joint decision-making. In the second survey conducted in 2022, farmers were asked to recall varieties used this previous year 2021, and this may be subject to recall bias (Kosmowski et al., 2021).

If farmers chose to recycle seed, these results illustrate that how they recycle FNP seed determines the benefits they derive from *Ms44*. This study showed a small, yet significant, yield benefit when recycling NPP hybrid seed compared to PP (conventional) hybrid seed. Farmers often select ears to save for planting the following season

TABLE 7 Number of ear rots and yield components and difference between non-pollen-producing (NPP) and pollen-producing (PP) plants of recycled 50% non-pollen-producing (FNP) hybrids under two management conditions (nitrogen stress and optimal) in on-station trials.

	Optimum			Nitrogen stress			Significance	
	PP	NPP	% diff	PP	NPP	% diff	Management	Management:FNP
Ear rots (number)	0.86	0.34	−60.5	1.53	0.80	−47.7	<0.001	0.272
Ear width (cm)	5.01	5.04	0.6	4.38	4.58	4.4	0.039	0.003
Ear length (cm)	15.05	15.00	−0.3	12.03	12.64	5.1	0.011	0.033
Kernel length (mm)	0.70	0.71	1.4	0.68	0.70	2.9	0.845	0.067
Kernel width (mm)	0.40	0.40	0.0	0.40	0.41	2.5	0.879	0.694
100 kernel weight (g)	32.79	33.22	1.3	30.83	32.72	6.1	0.813	0.013
Kernel number	161.10	155.40	−3.5	107.30	126.2	17.6	0.486	0.002

based on appearance (assumed yield potential). NPP plants have significantly longer ears, with a greater number of kernels per ear, compared to PP plants (Collinson et al., 2022) and therefore might be preferentially selected for seed recycling. However, further research on farmer selection of recycled FNP hybrids would be needed to confirm this. While FNP hybrids provide a yield benefit of 200 kg ha^{-1} benefit across a range of yield levels (Collinson et al., 2022), it was found that FNP in recycled hybrid seed from NPP plants conferred a yield benefit of 14% (116 kg ha^{-1}) relative to the PP control, while recycled seed from a mixture of PP and NPP plants conferred a yield benefit of 7% (62 kg ha^{-1}). Thus, conscientious farmers who select ears from NPP hybrid maize plants for the next season could expect a yield benefit of 116 kg ha^{-1} compared to farmers selecting ears from PP plants (derived from conventional hybrid seed). Trait preference studies have shown farmers in Zimbabwe prefer larger kernel size (Kassie et al., 2017; Setimela et al., 2017). Both kernel length and 100-kernel weight were significantly higher in recycled NPP hybrid seed compared to recycled PP hybrid seed, although the difference was relatively small, and the genetic background of the hybrid may have a larger effect on overall grain size.

The results of the logit models showed that farmers were more likely to plant recycled hybrid maize seed on steeper slopes, which is likely to result in greater fertility gradients and less fertilizer applied. Thus, N stress is likely to be prevalent in fields planted with recycled hybrid maize seed. Under on-station N stress trials, recycled NPP hybrid seed yielded almost 14% more than recycled seed from PP (conventional) hybrids. Thus, farmers could expect a small, yet significant, yield benefit to recycling NPP seed relative to PP. Yield gains were associated with significantly bigger ears with a larger number of kernels per ear, consistent with previous studies dissecting the yield benefit of FNP hybrids (Collinson et al., 2022; Fox et al., 2017; Loussaert et al., 2017). Interestingly, NPP plants have significantly less ear rots than PP plants, and this relationship needs to be further investigated. The lines used in this study were selected based on their tolerance to key abiotic and biotic stresses and were converted by backcrossing *Ms44* into each female used as the female of the single cross within a three-way hybrid to provide proof of concept for the yield benefit of *Ms44*. The aim of deploying SPTA is to simplify hybrid maize seed production and help drive hybrid replacement. Thus, lines subsequently converted with SPTA will commonly be used as the female of the single cross in new candidate hybrids advancing through maize breeding pipelines in eastern and southern Africa. However, unlike CMS, *Ms44* is stable across genetic backgrounds (Collinson et al., 2022; Fox et al., 2017), and the results will therefore be consistent across genetic backgrounds.

5 | CONCLUSIONS

The hybrid seed production technology previously provided the first documented example of a single gene technology in maize (*Ms44*) to significantly increase yields in low-input farmers' fields (Collinson et al., 2022). While recycling hybrid seed results in a yield penalty compared to hybrid maize seed due to inbreeding depression (Pixley & Banziger, 2004), it has previously been associated with female-headed household in Southern Africa. To ensure greater social inclusion within the validation stage of a new genetic technology, this study explored seed recycling patterns among households and investigated whether different recycling scenarios of FNP maize could provide a yield benefit.

Household use of recycled hybrid seed was found to vary across years. Recycling in this study was used by more resource-constrained farmers, with lower input use, and is therefore likely a coping strategy for resource-poor households to maximize the area under maize production while minimizing potential financial losses in seasons that are predicted to have below average rainfall. Recycling FNP hybrid maize would provide a small, yet significant, yield benefit to farmers planting recycled seed over conventional recycled hybrid seed. Recycling from NPP plants exclusively provided the largest yield benefit, although recycling randomly still generated some benefit; additional research on farmers' current recycling practices is needed to fully assess the implications of these yield gains. While the yield advantage is small, the additional yield benefit from FNP hybrid maize, even if it is recycled, may be important to vulnerable farmers during years marked by drought.

Since production technologies are often adapted by farmers, depending in part on the household's capabilities, resources or investment capacity (Thuijsman et al., 2022), it is important to understand how farmers might adapt technologies in unexpected or nonstandardized ways and what the impacts might be. The findings from this study illustrate why and how new technologies should be evaluated under real-world conditions, particularly those used by resource-poor farmers (Cairns et al., 2022; Voss et al., 2021). The results show the diversity of smallholder farmers found even within a relatively small geographical area and meaningful differences in practices among these groups, underscoring the value of bringing social considerations into new product design and testing strategies (Cullen et al., 2023). This study also reinforces the need to move away from homogenous comparisons of women and men and include household characteristics that interact with gender (Teeken et al., 2021; van Etten et al., 2023). This will help ensure, as crop breeding programs in SSA aim deliberately to engage and benefit a more diverse range of users (Lawali et al., 2024; Nchanji et al., 2024; Ssali et al., 2023; Teeken et al., 2021) that new genetic technologies help increase resource-poor farmers' yields, food security, and income (Crossa et al., 2017; Pixley et al., 2022; Prasanna et al., 2022).

AUTHOR CONTRIBUTIONS

The study was conceptualized by Esnath Tatenda Hamadziripi, Jill E. Cairns, Mike S. Olsen, and Sarah Collinson, Esnath Tatenda Hamadziripi and Jill E. Cairns led the field trials and Frédéric Baudron and Jill E. Cairns led the farm surveys. Esnath Tatenda Hamadziripi, Frédéric Baudron, and Juan Burgueño primarily undertook the data analysis. The manuscript Esnath Tatenda Hamadziripi and Jill E. Cairns wrote the first draft of the manuscript. All authors contributed to manuscript revision.

ACKNOWLEDGEMENTS

This study was supported through the Bill & Melinda Gates Foundation funded project “Seed Production Technology for Africa” (INV-018951), the UK Global Challenges Research Fund administered by the Biotechnology and Biological Sciences Research Council project “Addressing malnutrition with biofortified maize in Zimbabwe: from crop management to policy and consumers” (IATI Identifier: GB-GOV-13-FUND–GCRF-BB_T009047_1), a Non-CGIAR Center Program Participant Agreement, with funding from the Bill & Melinda Gates Foundation (INV-004985) via the CGIAR GENDER Impact Platform, and the CGIAR Research Program on Maize (MAIZE). The CGIAR Research Program MAIZE received W1&W2 support from the Governments of Australia, Belgium, Canada, China, France, India, Japan, Korea, Mexico, Netherlands, New Zealand, Norway, Sweden, Switzerland, UK, U.S., and the World Bank. We thank Boniface Nyamande, Alex Chikoshana and agricultural extension agents (Felistus Sibangani, Ngonidzashe Gwengwere, Petronella Mangena, Evans Magama, Florence Muchingami, Charles Kuzanga, Rufaro Chidemo, Susan Mujati, Odreck Jongwe, Oliver Mukutiri, Election Dube, Lawrence Makonyere, Tafara Mhoka, Mambanda Urayai, Matipedza Omega, Nyaradzai Chikari, Judith Mandizvidza, Monika Chaminuka, Florence Mazhazhate, Ancillia Chipatiso, Anthony Murembwa, Maurice Musungapasi, Ignasios Chitotombe, Eugenia Choga, Kennedy Pedzisai, Rudo Muchakacha, Benjamin Muparangi, Simon Gumindoga) for their technical support, Dr Chloe MacLaren for her statistical advice and the farmers who gave their valuable time to this study. We would also like to thank the three anonymous reviewers for their helpful comments.

CONFLICT OF INTERES STATEMENTT

All authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper. S.C. is an employee of Corteva Agriscience. Corteva Agriscience owns the rights to the technology. There are no competing interests as Corteva Agriscience is providing the technology royalty-free to licensed seed companies producing seed for smallholders in the region under the terms of the Seed Production Technology for Africa agreement (https://www.cimmyt.org/content/uploads/2019/03/CIMMYT-SPTA-project-brief-2020-07-web.pdf).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on CIMMYT Dataverse (https://data. cimmyt.org/). No personally identifiable information is included in these data sets.

ETHICS STATEMENT

Our research was deemed low risk and approval was granted by the CIMMYT internal ethics review committee (IREC). IREC complies with standards setup with CIMMYT internal policies, applicable legal framework, and requirements from Funders. Informed consent was sought by local representatives, ensuring participants understood participation was voluntary and they had the right to refuse participation, and participation could be stopped at any time.

ORCID

Esnath Tatenda Hamadziripi https://orcid.org/0000-0001-6929-0083
Sarah Collinson https://orcid.org/0000-0002-2947-300X
Rachel C. Voss https://orcid.org/0000-0002-0890-830X
Frédéric Baudron https://orcid.org/0000-0002-5648-2083
Maryke T. Labuschagne https://orcid.org/0000-0003-0593-2678
Angelinus C. Franke https://orcid.org/0000-0002-4150-7196
Mainassara Zaman-Allah https://orcid.org/0000-0002-8120-5125
Mike S. Olsen https://orcid.org/0000-0002-8818-6238
Juan Burgueño https://orcid.org/0000-0002-1468-4867
Jill E. Cairns https://orcid.org/0000-0002-2735-3485

REFERENCES

Adam, R. I., David, S., Cairns, J. E., & Olsen, M. (2021). A review of the literature on gender and chemical fertiliser use in maize production in sub-Saharan Africa. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, *122*(1), 91–102.

Almekinders, C. J. M., Hebinck, P., Marinus, W., Kiaka, R. D., & Waswa, W. W. (2021). Why farmers use so many different maize varieties in West Kenya. *Outlook on Agriculture*, *50*(4), 406–417. https://doi.org/10.1177/00307270211054211

Andorf, C., Beavis, W. D., Hufford, M., Smith, S., Suza, W. P., Wang, K., Woodhouse, M., Yu, J., & Lübberstedt, T. (2019). Technological advances in maize breeding: Past, present and future. *Theoretical and Applied Genetics*, *132*, 817–849. https://doi.org/10.1007/s00122-019-03306-3

Audet-Bélanger, G., Gildemacher, P., & Hoogendoorn, C. (2016). Zambia Study Report Seed Sector functioning and the adoption of improved maize varieties. Agricultural Fair Eastern Province Zambia Study Report. KIT. https://www.kit.nl/wp-content/uploads/2019/03/Zambia-study-report.pdf. Date accessed 22/01/2024.

Baudron, F., Zaman-Allah, M. A., Chaipa, I., Chari, N., & Chinwada, P. (2019). Understanding the factors influencing fall armyworm (*Spodoptera frugiperda* J.E. Smith) damage in African smallholder maize fields and quantifying its impact on yield. A case study in eastern Zimbabwe. *Crop Protection*, *120*, 141–150. https://doi.org/10.1016/j.cropro.2019.01.028

Burke, W. J., & Jayne, T. S. (2021). Disparate access to quality land and fertilizers explain Malawi's gender yield gap. *Food Policy*, *100*, 102002. https://doi.org/10.1016/j.foodpol.2020.102002

Burke, W. J., Li, S., & Banda, D. (2018). Female access to fertile land and other inputs in Zambia: Why women get lower yields. *Agriculture and Human Values*, *35*(4), 761–775. https://doi.org/10.1007/s10460-018-9872-6

Cairns, J. E., Baudron, F., Hassall, K. L., Ndhlela, T., Nyagumbo, I., McGrath, S. P., & Haefele, S. M. (2022). Revisiting strategies to incorporate gender-responsiveness into maize breeding in southern Africa. *Outlook on Agriculture*, *51*(2), 178–186. https://doi.org/10.1177/00307270211045410

Cairns, J. E., Chamberlin, J., Rutsaert, P., Voss, R. C., Ndhlela, T., & Magorokosho, C. (2021). Challenges for sustainable maize production in sub-Saharan Africa. *Journal of Cereal Science*, *101*, 103274. https://doi.org/10.1016/j.jcs.2021.103274

Cairns, J. E., & Prasanna, B. M. (2018). Developing and deploying climate-resilient maize varieties in the developing world. *Current Opinion in Plant Biology*, *45*, 226–230. https://doi.org/10.1016/j.pbi.2018.05.004

Calcagno, V., Calcagno, M. V., Java, S., & Suggests, M. (2020). Package ‘glmulti.’

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jäger, J., & Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences*, *100*(14), 8086–8091. https://doi.org/10.1073/pnas.1231332100

Chimonyo, V. G. P., Mutengwa, C. S., Chiduza, C., & Tandzi, L. N. (2020). Characteristics of maize growing farmers, varietal use and constraints to increase productivity in selected villages in the eastern Cape province of South Africa. *South African Journal of Agricultural Extension (SAJAE)*, *48*(2), 64–82. https://doi.org/10.17159/2413-3221/2020/v48n2a538

Chivasa, W., Worku, M., Teklewold, A., Setimela, P., Gethi, J., Magorokosho, C., Davis, N. J., & Prasanna, B. M. (2022). Maize varietal replacement in eastern and southern Africa: Bottlenecks, drivers and strategies for improvement. *Global Food Security*, *32*, 100589. https://doi.org/10.1016/j.gfs.2021.100589

Collinson, S., Hamdziripi, E., De Groote, H., Ndegwa, M., Cairns, J. E., Albertsen, M., Ligeyo, D., Mashingaidze, K., & Olsen, M. S. (2022). Incorporating male sterility increases hybrid maize yield in low input African farming systems. *Communications Biology*, *5*(1), 729. https://doi.org/10.1038/s42003-022-03680-7

Crossa, J., Pérez-Rodríguez, P., Cuevas, J., Montesinos-López, O., Jarquín, D., de los Campos, G., Burgueño, J., González-Camacho, J. M., Pérez-Elizalde, S., Beyene, Y., Dreisigacker, S., Singh, R., Zhang, X., Gowda, M., Roorkiwal, M., Rutkoski, J., & Varshney, R. K. (2017). Genomic selection in plant breeding: Methods, models, and perspectives. *Trends in Plant Science*, *22*(11), 961–975. https://doi.org/10.1016/j.tplants.2017.08.011

Cullen, B., Snyder, K. A., Rubin, D., & Tufan, H. A. (2023). 'They think we are delaying their outputs'. The challenges of interdisciplinary research: Understanding power dynamics between social and biophysical scientists in international crop breeding teams. *Frontiers in Sustainable Food Systems*, *7*, 1250709. https://doi.org/10.3389/fsufs.2023.1250709

Djurfeldt, A. A., Kalindi, A., Lindsjö, K., & Wamulume, M. (2019). Yearning to farm–youth, agricultural intensification and land in Mkushi, Zambia. *Journal of Rural Studies*, *71*, 85–93. https://doi.org/10.1016/j.jrurstud.2019.08.010

Doss, C. R. (2001). Designing agricultural technology for African women farmers: Lessons from 25 years of experience. *World Development*, *29*, 2075–2092. https://doi.org/10.1016/S0305-750X(01)00088-2

Doss, C. R., & Morris, M. L. (2001). How does gender affect the adoption of agricultural innovations? The case of improved maize technology in Ghana. *Agricultural Economics*, *25*, 27–39. https://doi.org/10.1016/S0169-5150(00)00096-7

FAO. (2023). The status of women in agrifood systems. Rome. https://doi.org/10.4060/cc5343en

FAO, IFAD, UNICEF, WFP. & WHO. (2023). The State of Food Security and Nutrition in the World 2023 Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum. FAO. https://doi.org/10.4060/cc3017en

Fox, T., DeBruin, J., Haug Collet, K., Trimnell, M., Clapp, J., Leonard, A., Li, B., Scolaro, E., Collinson, S., & Glassman, K. (2017). A single point mutation in Ms44 results in dominant male sterility and improves nitrogen use efficiency in maize. *Plant Biotechnology Journal*, *15*(8), 942–952. https://doi.org/10.1111/pbi.12689

Frischen, J., Meza, I., Rupp, D., Wietler, K., & Hagenlocher, M. (2020). Drought risk to agricultural systems in Zimbabwe: A spatial analysis of hazard, exposure, and vulnerability. *Sustainability*, *12*, 752. https://doi.org/10.3390/su12030752

Gaffney, J., Anderson, J., Franks, C., Collinson, S., MacRobert, J., Woldemariam, W., & Albertsen, M. (2016). Robust seed systems, emerging technologies, and hybrid crops for Africa. *Global Food Security*, *9*, 36–44. https://doi.org/10.1016/j.gfs.2016.06.001

Gebre, G. G., Isoda, H., Rahut, D. B., Amekawa, Y., & Nomura, H. (2019). Gender differences in the adoption of agricultural technology: The case of improved maize varieties in southern Ethiopia. *Women's Studies International Forum*, *76*, 102264. https://doi.org/10.1016/j.wsif.2019.102264

Hassall, K. L., Baudron, F., MacLaren, C., Cairns, J. E., Ndhlela, T., McGrath, S. P., Nyagumbo, I., & Haefele, S. M. (2023). Construction of a generalised farm typology to aid selection, targeting and scaling of onfarm research. *Computers and Electronics in Agriculture*, *212*, 108074. https://doi.org/10.1016/j.compag.2023.108074

Heisey, P., Morris, M. L., Byerlee, D., & Lopez-Pereira, M. A. (1997). Economics of hybrid maize adoption. In M. L. Morris (Ed.), *Maize seed industries in developing countries*. Lynne Rienner Publishers.

Hoogendoorn, J. C., Audet-Bélanger, G., Böber, C., Donnet, M. L., Lweya, K. B., Malik, R. K., & Gildemacher, P. R. (2018). Maize seed systems in different agro-ecosystems; what works and what does not work for smallholder farmers. *Food Security*, *10*, 1089–1103. https://doi.org/10.1007/s12571-018-0825-0

Kassie, G. T., Abdulai, A., Greene, W. H., Shiferaw, B., Abate, T., Tarekegne, A., & Sutcliffe, C. (2017). Modeling preference and willingness to pay for drought tolerance (DT) in maize in rural Zimbabwe. *World Development*, *94*, 465–477. https://doi.org/10.1016/j.worlddev.2017.02.008

Khaipho-Burch, M., Cooper, M., Crossa, J., de Leon, N., Holland, J., Lewis, R., McCouch, S., Murray, S. C., Rabbi, I., Ronald, P., Ross-Ibarra, J., Weigel, D., & Buckler, E. S. (2023). Genetic modification can improve crop yields — But stop overselling it. *Nature*, *621*(7979), 470–473. https://doi.org/10.1038/d41586-023-02895-w

Kim, Y. J., & Zhang, D. (2018). Molecular control of male fertility for crop hybrid breeding. *Trends in Plant Science*, *23*(1), 53–65. https://doi.org/10.1016/j.tplants.2017.10.001

Kosmowski, F., Chamberlin, J., Ayalew, H., Sida, T., Abay, K., & Craufurd, P. (2021). How accurate are yield estimates from crop cuts? Evidence from smallholder maize farms in Ethiopia. *Food Policy*, *102*, 102122. https://doi.org/10.1016/j.foodpol.2021.102122

Langyintuo, A. S., Mwangi, W., Diallo, A. O., MacRobert, J., Dixon, J., & Bänziger, M. (2010). Challenges of the maize seed industry in eastern and southern Africa: A compelling case for private–public intervention to promote growth. *Food Policy*, *35*(4), 323–331. https://doi.org/10.1016/j.foodpol.2010.01.005

Lawali, S., Boureima, S., & Idi, S. (2024). A gender-responsive breeding approach to the intensification of sesame (*Sesamum indicum* L.) production in the Maradi region of Niger. *Frontiers in Sociology*, *9*, 1254094. https://doi.org/10.3389/fsoc.2024.1254094

Loussaert, D., De Bruin, J., Pablo San Martin, J., Schussler, J., Pape, R., Clapp, J., Mongar, N., Fox, T., Albertsen, M., Trimnell, M., & Collinson, S. (2017). Genetic male sterility (Ms44) increases maize grain yield. *Crop Science*, *57*(5), 2718–2728. https://doi.org/10.2135/cropsci2016.08.0654

Makanza, R., Zaman-Allah, M., Cairns, J. E., Eyre, J., Burgueño, J., Pacheco, Á., Diepenbrock, C., Magorokosho, C., Tarekegne, A., Olsen, M., & Prasanna, B. M. (2018). High-throughput method for ear phenotyping and kernel weight estimation in maize using ear digital imaging. *Plant Methods*, *14*(1), 49. https://doi.org/10.1186/s13007-018-0317-4

Nchanji, E. B., Chisorochengwe, N., Tsekenedza, S., Gutsa, F., Musyoka, J. N., & Lutomia, C. K. (2024). Breaking ground: Transformative partnerships for inclusive bean breeding in Zimbabwe. *Frontiers in Sustainable Food Systems*, *8*, 1155856. https://doi.org/10.3389/fsufs.2024.1155856

Ndiritu, S. W., Kassie, M., & Shiferaw, B. (2014). Are there systematic gender differences in the adoption of sustainable agricultural intensification practices? Evidence from Kenya. *Food Policy*, *49*, 117–127. https://doi.org/10.1016/j.foodpol.2014.06.010

Peterman, A., Behrman, J. A., & Quisumbing, A. R. (2014). A review of empirical evidence on gender differences in nonland agricultural inputs, technology, and services in developing countries. In A. Quisumbing, R. Meinzen-Dick, T. Raney, A. Croppenstedt, J. Behrman, & A. Peterman (Eds.), *Gender in Agriculture* (pp. 145–186). Springer. https://doi.org/10.1007/978-94-017-8616-4_7

Pixley, K., & Banziger, M. (2004). Open-pollinated maize varieties: A backward step or valuable option for farmers. In *Seventh eastern and southern Africa regional maize conference*;CIMMYT: Mexico City, Mexico (pp. 22–28).

Pixley, K. V., Falck-Zepeda, J. B., Paarlberg, R. L., Phillips, P. W. B., Slamet-Loedin, I. H., Dhugga, K. S., Campos, H., & Gutterson, N. (2022). Genome-edited crops for improved food security of smallholder farmers. *Nature Genetics*, *54*(4), 364–367. https://doi.org/10.1038/s41588-022-01046-7

Prasanna, B. M., Burgueño, J., Beyene, Y., Makumbi, D., Asea, G., Woyengo, V., Tarekegne, A., Magorokosho, C., Wegary, D., & Ndhlela, T. (2022). Genetic trends in CIMMYT's tropical maize breeding pipelines. *Scientific Reports*, *12*(1), 20110. https://doi.org/10.1038/s41598-022-24536-4

Prasanna, B. M., Cairns, J. E., Zaidi, P. H., Beyene, Y., Makumbi, D., Gowda, M., Magorokosho, C., Zaman-Allah, M., Olsen, M., Das, A., Worku, M., Gethi, J., Vivek, B. S., Nair, S. K., Rashid, Z., Vinayan, M. T., Issa, A. B., San Vicente, F., Dhliwayo, T., & Zhang, X. (2021). Beat the stress: Breeding for climate resilience in maize for the tropical rainfed environments. *Theoretical and Applied Genetics*, *134*(6), 1729–1752. https://doi.org/10.1007/s00122-021-03773-7

Quisumbing, A. R., Rubin, D., Manfre, C., Waithanji, E., van den Bold, M., Olney, D., Johnson, N., & Meinzen-Dick, R. (2015). Gender, assets, and market-oriented agriculture: learning from high-value crop and livestock projects in Africa and Asia. *Agriculture and Human Values*, *32*, 705–725. https://doi.org/10.1007/s10460-015-9587-x

R Core Team. (2024). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH image to ImageJ: 25 years of image analysis. *Nature Methods*, *9*(7), 671–675. https://doi.org/10.1038/nmeth.2089

Setimela, P. S., Magorokosho, C., Lunduka, R., Gasura, E., Makumbi, D., Tarekegne, A., Cairns, J. E., Ndhela, T., Erenstein, O., & Mwangi, W. (2017). On-farm yield gains with stress tolerant maize in eastern and southern Africa. *Agronomy Journal*, *109*, 406–417. https://doi.org/10.2134/agronj2015.0540

Shiferaw, B., Prasanna, B. M., Hellin, J., & Bänziger, M. (2011). Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security*, *3*(3), 307–327. https://doi.org/10.1007/s12571-011-0140-5

Smale, M., Phiri, A., Chikafa, G. A., Heisey, P. W., Mahatta, F., Msowoya, M. N. S., Mwanyongo, E. B. K., Sagawa, H. G., & Selemani, H. A. C. (1998). CIMMYT Institutional Change and Discontinuities in Farmers'. In *Use of hybrid maize seed and fertilizer in Malawi: Findings from the 1996–97 CIMMYT/MoALD survey. Economics working paper 98-01*. CIMMYT.

Ssali, R. T., Mayanja, S., Nakitto, M., Mwende, J., Tinyiro, S. E., Bayiyana, I., Okello, J., Forsythe, L., Magala, D., Yada, B., Mwanga, R. O. M., & Polar, V. (2023). Gender mainstreaming in sweetpotato breeding in Uganda: A case study. *Frontiers in Sociology*, *8*, 1233102. https://doi.org/10.3389/fsoc.2023.1233102

Teeken, B., Garner, E., Agbona, A., Balogun, I., Olaosebikan, O., Bello, A., Madu, T., Okoye, B., Egesi, C., Kulakow, P., & Tufan, H. A. (2021). Beyond "Women's traits": Exploring how gender, social difference, and household characteristics influence trait preferences. *Frontiers in Sustainable Food Systems*, *5*, 740926. https://doi.org/10.3389/fsufs.2021.740926

Thuijsman, E. S., den Braber, H. J., Andersson, J. A., Descheemaeker, K., Baudron, F., López-Ridaura, S., Vanlauwe, B., & Giller, K. E. (2022). Indifferent to difference? Understanding the unequal impacts of farming technologies among smallholders. *A Review. Agronomy for Sustainable Development*, *42*, 41. https://doi.org/10.1007/s13593-022-00768-6

Tsiko, S. (2021). Good rainy season expected - report. The Herald. https://www.herald.co.zw/good-rainy-season-expected-report/ (Date accessed: 20th January 2024)

Tsiko, S. (2022). SADC climate experts meet for 2021/22 season forecast. The Herald. https://www.herald.co.zw/sadc-climate-experts-meet-for-202122-season-forecast/ (Date accessed: 20th January 2024)

Tufan, H. A., Grando, S., & Meola, C. (2018). State of the Knowledge for Gender in Breeding: Case Studies for Practitioners. Working Paper. International Potato Center (CIP).

van Etten, J., de Sousa, K., Cairns, J. E., Dell'Acqua, M., Fadda, C., Guereña, D., van Heerwaarden, J., Assefa, T., Manners, R., Müller, A., Pèd, M. E., Polar, V., Ramirez-Villega, J., Solbergb, S. Ø., Teeken, B., & Tufan, H. A. (2023). Data-driven approaches can harness crop diversity to address heterogeneous needs for breeding products. *Proceedings of the National Academy of Sciences*, *120*, 2205771120. https://doi.org/10.1073/pnas.2205771120

Voss, R. C., Cairns, J. E., Olsen, M., Muteti, F. N., Magambo, G., Hamadziripi, E., Ligeyo, D., Mashingaidze, K., Collinson, S., & Wanderi, S. (2023). Innovative approaches to integrating gender into conventional maize breeding: Lessons from the seed production Technology for Africa project. *Frontiers in Sociology*, *8*, 1254595. https://doi.org/10.3389/fsoc.2023.1254595

Voss, R. C., Donovan, J., Rutsaert, P., & Cairns, J. E. (2021). Gender inclusivity through maize breeding in Africa: A review of the issues and options for future engagement. *Outlook on Agriculture*, *50*(4), 392–405. https://doi.org/10.1177/00307270211058208

Voss, R. C., Gitonga, Z. M., Donovan, J., Garcia-Medina, M., & Muindi, P. (2023). Can I speak to the manager? The gender dynamics of decision-making in Kenyan maize plots. *Agriculture and Human Values*, *41*, 205–224. https://doi.org/10.1007/s10460-023-10484-w

Wan, X., Wu, S., & Xu, Y. (2021). Male sterility in crops: Application of human intelligence to natural variation. *The Crop Journal*, *9*(6), 1219–1222. https://doi.org/10.1016/j.cj.2021.11.001

Zambezi, B. T., Nyondo, F. K., Nkhono, G., Mbingwani, G. F., & Chakhuta, T. F. (1997). Evaluation of recycled maize hybrids at three levels of nitrogen in Malawi. 5. Proceedings of the Eastern and Southern Africa Regional Maize Conference, , 3-7 Jun 1996.

ZimVAC. (2020). *Zimbabwe vulnerability assessment committee 2020 rural livelihoods assessment report*. Food and Nutrition Council.

Zingore, S., Murwira, H. K., Delve, J. R., & Giller, K. E. (2007). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture, Ecosystems and Environment*, *119*(1–2), 112–126. https://doi.org/10.1016/j.agee.2006.06.019

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Hamadziripi, E. T., Collinson, S., Voss, R. C., Baudron, F., Labuschagne, M. T., Franke, A. C., Zaman-Allah, M., Olsen, M. S., Burgueño, J., & Cairns, J. E. (2024). Validating a novel genetic technology for hybrid maize seed production under management practices associated with resource-poor farmers in Zimbabwe. *Plants, People, Planet*, 1–15. https://doi.org/10.1002/ppp3.10590