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Participatory variety selection and stability of agronomic performance of advanced sorghum lines in Zimbabwe

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ABSTRACT

Traditional variety selection practices rarely involve end-users of breeding products, which is regarded as a major factor for the continued reliance by farmers on unproductive landraces and old varieties. Here, we report on a participatory variety selection (PVS) approach involving on-farm trials established across five drought-prone districts of Zimbabwe during the 2018–19 summer season. The objective of this study was to evaluate nine prereleased sorghum lines developed by ICRISAT against three commercial check varieties to identify the high-yielding, stable sorghum (*Sorghum bicolor* (L.) Moench) improved breeding lines, with desirable agronomic attributes as per farmers' perceptions. Results demonstrated that although there was a positive and significant relationship between the across-location grain yield (GY) and the overall genotype performance score (OGPS, ranking by farmers), farmers' choices were related to locality (i.e., resident districts) and grain color. Arid locations were the most ideal for sorghum evaluation. Advanced lines IESV91070DL (1.41 t ha^{-1}) and ASARECA 12-3-1 (1.9 t ha^{-1}), as well as a commercial variety (Macia, 1.73 t ha^{-1}) were high-yielding, stable and most preferred by farmers. Although the selection criteria of both the farmers and researchers pointed to selection for high yield performance, red sorghum genotypes (e.g., IESV99061DL and SDS3472), which showed high GY performance and stability were not among the most preferred by farmers. Overall, results demonstrated that PVS approaches should be combined with traditional varietal selection tools as this may increase adoption of new varieties.

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Introduction

Sorghum (*Sorghum bicolor* (L.) Moench), popular because of its resilience under drought and heat stress conditions, is among the most important food-security crops in the stress-prone regions of the world (Ajeigbe et al. 2018;

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Salim, El Aziz Ahmed, and Mohamed 2017). Among the food-security crops, sorghum is ranked fifth after maize (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) (Mare et al. 2017; Mundia et al. 2019). However, in Africa, sorghum ranks second in importance after maize (Msongaleli et al. 2017). In areas where the crop is cultivated, it is commonly utilized as a food or feed source, apart from its industrial utility (i.e., raw material for beer and starch production) (Xiong et al. 2019). Sorghum is also considered a nutritional-security crop, as it contains slowly digestible and resistant starch components known to reduce postprandial hyperglycemia in humans (Teferra and Awika 2019).

Sorghum cultivation is popular in southern Zimbabwe, which is classified as arid or semi-arid; the area receives an average annual rainfall of <450 mm (Mugandani et al. 2012; Tsusaka et al. 2015). Sorghum is considered drought-resilient (Amare et al. 2015; Chanza 2018; Dube et al. 2018). As predicted by climate-change models (Bosire et al. 2018; Eggen et al. 2019; Hadebe, Modi, and Mabhaudhi 2017), abiotic stresses, particularly drought stress and heat stress, are expected to continue to surge; and, likewise, the importance of sorghum as a food, feed, nutritional-security, and industrial crop is expected to increase (Dahlberg, Wilson, and Synder 2003; Rukuni et al. 2015). Therefore, it is imperative to direct efforts toward improving the agronomic value of this crop to confront these predicted climatic scenarios.

Regardless of its popularity as a abiotic stress-resilient crop (Chanza 2018; Dube et al. 2018; Tack, Lingenfelser, and Jagadish 2017), in sub-Saharan Africa (SSA), average yield of sorghum per hectare, ranging between 0.3 and 1 t ha^{-1}, is one-third that of other important cereals, such as maize and wheat. Farmers' resistance to adopt improved varieties is usually used to explain these low yields (Ncube et al. 2007). For instance, in Zimbabwe, notwithstanding the development of improved varieties by both the national and private breeding programs, as well as their availability in the seed market, sorghum growers surprisingly continue to grow traditional landrace varieties (Orr et al. 2016), which often fail to produce reasonably high yields (Mukondwa et al. 2020). To change the status quo, it is important to holistically scrutinize the seed development, production and marketing systems and identify areas that may need improvement, so that farmers benefit from the breeding efforts to enhance sorghum productivity.

Critical decisions in plant breeding programs, e.g., variety selection, predominantly hinge on multi-environmental trials (METs), wherein new breeding materials are tested for adaptation to stress and non-stress conditions, with average yield ranks, and sometimes, grain yield stability, used as the basis to select the most ideal genotypes. These experiments are researcher-managed and the end-users (growers) of the intended products (new varieties) are often not involved, which is a major factor for the low acceptance of new varieties by farmers. For years, farmers have been involved in seed selection and this is evidenced by the existence of seed banks (especially for the neglected and under-utilized crops) that are only found in farmers' rural communities but absent in the seed market. If given an opportunity, farmers can play a pivotal role in crop improvement. To build a collaboration between plant breeders and farmers, use of a variety-evaluation system, known as "Participatory Variety Selection" (PVS), produced interesting results in Central and Northern Tanzania (Ojulong et al. 2016). The study found that since farmers were involved in developing new finger millet (*Eleusine coracana* (L.) Gaertn.) varieties, their adoption rate among farmers was quite high (Ojulong et al. 2016). In general, PVS provides a wide range of varieties to farmers to evaluate on their own farms, using their own resources (Gowda et al. 2000). It is pertinent to note that Kang (2020) has suggested that participatory plant breeding should be expanded, especially in developing countries, which should help broaden the genetic base of crops and stabilize food production as a result of farmers developing, identifying, and using locally adapted crop varieties that are acceptable and accessible to them.

Although the PVS approach has proved to be effective in finger millet in Tanzania and India, its usefulness for sorghum is poorly documented. Thus, the objective of this study was to identify advanced ICRISAT-bred, high-yielding, stable sorghum lines, possessing farmer-preferred desirable agronomic attributes. We hypothesize that, although several traits may be used to describe a desirable sorghum variety for cultivation, genotypes possessing high yield and performance stability will be most preferred by farmers, regardless of their gender and age.

Materials and methods

Germplasm and test locations

Twelve sorghum genotypes, consisting of nine advanced lines developed by ICRISAT and three check varieties (i.e., two commercial varieties + a farmers' variety) (Table 1), were evaluated on farmers' fields during the 2018–19 season across five arid and semi-arid locations (i.e., districts), namely, Chiredzi, Gwanda, Matobo, Mwenezi NRIV and Mwenezi NRV, which represented sorghum-growing areas in Zimbabwe (Figure 1; Table S1). These locations are characterized by low and poorly distributed rainfall, high temperatures and mid-season drought (Mukarumbwa and Mushunje 2010). The farmers' variety varied by location, as each farmer used a variety that was popular within his/her locality. The farmers' varieties used at each of the five locations were landraces (Table 1).

Table 1. Description of the nine advanced sorghum lines evaluated alongside three checks, in on-farm trials conducted at five locations during the 2018–19 rainy season in Zimbabwe.

Code	Genotype name	Environment mean yield performance (t/ha)	Type and breeding status	Description	Grain color	Origin
G9	ASARECA 12-3-1	1.9	Grain/Advanced/ICRISAT	Experimental line	White	ICRISAT-India
G10	Macia	1.7	Grain/Released/ICRISAT	Check	White	ICRISAT-India
G7	ICSV 111 IN	1.6	Grain/Advanced/ICRISAT	Experimental line	White	ICRISAT-India
G8	IESV 99061 DL	1.6	Grain/Advanced/ICRISAT	Experimental line	Red/Brown	ICRISAT-India
G2	Gadam el hamam	1.5	Grain/Advanced/ICRISAT	Experimental line	White	ICRISAT-India
G4	IESV 91070 DL	1.4	Grain/Advanced/ICRISAT	Experimental line	White	ICRISAT-India
G5	SDS 3472	1.2	Grain/Advanced/ICRISAT	Experimental line	Red/Brown	ICRISAT-India
G6	Wahi	1.1	Grain/Advanced/ICRISAT	Experimental line	White	ICRISAT-India
G1	IESV 23006	1.1	Grain/Advanced/ICRISAT	Experimental line	Red/Brown	ICRISAT-India
G11	SV4	0.9	Grain/Released/CBI	Check	White	CBI-Zimbabwe
G3	ICSR 161	0.7	Grain/Advanced/ICRISAT	Experimental line	White	ICRISAT-India
G12	Farmer own variety	0.7	Local landraces	Check	White	Isigobane (Matopos & Gwanda), Chitichi (Chiredzi) & Mukadziusaende (Mwenezi)

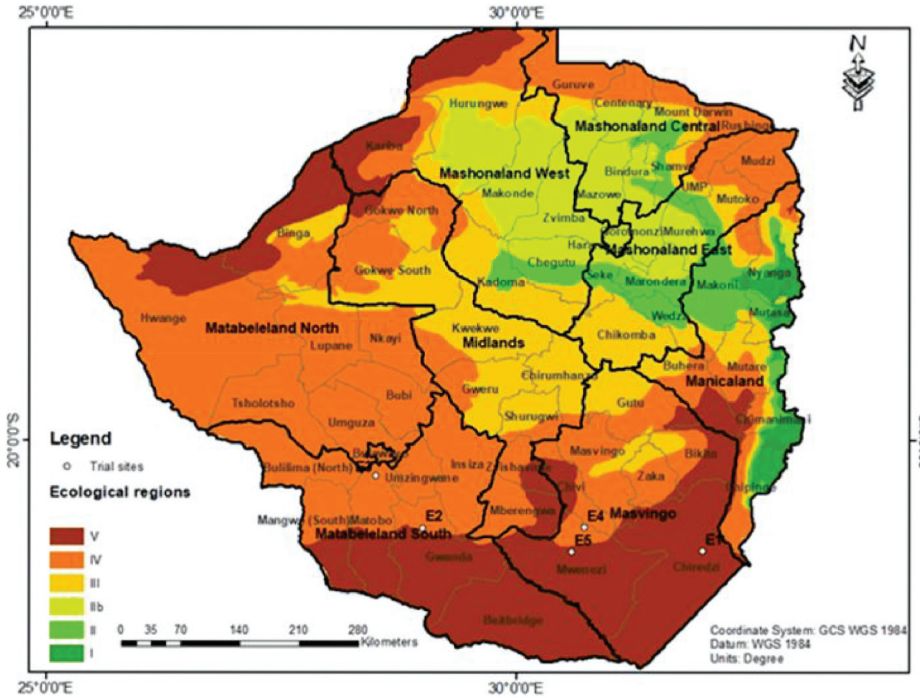

Figure 1. A map showing the locations used to evaluate the nine advanced sorghum lines, planted together with three checks during the 2018–19 rainy season in Zimbabwe. Locations are marked by white dots (*modified from* Raymond Mugandani 2012).

Trial establishment and agronomic data collection

The 12 sorghum genotypes were arranged in the field using a randomized complete block design (RCBD), with two replications at each location. From each location, two farmers, growing the same set of varieties, were selected and each farmer was regarded as a replicate. Each cultivar was planted in a five-row plot, which was 5 m long, with an interrow spacing of 0.75 m and an intrarow spacing of 0.2 m, to give a plant population of 125 plants per plot. Grain weight (GW) was measured from the grain collected from heads of plants from the middle three rows of each plot; a 0.5-m border on each end of rows was discarded to eliminate border effects. This resulted in a net plot size of 9 m^2 (i.e., 3 rows × 0.75 m × 4 m row length), which was equivalent to a population of 60 plants per plot. Grain moisture (GM) was measured using a KM 36 G cereal grain-moisture meter (Corousell, Bulacan, Philippines). Grain yield (GY) was computed from the grain weight per net plot at 12% moisture content and expressed in tons per hectare using the following formula:

$$\textbf{Grain yield}\left(\textbf{tha}^{-1}\right) = 1000 \times \frac{Net\,plot\,grain\,weight(kg)}{Net\,plot\,size(\mathrm{m}^2)}$$

Participatory variety selection (PVS) procedure

The PVS strategy was designed to achieve two objectives, viz., (i) to determine the most important trait for selection, and (ii) select the most ideal genotype for commercialization. Procedural details are given below.

Determination of the farmers' preferred traits and their ranking in variety selection

To determine the most important traits of interest to farmers for selecting sorghum varieties, focus group discussions (FGDs) were conducted at four locations (Figure 1; Table S1), viz, Chiredzi, Gwanda, Mwenezi (Region IV) and (Mwenezi Region V). To minimize bias, Matobo was avoided because most of the farmers in this district had a long working and personal relationship with ICRISAT in Zimbabwe, as the ICRISAT Research Station is based in this district. A total of 25 farmers in each of the four study locations, known to be sorghum producers and identified by the government of Zimbabwe's extension services, participated in the PVS. The FGDs were conducted using a pairwise ranking matrix, which is a systematic way of comparing the options in pairs, as described by Gay, Stubbs, and Galindo-Gonzalez (2016). In this method, each item is compared to the other items individually so that the number of times it was chosen is summed, and the item with the largest sum is regarded as the most important item (Gay, Stubbs, and Galindo-Gonzalez 2016). Following this procedure, farmers ranked GY as the most important trait of interest, followed by days to physiological maturity (DPM; number of days from planting until the formation of a black layer above the hilar region of the seed), plant height (PHT; the distance from the base of the plant to the tip of the main head panicle, determined as an average height of 10 plants) and grain color (GC; the color of grain on the panicle, which was either red, or brown or white). GY, DPM, PHT and GC were given a weightage of 40%, 30%, 20% and 10%, respectively, based on farmers' sorghum variety-selection criteria.

Ideal genotypes for commercialization

At physiological maturity, local farmers (maximum target = 25 respondents) were invited to participate in variety selection. Between the two farmers, who hosted the trials in each of the selected four districts, one farmer, who had a better-managed trial based on the existence of complete data and also having demonstrated good crop husbandry and trial management based on the specified trial protocols, was chosen to host the PVS. A total of 82 farmers from a target sample of 100 (i.e., 25 respondents per location) participated in the PVS, a process that involved scoring each of the 12 genotypes against each of the four farmer-prioritized traits (i.e., GY, DPM, PHT and GC) on a scale of 1–5, where 5 = a very good genotype, 4 = good, 3 = average, 2 = below average, and 1 = poor. Scoring was done on individual plot; genotypes were not labeled but only plot numbers were mentioned to avoid bias. During variety scoring, farmers were presented with a survey form that was designed to capture farmers' scoring of genotypes and also to provide personal details, including, sex, age, level of education and locality (i.e., district) (Table S2).

Final ranking of genotypes was based on overall performance score of a genotype (Y), which was determined using the below-given formula (the weightage for different traits varied from 0.4 to 0.1):

Y = N [GYD (g) (0.4) + DTM (d) (0.3) + PHT(p) (0.2) + GC (c) (0.1)]

where N = Total number of farmers who participated in PVS, GYD (g) = Grain yield score on a 1–5 scale, DMT (d) = Days to maturity score on a 1–5 scale, PHT (p) = Plant height score on a 1–5 scale, and GC (c) = Grain color score on a 1–5 scale. The farmer's variety was not considered for this analysis since different varieties were used in different districts.

Statistical analyses

Grain yield data from each of the five districts were first subjected to individual and across-site analysis of variance (ANOVA) using GenStat Software 17th Edition (Payne et al. 2009). Genotype means were separated using the least significant difference (LSD) at 5% probability level. For GY stability analysis, the "genotype + genotype × environment" (GGE) biplots were drawn following the procedures in Payne et al. (2009) using the GenStat Software 17th Edition; GY data from all five locations were used (*see* Table S3). First, to identify advanced sorghum lines with specific adaptation to different locations, the "scatter" GGE biplot was created. In this plot, the equality lines divided the biplot into sectors, and the best genotype for each sector was the one located on the respective vertex. To identify stable advanced lines, genotypic performance and biplot analysis were performed using the average environment coordinate (AEC). For the definition of an ideal genotype, see Yan and Kang (Yan and Kang 2003; page 88). The genotypes positioned furthest away from the AEC were judged to be "least stable", whereas those closest to the AEC were regarded as "most stable". Lastly, to establish relationships among test environments and to identify discriminating environments, the "scatter" GGE biplot was used. The locations with the longest vectors (a vector is the line connecting the test environment with the biplot origin) were regarded as the most discriminating environments. An acute angle between two vectors represented positive correlation, whereas an obtuse angle indicated no correlation between test locations (Yan and Tinker 2006). To determine how age, sex, level of education and locality/environment influenced farmers' variety selection and preferences, PVS data (i.e., overall genotype performance score) were subjected to regression analysis using Statistical Package for the Social Sciences (SPSS) [Release 16.0.0 (13 September 2007)]. In the regression model, the predictor values (i.e., constant) were sex, age, level of education and locality, whereas the overall genotype performance score was the dependent variable. To visualize characteristics of the respondents (i.e., farmers) with respect to age, sex, level of education and locality, 3-dimensional pie-charts were created using the "*pie3D*" function in the plotrix v3.7–2 R package (Lemon 2006). To determine the relationship between PVS procedure and the traditional variety selection protocol (predominantly based on across multi-environmental trial GY performance rankings), average GY data across the five locations (farmer's variety was excluded) were regressed against the overall genotype performance score (OGPS). This was done using the "*lm*" function in the agricolae v1.3–1 R package and the linear relationships were visualized using the "*plot*" function in the gplots v3.0.1 R package (Warnes et al. 2016).

Results

On-farm grain-yield performance

Individual and across-site analyses of variance (ANOVA) revealed significant genotypic effects for GY performance (Tables 2 and 3). The location Mwenezi Region IV showed the highest mean GY (2.2 t ha^{-1}), whereas the lowest-performing location was Gwanda, with a mean GY of 0.7 t ha^{-1} (Table 2). The highest GY-performing advanced line across all the locations was G9 (1.9 t ha^{-1}) (Tables 3 and 4).

On-farm grain yield stability and specific adaptation

The GGE "ranking" biplot identified the advanced lines G9 (GY = 1.9 t ha^{-1}) and G4 (GY = 1.41 t ha^{-1}) as both high yielding and stable since the distance from the AEC was small (Figure 2). The identified best-performing ICRISAT-bred check variety with respect to GY, G10 (GY = 1.73 t ha^{-1}) was also highly stable. G6 (GY = 1.05 t ha^{-1}) and G3 (GY = 0.74 t ha^{-1}) had stable but below average performance (Figure 2; Table 5).

The "scatter" GGE biplot placed the five locations into two distinct groups, in which Gwanda, Matopos, Mwenezi Region IV and Mwenezi Region V belonged to one group (GPL1), whereas Chiredzi formed the other group (GPL2). The advanced lines G2, G4, G5, G7 and G9 were adapted to GPL1, with G2 and G9 being the most ideal genotypes. The advanced line G8

Table 2. Individual site analysis of variance (ANOVA) for the advanced sorghum genotypes evaluated alongside three checks, in on-farm trials conducted at five locations during the 2018–19 rainy season in Zimbabwe.

		E1 (Chiredzi)		E2 (Gwanda)		E3 (Matopos)		E4 (Mwenezi VI)		E5 (Mwenezi V)	
Source of variation	Degrees of freedom	Mean square (MS)	P-value	MS	P-value	MS	P-value	MS	P-value	MS	P-value
Farmers	1	0.0002	0.339	0.2519	0.103	0.0542	0.232	1.5167	<0.001	0.2282	<0.001
Genotypes	11	0.9577	<0.001	0.2388	0.041	0.707	<0.001	0.843	<0.001	1.0823	<0.001
Residual	11	0.0002		0.0799		0.0338		0.01702		0.0073	
Grand Mean (tha^{-1})		0.7708		0.6875		1.4042		2.1917		1.3375	
Least significant difference (5% probability level)		0.03		0.62		0.40		0.29		0.19	

Table 3. Across site analysis of variance (ANOVA) for the advanced sorghum genotypes evaluated alongside three checks, in on-farm trials conducted at five locations during the 2018–19 rainy season in Zimbabwe.

Source of variation	Degrees of freedom	Sums of squares	Mean squares	P-value
Farmers	1	0.30	0.30	0.025
Districts	4	39.85	9.96	<.001
Genotypes	10	13.33	1.33	<.001
Genotypes × Districts	40	22.25	0.56	<.001
Residual	54	3.07	0.06	
Grand Mean (tha^{-1})			1.33	
Least significant difference (5% probability level)			*0.21*	

was the most ideal in GPL2, although the commercial variety, G10, also performed well in the same environment (Figure 3).

Relationships among test environments and their discriminating ability

The GGE "scatter" biplot showed acute angles among E2 (Gwanda), E3 (Matopos), E4 (Mwenezi Region IV) and E5 (Mwenezi Region V), thereby indicating positive correlations among these locations. An obtuse angle between E1 (Chiredzi) and E3 (Matopos) indicated the existence of a negative relationship between the two test locations. The most discriminating location (ideal test environment) was E1 (Chiredzi); E5 (Mwenezi Region V) was almost similar to E1 (Figure 4). The location E2 (Gwanda) showed the least discriminating power, as it had the shortest vector length and had the highest LSD of 0.62 t ha^{-1} (Figure 4; Table 2).

Ideal genotypes as per farmers' perceptions

Characterizing the farmers based on education level revealed that about 50% had primary-level, 44% secondary-level, and 6% tertiary-level education. Of the 82 respondents, approximately 40% were males and 60% females. Furthermore, about 17% of the respondents were categorized as youth (18–35 years), 77% middle aged (36–65 years), and 6% old (>65 years). The highest number of respondents (23 out of the expected 25) was from E5 (Mwenezi Region V), whereas E2 (Gwanda) had the least number of respondents (18 out of 25) that participated in the PVS. However, female farmers dominated as respondents in each of the four PVS locations (Figure 5).

Genotypes were ranked differently at each of the four PVS locations. Across the locations, the advanced lines G4 and G2 were the first and third most favored by farmers, respectively, whereas the commercial check variety G10 was the second preferred genotype (Table 5). Although sex, age and level of education seemed to have no influence on how farmers ranked the

Table 4. Grain yield averages for the advanced sorghum genotypes evaluated alongside three checks, in on-farm trials conducted at five locations during the 2018–19 rainy season in Zimbabwe.

Genotype	Genotype name	Type and breeding status	Description	Grain color	Chiredzi (tha^{-1})	Gwanda (tha^{-1})	Matopos (tha^{-1})	Mwenezi NRIV (tha^{-1})	Mwenezi NRV (tha^{-1})	Across Average (tha^{-1})
G1	IESV 23006	Grain/Advanced/ ICRISAT	Experimental line	Red/ Brown	0.15	0.4	1.95	2.35	0.45	1.06
G10	Macia	Grain/Released/ ICRISAT	Check	White	1.8	1.1	1.4	2.9	1.45	1.73
G11	SV4	Grain/Released/CBI	Check	White	1.2	0.6	1.05	1.25	0.4	0.9
G12	Farmer own variety	Local landraces	Check	White	1.1	0.35	0.5	1.2	0.4	-
G2	Gadam el hamam	Grain/Advanced/ ICRISAT	Experimental line	White	0.3	1	2.1	2.5	1.5	1.48
G3	ICSR 161	Grain/Advanced/ ICRISAT	Experimental line	White	0.2	0.5	1	1.3	0.7	0.74
G4	IESV 91070 DL	Grain/Advanced/ ICRISAT	Experimental line	White	0.2	1.05	0.8	3.05	1.95	1.41
G5	SDS 3472	Grain/Advanced/ ICRISAT	Experimental line	Red/ Brown	0.2	0.55	1.25	1.9	2.15	1.21
G6	Wahi	Grain/Advanced/ ICRISAT	Experimental line	White	0.2	0.3	1.4	2.15	1.2	1.05
G7	ICSV 111 IN	Grain/Advanced/ ICRISAT	Experimental line	White	1	0.6	2.25	2.8	1.3	1.59
G8	IESV 99061 DL	Grain/Advanced/ ICRISAT	Experimental line	Red/ Brown	2.1	0.4	0.95	2.4	1.95	1.56
G9	ASARECA 12-3-1	Grain/Advanced/ ICRISAT	Experimental line	White	0.8	1.4	2.2	2.5	2.6	1.9

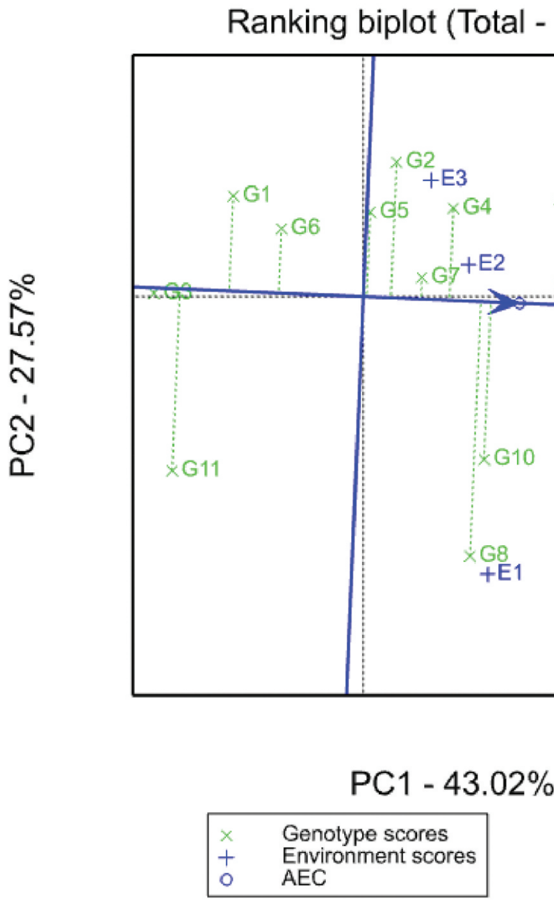

Figure 2. GGE “ranking” biplot showing stable advanced sorghum lines, evaluated alongside three checks in on-farm trials conducted at five locations during the 2018–19 rainy season in Zimbabwe. Genotypes with small distances away from the average environment coordinate (AEC) are the most stable, whereas those furthest away from the AEC are unstable (Yan and Tinker 2006).

sorghum genotypes, locality (i.e., resident district) was found to be an important factor that influenced farmers’ variety choices (Table 6). Although a positive and significant relationship was found between the across-sites mean grain yield and the OGPS (Figure 6), farmers’ choices seemed to be biased more toward the white-grain sorghum than toward the red-grain sorghum, regardless of grain yield performance and stability (Table 5).

Table 5. Site by site and across sites genotype preference ranking based on outcomes of the participatory variety selection (PVS) procedures conducted at four locations.

Genotype	Genotype name	Description	Grain color	Chiredzi	Rank	Gwanda	Rank	Mwenezi IV	Rank	Mwenezi V	Rank	Overall score performance	Rank overall	Grain yield average overall	Rank_Grain yield average overall
G1	IESV 23006	Experimental line	Red/ Brown	47.3	12	73.4	6	49.2	9	29.1	12	199	10	1.06	8
G10	Macia	Check	White	92.7	2	76.6	5	78.8	2	87.6	4	335.7	2	1.73	2
G11	SV4	Check	White	84.7	4	64.6	7	69.5	5	72.1	7	290.9	6	0.9	10
G12	Farmer own variety	Check	White	84.4	5	54.1	10	78.3	3	38.4	11	-	-	-	-
G2	Gadam el hamam	Experimental line	White	77.2	7	97.8	3	62.5	8	87.7	3	325.2	4	1.48	5
G3	ICSR 161	Experimental line	White	50.2	10	63.2	8	37.8	12	45.9	10	197.1	11	0.74	11
G4	IESV 91070 DL	Experimental line	White	84.8	3	100.1	2	68.1	6	93.6	1	346.6	1	1.41	6
G5	SDS 3472	Experimental line	Red/ Brown	48.7	11	87.9	4	43.3	11	67.5	8	247.4	8	1.21	7
G6	Wahi	Experimental line	White	96.5	1	40.8	12	76.7	4	85	5	299	5	1.05	9
G7	ICSV 111 IN	Experimental line	White	76.8	8	58.9	9	79.7	1	74.6	6	290	7	1.59	3
G8	IESV 99061 DL	Experimental line	Red/ Brown	72.8	9	50.5	11	46.3	10	64.9	9	234.5	9	1.56	4
G9	ASARECA 12-3-1	Experimental line	White	80.8	6	103.3	1	62.9	7	88.3	2	335.3	3	1.9	1

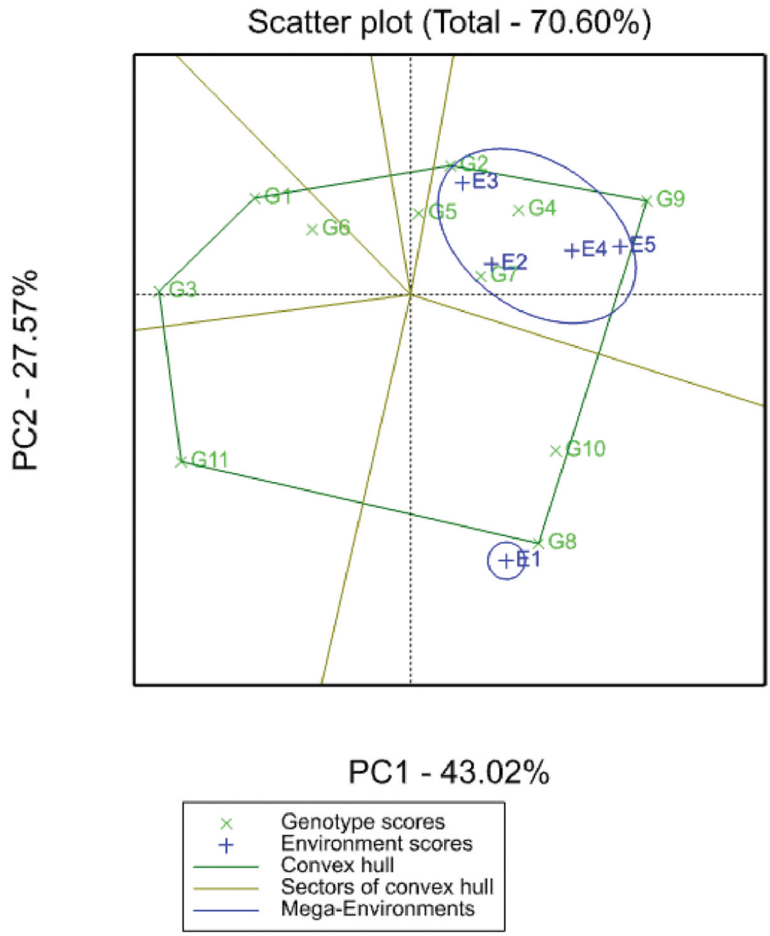

Figure 3. GGE "scatter" biplot showing the advanced sorghum lines adapted to specific environments. the drawn equality lines divided the biplot into sectors, and the best genotype for each sector is the one located on the respective vertex (Yan and Tinker 2006).

Discussion

In plant breeding programs, critical decisions are usually based on multi-environmental trial (MET) data, with average yield ranks across stress and non-stress conditions and sometimes grain yield stability is used as a basis to select the most ideal genotypes for advancement or commercialization (Malosetti, Ribaut, and van Eeuwijk 2013; Ramburan, Dlamini, and Labuschagne 2018; Rincent, Kuhn, and Monod 2017). METs are predominantly researcher-managed, whereas the end users of the intended products (i.e., the farmers) are often kept out of the loop and this practice is increasingly considered a major factor responsible for low adoption rates of new varieties (Goa and Ashamo 2017). Here, a PVS approach was used to identify high-yielding, stable advanced ICRISAT-bred sorghum lines, but with

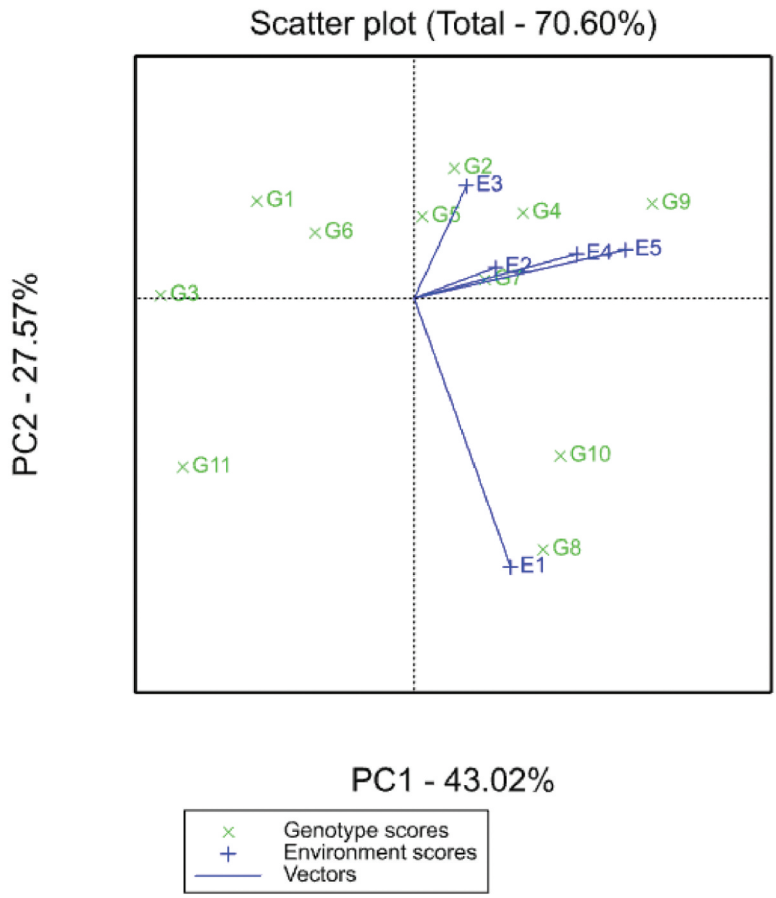

Figure 4. GGE "scatter" biplot showing relationships among the five locations used to evaluate the advanced sorghum lines in during the 2018–19 rainy season in Zimbabwe. Locations with the longest environmental vectors (i.e., line connecting the test environment with the biplot origin) are regarded as the most discriminating environments. an acute angle represents positive correlation whereas an obtuse angle indicates no correlation between test locations (Yan and Tinker 2006).

desirable agronomic attributes as per farmers' perceptions. Data demonstrated that, although there was a positive and significant relationship between across location grain yield performance and OGPS (i.e., farmer's genotype rankings), farmers' choices were affected by locality (i.e., resident districts) as well as by grain color. In addition, the most ideal testing locations for sorghum in Zimbabwe were identified.

To begin with, the variation in GY of the advanced sorghum lines under the drought-prone locations (Tables 2 and 3), was encouraging because it demonstrated potential for making effective selections within the advanced sorghum populations in the ICRISAT breeding program. In addition, the significant influence of location on GY indicated the need to identify

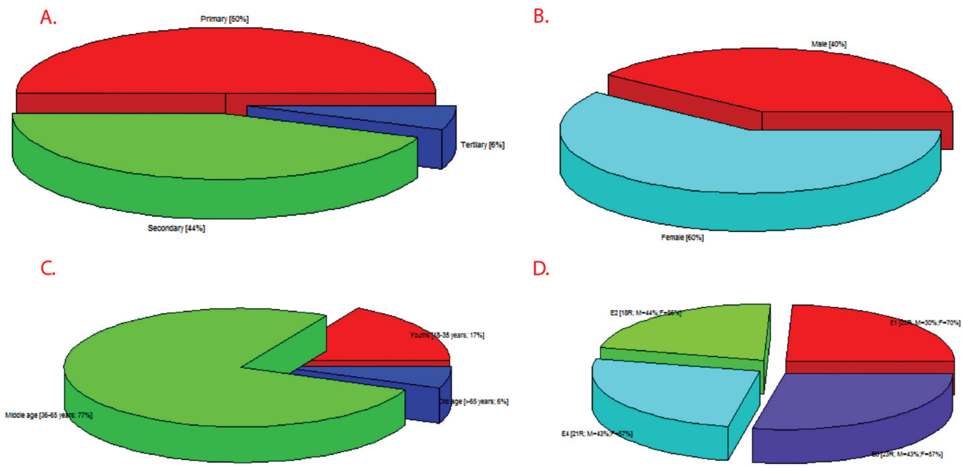

Figure 5. Descriptive information on sex, age, level of education and locality based on demographic data generated using the 82 farmers who participated in the PVS procedures conducted in four districts during the 2018–19 rainy season in Zimbabwe.

Table 6. Regression analysis showing effect of sex, age, level of education and locality/environment on farmer's variety selection and preferences of the 12 sorghum genotypes evaluated in on-farm during the 2018–19 rainy season Zimbabwe.

		Sex		Age		Education level		Locality	
Source of variation	Degrees of freedom	Mean squares	P-value	Mean squares	P-value	Mean squares	P-value	Mean squares	P-value
Regression	12	0.331	0.166	0.334	0.099	0.359	0.497	12.727	<0.001
Residual	69	0.228		0.203		0.375		0.515	
Total	81								

genotypes that were stable across locations and/or specifically adapted genotypes for recommendation purposes. For example, the high-yielding and stable advanced lines identified in this study [e.g., G9 (GY = 1.9 tha^{-1}) and G4 (GY = 1.41 tha^{-1})] can be recommended for release to farmers in different sorghum-growing environments of Zimbabwe, and they can also be used in future breeding programs as sources of desirable genes. The most encouraging part of these two lines was that they were among the three genotypes selected as desirable by the farmers; hence adoption rates of these as new varieties can be anticipated to be high. In addition to promoting these two new lines in the market, an already commercialized ICRISAT-developed variety, G10 (Macia; GY = 1.73 tha^{-1}), which also was highly stable and ranked second by the farmers (Figure 2; Table 5), can also be promoted. It is highly likely that farmers were not aware of this evidently good commercial variety, as they did not use it as a check variety; therefore, by promoting its adoption, farmers can replace the unproductive and highly unstable landraces (Figure 2; Table 5). A PVS study carried out by Ojulong et al. (2016) in

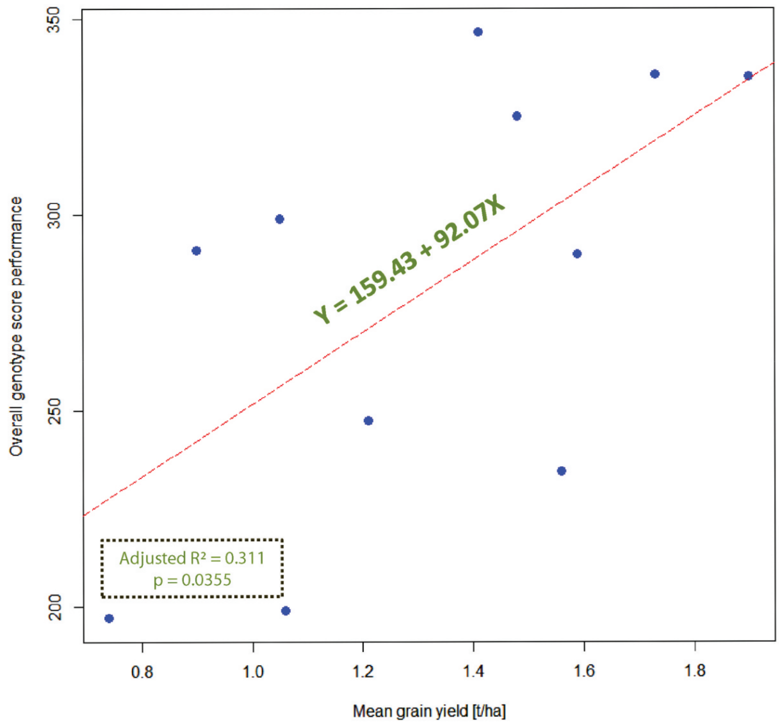

Figure 6. A regression plot showing the relationship between the overall genotype performance score (OGPS) and average grain yield values generated from on-farm sorghum trials conducted in Zimbabwe during 2018–19 rainy season.

Central and Northern Tanzania demonstrated that farmers' participation in the development of new varieties would enhance their rates of adoption.

It is worth mentioning that in breeding programs, focusing only on genotype stability may be very risky since some varieties can be unproductive across diverse locations but very good under some specific environments (Horn et al. 2018; Mengesha et al. 2019). In the current study, a good example will be the advanced line G8 (1.56 tha^{-1}), which yielded higher than the farmers' most preferred variety G4, but it was not stable across locations (Figure 2; Table 5). Interestingly, the same variety was identified as the most ideal in yield performance in "GPL2′ (i.e., Chiredzi), but it was ironically not the farmers" favorite even in Chiredzi where it outperformed all the other genotypes. This suggested that although GY stability remains the most ideal agronomic trait by seed companies aiming at cutting down costs of production by developing varieties with wide adaptation to fulfill requirements of a huge market base, in some cases, specifically adapted genotypes may need to be developed, targeting environments with unique climatic and edaphic characteristics. Although genotypic superiority in GY performance was the most important characteristic considered in selecting ideal sorghum genotypes by both the researchers and the farmers (*see* Figure 6), grain color also greatly influenced farmers' choices. It is evident that G8 was not favored by the farmers because of its red/brown grain color, which is usually targeted for use by the brewing industry, as most of these farmers grew white sorghum. However, G8 should be targeted for release in Chiredzi, as it can be highly useful for the brewery industry because of its high malt content (Agu and Palmer 2013; Schnitzenbaumer et al. 2013). Mbulwe, Lwaile, and Chisi (2015) showed that 66% of the households interviewed indicated that they most preferred white sorghums for food over red or brown colored sorghums and further revealed that grain color was not an issue if sorghum was grown for sale. We suggest that since sorghum is a multi-purpose crop, in future, PVS studies should also target commercial farmers and industrial outfits, who grow or use the crop not only for food, but also for other purposes, including feed, beer and starch manufacturing. That way, genotypes suitable for these multi-purposes but favored by the end-users will be identified.

On another note, important insights that can guide sorghum breeding programs in Zimbabwe as well as other sorghum breeding programs worldwide were also generated. Specifically, environments that are climatically classified as arid and semi-arid (*see* Figure 1) were used in this study and stability analysis identified Chiredzi and Mwenezi Region V as the most ideal/discriminating environments for sorghum testing (Figure 4). These two locations are climatically classified as arid. We can conclude that for cost-effective identification of drought and heat stress-resilient sorghum genotypes, arid (very dry) locations should be used for variety testing.

Lastly, as expected, female farmers constituted majority of the respondents across all the PVS locations (Figure 5). This made sense, as in rural areas, the majority of males move to urban areas, farms or mines to look for employment and leave behind their wives to take care of the family. Variety selection seemed not to be affected by sex, age and level of education (Table 6). This was because, in the drought-prone areas, where the respondents were drawn from, with the majority being female farmers in the middle age group (36–65 years old) (Figure 5), farming might be their major source of livelihood. Under such circumstances, it was logical for farmers not to differ in how they perceived an ideal genotype as all of them would be more concerned about being food secure at the household level. Therefore, it is not surprising that genotypes with stable GY performance across all locations were selected as the most ideal varieties by the farmers.

In conclusion, it was evident that performance-based approaches as traditionally practiced by plant breeders using grain yield stability analysis were effective in identifying superior genotypes that were also favored by farmers. Coupling such approaches with PVS strategies should increase adoption rates of new varieties. Embracing PVS strategies should help plant breeders develop varieties that meet farmers' needs and preferences, which has been the missing link of late, resulting in low adoption of improved varieties or technologies by the farmers. However, because of the multipurpose nature of sorghum, in future, PVS studies can also include not only the farmers, but also other end-users, such as the brewery, starch and feed industries.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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