

RESEARCH

Yield of Photoperiod-sensitive Sorghum Hybrids Based on Guinea-race Germplasm under Farmers' Field Conditions in Mali

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ABSTRACT

The first sorghum [*Sorghum bicolor* (L.) Moench] hybrids based on West African Guinea-race-derived parents were created to enhance farmer's food security and income through increased yields. To assess their performance, eight hybrids, six experimental pure-line cultivars, one pure-line check (Lata), and a highly adapted landrace cultivar (Tieble) were evaluated in 27 farmer-managed and two on-station yield trials in Mali, West Africa, from 2009 to 2011. The hybrids were confirmed to have photoperiod sensitivity similar to the well-adapted Guinea landrace check cultivar. Genotypic differences for on-farm grain yield were highly significant and genotype \times environment crossover interactions were limited. The yield superiorities of individual hybrids, relative to the landrace check, ranged from 17 to 37% over the 27 on-farm trials. The three top yielding hybrids showed 30% yield advantages across productivity levels, with absolute yield advantages averaging 380 kg ha⁻¹ under lower (1.0–1.5 t ha⁻¹) and 660 kg ha⁻¹ under higher (2.0–3.5 t ha⁻¹) productivity conditions. A mean male-parent (better parent) heterosis of 26% was observed for the four hybrids having Lata as a male parent. As the hybrids studied here were obtained with a low intensity of selection using a limited number of parents, even greater yield superiorities may be attained with development of distinct parental pools and scaled-up hybrid breeding.

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Abbreviations: BLUP, best linear unbiased predictor; GGE, genotype + genotype \times environment interaction; IER, Institut d'Economie Rural.

THE GUINEA-RACE of sorghum [*Sorghum bicolor* (L.) Moench], ennobled in tropical West Africa (De Wet and Huckabay, 1967), possesses a suite of traits important for adaptation across the Sudan Savanna zone (700–1000 mm) of Senegal, Mali, and Burkina Faso in West Africa (Barro-Kondombo et al., 2008). The generally high degree of photoperiod sensitivity of the Guinea race (Grenier et al., 2001) enables phenotypic plasticity of the crop cycle to better match the available season length, where sowing dates are highly variable but the dates for end-of-moisture availability are fairly fixed, and thus help assure good grain filling and pest avoidance (Hausmann et al., 2012). The gaping glumes, lax panicle, and corneous endosperm of the Guinea race help reduce grain damage from the insect–mold complex. These adaptive characteristics contribute to the dominance of the Guinea race in this zone (Touré and Scheuring, 1982; Touré et al., 1998), where

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Table 1. Sorghum entries tested in on-farm yield trials 2009 to 2011, their mean anthesis dates from June 26 and July 15 sowings at the ICRISAT research station, the number of days delay in anthesis of the second sowing relative to the first, and the computed photoperiod sensitivity index (*K_p*).

Type [†]	Entry	Name	Pedigree/breeders' code	Anthesis date 26 June sowing	Anthesis date 15 July sowing	Delay 50% anthesis	<i>K_p</i>
						d	
PL	5	Wanti	07-CZ-F5P-23	8 Sept.	22 Sept.	13.9	0.27
PL	6	Tokotigui	07-BE-F5P-13	8 Sept.	22 Sept.	13.9	0.27
PL	3	Yamba	07-CZ-F5P-16	10 Sept.	23 Sept.	12.7	0.33
PL	4	Tanko	07-CZ-F5P-17	11 Sept.	24 Sept.	12.7	0.33
PL	2	Sawaba	07-CZ-F5P-15	15 Sept.	27 Sept.	11.8	0.38
PL	1	Yebele	07-KO-F5DT-58	11 Sept.	21 Sept.	9.6	0.49
Hyb	8	Sigui Kumbe	97-SB-F5DT-150A × 00-KO-F5DT-19	19 Sept.	26 Sept.	7.2	0.62
Hyb	7	Sewa	97-SB-F5DT-150A × 02-SB-F4DT-298	28 Sept.	1 Oct.	3.5	0.82
Hyb	10	Mona	PR3009A × Lata	23 Sept.	27 Sept.	3.3	0.83
Hyb	12	Massa	97-SB-F5DT-150A × Lata	26 Sept.	28 Sept.	2.3	0.88
Hyb	13	Yougo	02-SB-F5DT-12A × CGM 19/9-1-1	29 Sept.	1 Oct.	2.0	0.89
Hyb	11	Mara	GP271-20A × Lata	28 Sept.	29 Sept.	1.8	0.91
Hyb	14	Gamo	GP271-20A × CGM19/9-1-1	28 Sept.	30 Sept.	1.7	0.91
Hyb	9	Fadda	02-SB-F5DT-12A × Lata	29 Sept.	1 Oct.	1.5	0.92
BVC	15	Lata	GPN01 S01 267-9-3-3v	28 Sept.	28 Sept.	0.0	1.00
LVC	16	Tieble	CSM 335	30 Sept.	4 Oct.	4.0	0.79
Standard error of difference (<i>P</i> = 0.05), d				1.7	1.1	1.42	

[†]PL, inbred line experimental cultivar; Hyb, hybrid experimental cultivar; BVC, bred-cultivar check; and LVC, landrace-cultivar check.

it is a staple crop of major importance for food security and farmers' income.

Although landrace sorghum cultivars are well adapted to the complex of biotic and abiotic constraints prevalent in the Sudan Savanna zone of West Africa, the average farmers' yields are only about 1 t ha⁻¹ in Mali (FAO, 2010). These low yield levels are due in part to the extensive cultivation of sorghum under low soil fertility and low-input production conditions (Buerkert et al., 2001; Vom Brocke et al., 2010). In fact, the median plant-available P level of 5.5 mg P kg⁻¹ soil Bray 1-P in a sampling of Malian sorghum fields (Leiser et al., 2012) is below the threshold considered to be sufficient for West African sorghum production (Doumbia et al., 1993).

The potential of sorghum hybrids to provide yield superiorities over local cultivars under experiment station conditions in several African countries has been documented (House et al., 1997; Haussmann et al., 1998). Initial work in Mali on hybrids using local cultivars as male parents and introduced female lines concluded that hybrids could provide higher yields, but must be based on parents with appropriate grain characteristics and adaptation to be commercially viable (Touré and Scheuring, 1982; Touré et al., 1998). Such parents have been lacking until the recent creation of cytoplasmic male-sterile female parents based on West African Guinea-race landraces and Guinea-Caudatum interracial breeding lines. These new parents have enabled the first series of Guinea-race hybrids to be produced.

The purpose of this study was to assess the yield benefits or risks of newly created Guinea race, and possibly

photoperiod-sensitive, sorghum hybrids under diverse farmers' field conditions. The specific objectives were to assess these hybrids for (i) their degree of photoperiod sensitivity, (ii) their yield performances relative to a well-adapted landrace cultivar over a wide range of farmers' production conditions, and (iii) the risk of farmers not recovering their investment in purchased hybrid seed.

MATERIALS AND METHODS

Eight hybrids of relatively shorter height (<3 m) were identified for farmer-participatory testing out of a set of 55 hybrids based on grain yield and plant height data from trials at the Institut d'Economie Rural (IER) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) research stations near Bamako, Mali, in 2007 and 2008. The eight hybrids in this study were produced using four A1 cytoplasmic male-sterile lines, with the maintainer lines 97-SB-F5DT-150B, 02-SB-F5DT-12B, and PR3009B identified from IER breeding materials developed through biparental crossing and backcrossing of Malian Guinea-landrace cultivars with introduced Caudatum-race breeding materials, and the maintainer line GP271B derived from an ICRISAT-IER random-mating Guinea population with a Caudatum-race source of genetic male sterility (Rattunde et al., 1997). The male parent restorer lines were identified from a biparental Guinea-race cross derivative with intermediate stem and rachis internode length (CGM 19/9-1-1) and from the same pools of IER breeding lines (00-KO-F5DT-19, 02-SB-F4DT-298) and random-mating Guinea population-derived progenies (Lata) from which the maintainer lines originated (Table 1).

The six pure-line experimental cultivars included in the yield trials were derived in the F₅ generation from the same IER breeding materials referred to above. They were bred for

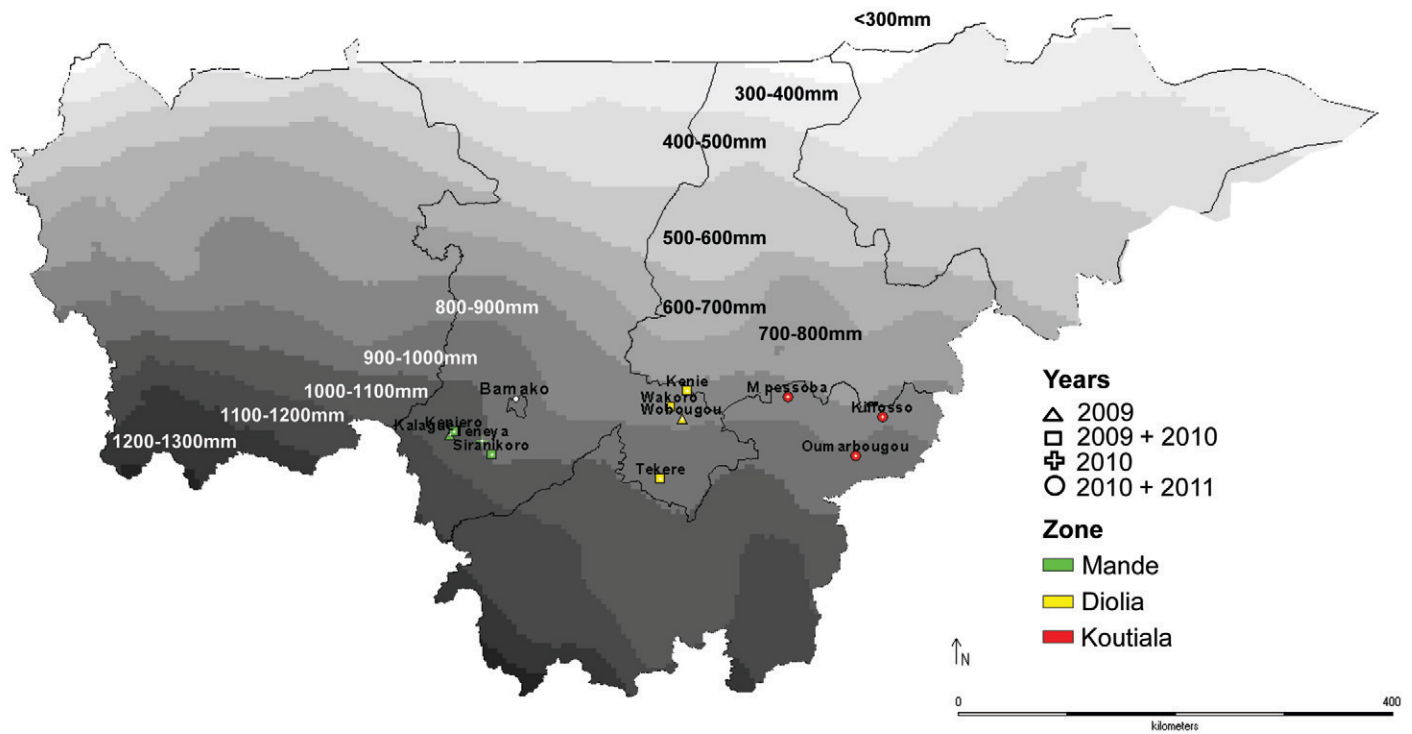


Figure 1. Map of southern Mali indicating villages and years in which farmer-managed sorghum yield trials were conducted and annual precipitation isohyets (in mm) averaged for the period 1950 to 2000 (based on Hijmans et al., 2005).

Table 2. Grain yield mean (range in parentheses), sowing date range, and soil Bray1-P mean (range in parentheses) of on-farm sorghum trials by zone and year.

Zone	Trial yields			Trial sowing dates			Bray1-P
	2009	2010	2011	2009	2010	2011	2009–2010
	g m ⁻²						mg P kg ⁻¹ soil
Mande	201 (169–266)	149 (114–215)	–	11 July–27 July	27 June–20 July	–	5.5 (2.3–8.9)
Dioila	166 (122–249)	192 (107–342)	–	7 July–19 July	23 June–2 July	–	8.7 (1.7–30.5)
Koutiala	–	162 (74–229)	178 (119–248)	–	14 June–27 June	24 June–13 July	–

high yield, and identified by 1 to 2 yr of simultaneous testing at the IER research stations near Bamako and on-farm at Cinzana, Bema, and Kolombada, Mali.

The two check cultivars included were Tieble (CSM335 from the Malian Collection), a well-adapted tall landrace cultivar from Mali, much appreciated by farmers for its stable productivity and good grain quality, and Lata, a cultivar of intermediate height cultivated as a cultivar per se and the male parent of four hybrids in this study.

A total of 37 on-farm yield trials were conducted in three zones representing the main sorghum production area of Mali: the Dioila and Koutiala zones with more intensified agriculture and stronger history of cotton (*Gossypium hirsutum* L.) production, and the Mande zone with less intensified agriculture (Fig. 1). Yield trials were conducted in three villages per zone (four villages in Dioila 2009) by two farmers per village over two consecutive years (2009–2010 for Dioila and Mande and 2010–2011 for Koutiala) (Table 2) as part of an ongoing participatory sorghum cultivar testing program (Weltzien et al., 2008).

An α -lattice design with block size of four plots and two replicates was used for all on-farm trials. Plots consisted of six rows of 5-m length, with rows generally of 75-cm width and

40 cm between hills, with the hills generally thinned to two plants. Sowing, weeding, thinning, and fertilization were conducted by the farmers. Sufficient fertilizer and calibrated measuring cups were provided to the farmers for manual application of 100 kg ha⁻¹ diammonium phosphate, generally after the first weeding at 2 to 5 wk after sowing, and 50 kg ha⁻¹ urea, which was generally applied after the second weeding. Soil samples were taken in 20 of the 25 trials in the Mande and Dioila zones at the time of sowing and analyzed for plant-available soil phosphorus as Bray1-P (Bray and Kurtz, 1945).

The level of photoperiod sensitivity of all test entries was assessed in experiments conducted at the ICRISAT-Mali research station sown in the same field on 26 June 2009 and 15 July 2010 using an α -lattice design and four replicates. Dates of 50% anthesis were recorded and a photoperiod sensitivity index (K_p) was computed using the formula:

$$K_p = (\text{DurF1} - \text{DurF2}) / (\text{DS2} - \text{DS1})$$

where DurF1 and DurF2 are the duration in days from sowing to 50% anthesis in the 26 June and 15 July sowings, respectively, and DS1 and DS2 the first and second sowing dates in

Julian days (Kouressy et al., 1998; Clerget et al., 2007). K_p is expected to vary from 0, for photoperiod-insensitive cultivars that do not change the duration of their vegetative phase, to 1.0, for the most strongly photoperiod-sensitive cultivars that reduce their vegetative phase to the same extent as the delay in sowing.

Statistical Analysis

The 37 farmer's trials were analyzed individually using SAS GLM Procedure (SAS/STAT 9.3 user's guide; SAS Institute, 2008), with each trial considered as a distinct environment with genotypes, replications, and blocks within replications as fixed. Best linear unbiased estimates of genotypes from individual environment analyses and their pairwise contrasts were computed within each environment. Repeatability (h^2) was calculated for each trial with a formula appropriate for unbalanced data sets (Eq. [19] in Piepho and Mohring, 2007). The 27 trials with repeatability estimates >0.3 were used for further analyses. The cutoff was set as low as possible yet the individual entries' yields levels were plausible, particularly for the check cultivars and their performance relative to the test entries. Observations made in the 10 trials dropped from further analysis indicate that they had one or more of the following: variable, not genotype-specific, establishment and plant density, highly heterogeneous growth, high but inconsistent *Striga* infestation, or very late weeding.

Two models were fitted to assess variation attributed to different sources over the 27 trials and also to test significance of genotype and genotype \times environment interaction. One model considering environments as an unstructured population of all the farmers' trials and the other considering the farmer, year, and geographic structure of the trials. Since variance among trials were found heterogeneous using the Bartlett test (Bartlett, 1937), data was transformed by dividing original values by standard errors of the corresponding trial. The first mixed model considering environments, replications, blocks within replications as fixed, and genotypes as random was fitted using Proc Mixed in SAS:

$$Y_{ijkl} = \mu + G_i + GE_{ij} + E_j + E(R)_{jk} + E[R(B)]_{jkl} + e_{ijkl}$$

where Y_{ijkl} is the observed value of the i th genotype in the l th incomplete block within the k th replication within the j th environment, μ is the grand mean, G_i is the effect of the i th genotype, E_j the effect of the j th environment, R_k the effect of the k th replication, B_l the effect of the l th incomplete block, and e_{ijkl} is the error term of each Y_{ijkl} with $N(0, \sigma^2)$. The best linear unbiased predictor (BLUP) of genotypes' grain yields presented in this study were based on this model.

The second model was fitted with a full hierarchical model using restricted maximum likelihood approach considering all factors as random:

$$\begin{aligned} Y_{ijklmno} = & \mu + G_i + Y_j + Y(Z)_{jk} + Y[Z(V)]_{jkl} \\ & + Y\{Z[V(F)]\}_{jklm} + GY_{ij} + GY(Z)_{ijk} + \\ & GY[Z(V)]_{ijkl} + GY\{Z[V(F)]\}_{ijklm} \\ & + Y\{Z\{V[F(R)]\}\}_{jklmn} \\ & + Y\{Z\{V\{F[R(B)]\}\}\}_{jklmno} + e_{ijklmno} \end{aligned}$$

where $Y_{ijklmno}$ is the observed value of the i th genotype in the o th incomplete block within the n th replication within the m th farm within the l th village within the k th zone within the j th year. G_i is the effect of the i th genotype, Y_j the effect of the j th year, Z_k the effect of the k th zone, V_l the effect of the l th village, F_m the effect of the m th farmer, R_n the effect of the n th replication, B_o the effect of the o th incomplete block, and $e_{ijklmno}$ is the error term of each $Y_{ijklmno}$ with $N(0, \sigma^2)$.

The trials were classified into low-, medium-, and high-productivity groups based on the trial mean grain yields. A genotype + genotype \times environment interaction (GGE) biplot (Yan and Kang, 2003) scaled for heritability for visualizing the genotype \times environment interactions over the 27 environments was produced using GenStat 15th edition for Windows (VSN International, 2012) as described by Yan and Holland (2010). Genotype \times environment crossover-type interactions (Yang, 2007) were identified among all genotype-environment pairwise combinations over the 15 trials with genotype variation significant at $p < 0.10$, with restriction of the trials included in this analysis to minimize spurious crossovers. The GGE biplots and crossover interactions analyses were based on genotypes considered as random and the BLUPs computed using SAS Proc Mixed.

RESULTS

Photoperiod Sensitivity

The flowering dates (50% anthesis) of hybrids sown on the 26 June and 15 July were nearly identical (Table 1). Their computed photoperiod-sensitivity indices were high, with only one of the eight hybrids being inferior to the landrace check. In contrast, all six of the experimental pure-line cultivars were earlier flowering and had considerably larger delay of anthesis with later sowing and much lower photoperiod sensitivity index values than that of the landrace check.

Characterization of Trial Yield Levels and Repeatabilities

The 37 on-farm trials had mean grain yields ranging from 74 to 342 g m⁻², with a two- to threefold yield range among trials within each zone and year (Table 2). The sowing dates ranged from 14 June to 27 July, with trials in the Mande zone typically sown later than in Dioila and Koutiala. Trial mean yields showed no relation with date of sowing ($n = 37$, $r = 0.06$, $p = 0.80$) but did with soil Bray1-P level ($n = 20$, $r = 0.56$, $p = 0.01$).

The repeatability estimates (h^2) for grain yield ranged from 0.00 to 0.91 for individual trials with an average of 0.46 over the 37 trials. No correlation between repeatability estimate and trial mean yields ($r = 0.26$, $p = 0.12$) was observed. The mean repeatability of the 27 trials retained for combined analyses was 0.61.

Genotype and Genotype \times Environment Interaction Variance over 27 Environments

Genotypes ($p = 0.01$) explained slightly more variation than Genotype \times Environment interactions ($p < 0.001$), having

Table 3. Estimates of variance components for sorghum cultivar and cultivar × environment interactions from the full hierarchical model of 27 farmer trials for grain yield.

Source of variance	Estimate
Cultivar	0.884*
Cultivar × Year	-0.081
Cultivar × Zone(Year)	0.174†
Cultivar × Village(Year × Zone)	0.113
Cultivar × Farmer(Year × Zone × Village)	0.467***

* $p < 0.05$.

*** $p < 0.001$.

† $p < 0.10$.

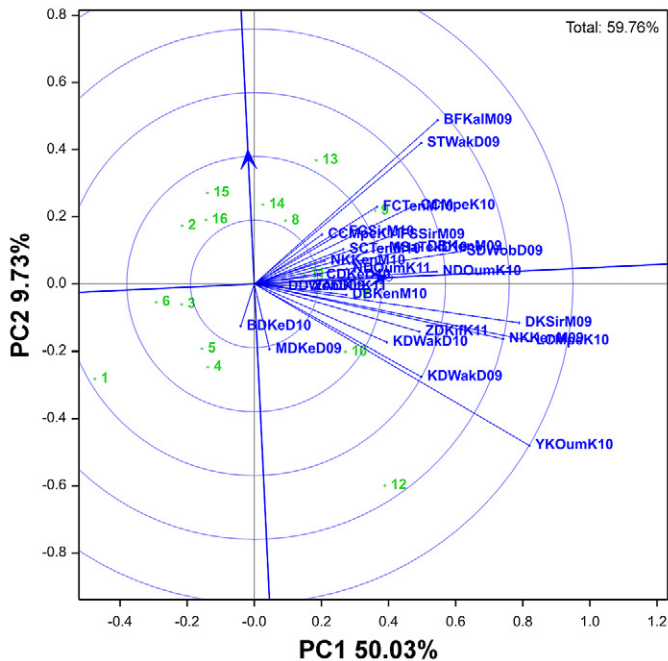


Figure 2. Genotype + genotype × environment interaction (GGE) biplot with heritability scaling for grain yield of 16 sorghum genotypes (denoted with entry numbers from Table 1) over 27 environments. PC, principal component.

the ratio of variance components of 1:0.80, in the simple combined analysis (data not shown). The analysis with the full hierarchical model showed Genotype × Environment interaction occurring primarily at the individual farmer-field level, with only marginal Genotype × Zone interaction within Year, and no Genotype × Year or Genotype × Village interactions (Table 3). Visualization of Genotype × Environment interaction with a GGE biplot scaled for heritability over the 27 environments (Fig. 2) revealed a single group of 25 environments and two outlier environments, one (BDKeD10) with the highest mean yield (342 g m^{-2}) where organic manure had been applied and having a repeatability of only 0.42, and one (MDKeD09) with low mean yield (122 g m^{-2}) and heavy but inconsistent *Striga* infestation (Fig. 2). Crossover analysis in 15 environments with Genotype $p < 0.10$ and repeatability estimates >0.56 indicated only 1.9% significant ($p < 0.10$) Genotype × Environment crossover

Table 4. Sorghum cultivar least square mean grain yields over 27 on-farm trials, yield differences relative to the landrace check Tieble in absolute and percentage basis, and the significance of comparisons.

Name	Type†	Mean yield	Absolute	Superiority	Pr > t
			yield difference		
		g m ⁻²	%		
Wanti	PL	171	7	4	0.60
Tokotigui	PL	159	-5	-3	0.44
Yamba	PL	170	6	4	0.68
Tanko	PL	166	2	1	0.64
Sawaba	PL	163	-1	-1	0.90
Yebele	PL	126	-38	-23	<0.001
Sigui-Kumbe	Hyb	200	36	22	<0.001
Sewa	Hyb	219	55	34	<0.001
Mona	Hyb	210	46	28	<0.001
Massa	Hyb	223	59	36	<0.001
Yougo	Hyb	210	46	28	<0.001
Mara	Hyb	202	38	23	<0.001
Gamo	Hyb	191	27	17	0.01
Fadda	Hyb	224	60	37	<0.001
Lata	BVC	170	6	4	0.68
Tieble	LVC	164	-	-	

†PL, inbred line experimental cultivar; Hyb, hybrid experimental cultivar; BVC, bred-cultivar check; and LVC, landrace-cultivar check.

interactions among all pairwise genotype–environment comparisons. Among the eight trials in the crossover analysis with soil Bray1-P values there was no noticeable difference for frequency of crossovers among pairs of environments with higher plant-available P (Bray1-P values 8.9–12.0 mg P kg⁻¹ soil) (mean 2.5 crossovers per pair of environments) as compared to pairs of environments where one had low (Bray1-P 2.3–7.2 mg P kg⁻¹ soil) and the other high soil P (mean 1.9 crossovers per pair of environments), whereas there were only on average 0.7 crossovers per pair of environments with low Bray1-P values.

No linear relationship between grain yield and date of sowing could be found for any of the 16 test entries, with individual regressions of each genotype’s grain yield on the sowing date (Julian days) across the 27 trials, all being nonsignificant ($p > 0.10$).

Hybrid Yield Performance

The hybrid grain yield BLUPs ranged from 191 to 224 g m⁻², representing yield superiorities of 27 to 60 g m⁻² (17–37%) over the landrace check Tieble over 27 farmers’ test environments (Table 4). In contrast, grain yield of the pure-line bred-cultivar check Lata was only 6 g m⁻² (4%) higher than Tieble. Likewise, none of the experimental pure lines in the trial exhibited significant yield superiority over Tieble.

The three highest yielding hybrids (Massa, Fadda, and Sewa) all exhibited $>500 \text{ kg ha}^{-1}$ mean yield superiorities over Tieble; equivalent to $>30\%$ of local check cultivar

Table 5. Least square mean grain yields and percent yield superiorities of eight sorghum hybrids and a pure-line bred-cultivar check relative to the landrace cultivar Tieble in low-, medium-, and high-yielding environments.

Cultivar name	Type [†]	Mean yield (g m ⁻²)			Superiority over Tieble		
		Low [‡]	Medium [§]	High [¶]	Low [‡]	Medium [§]	High [¶]
		g m ⁻²			%		
Fadda	Hyb	153**	212**	284**	32	32	31
Massa	Hyb	153**	205*	289**	32	27	33
Sewa	Hyb	156**	206*	276**	35	28	27
Mona	Hyb	137**	190 ^{NS#}	285**	18	18	31
Yougo	Hyb	150**	199 ^{NS}	264**	29	24	22
Mara	Hyb	147**	178 ^{NS}	265**	27	11	22
Sigui-Kumbe	Hyb	131 ^{NS}	189 ^{NS}	266**	13	17	23
Gamo	Hyb	126 ^{NS}	185 ^{NS}	251*	9	15	16
Lata	BVC	124 ^{NS}	155 ^{NS}	228 ^{NS}	7	-4	5
Tieble	LVC	116	161	217	-	-	-

* Significant at $p < 0.05$, relative to Tieble.

** Significant at $p < 0.01$, relative to Tieble.

[†] Hyb, hybrid experimental cultivar; BVC, bred-cultivar check; and LVC, landrace-cultivar check.

[‡] Nine trials with mean yields of 100–149 g m⁻².

[§] Eight trials, 150–200 g m⁻².

[¶] Ten trials, >200 g m⁻².

NS, nonsignificant at $p < 0.05$, relative to Tieble.

yield. Furthermore, their yield superiorities were quite stable over differing levels of productivity, averaging 30% in the trials with highest productivity, 29% in the intermediate, and 33% in the trials with lowest productivity (Table 5 and Fig. 3). Likewise, by classifying the test environments according to soil plant-available Bray1-P, the mean yields of these hybrids exceeded Tieble across the range of available-P conditions; with a superiority of 30% in the single environment with high Bray1-P (30.5 mg P kg⁻¹ soil), 46% in five environments with intermediate Bray1-P (7.2–12.0 mg P kg⁻¹ soil), and 32% in the nine environments with low Bray1-P (2.3–4.7 mg P kg⁻¹ soil) measurements.

The yield contrasts of each hybrid with Tieble were examined in each of the 27 individual farmers' trials to assess individual farmers' risks of experiencing a yield loss with a given hybrid relative to the local cultivar. Among all hybrids across the 27 trials there was only one hybrid in a single environment with significant ($p = 0.05$) yield inferiority relative to Tieble. The three highest yielding hybrids, Fadda, Massa, and Sewa, actually exhibited yield advantages that exceeded 10 gm⁻² in 81, 85, and 89% of trials, respectively. Further, these hybrids gave yield advantages exceeding 25 gm⁻² in 74 to 78% of the individual trials and exceeding 50 gm⁻² in 59, 67, and 44% of trials, respectively.

DISCUSSION

The farmer-managed field trials provided a rigorous evaluation of new photoperiod-sensitive sorghum hybrids. The

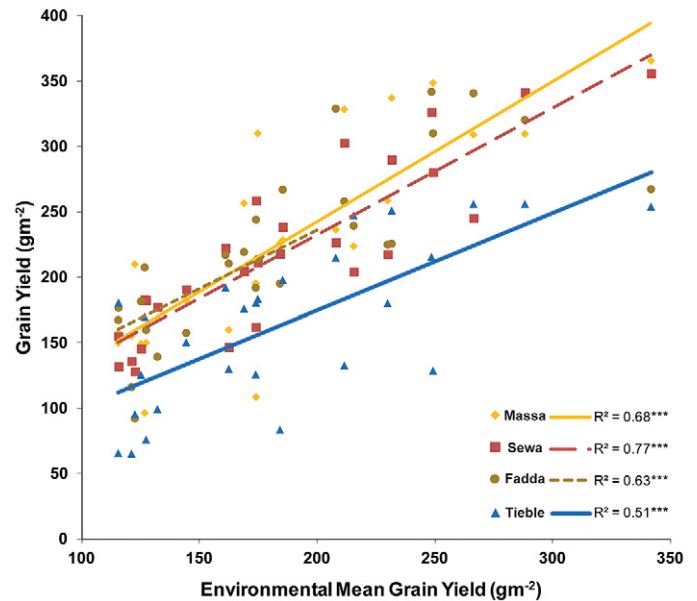


Figure 3. Grain yields (g m⁻²) of sorghum hybrids Massa, Sewa, Fadda, and landrace cultivar Tieble in 27 individual trials and their regressions on trial-mean yields.

trials covered very diverse sowing dates and differing soil conditions, with soil plant-available phosphorus levels that varied from adequate to highly deficient. Likewise farmers' management practices varied considerably, with fertilizer either being broadcast or incorporated, and the time of fertilization and the first weeding occurring between 2 to 5 wk or more after sowing on the different farms. *Striga* infestation was also variable, occurring at moderate ($n = 6$) to severe ($n = 3$) levels among the 27 trials retained for analysis. The observed Genotype \times Environment interactions for grain yield, occurring primarily at the individual farmer's field level, likely reflected the complex combinations of many factors that define sorghum production environments in Mali.

More inorganic fertilizer was applied in the on-farm trials than farmers typically use on their sorghum fields in an attempt to obtain more uniform growing conditions and repeatable results. Nevertheless, the yield levels varied widely, covering the range encountered in the region, but with a higher overall mean (FAO, 2010). The limited genotype–environment crossover interactions and difficulty to discern major patterns of Genotype \times Environment interactions suggests that any adaptive advantages provided by photoperiod sensitivity were masked by the complex of environmental factors and the advantage provided by heterosis. Also, no genotypic differences for responsiveness to plant-available soil phosphorus were evident despite a highly significant correlation between trial means and Bray1-P

Yield superiorities of sorghum hybrids over local cultivars have been reported to range between 49 and 185% for single-environment trials in Niger and Burkina Faso

(House et al., 1997) and between 10 and 14% averaged across eight environments in the semiarid tropics of Kenya (Hausmann et al., 1998). The relative hybrid superiorities reported in this study are within the range of the above cited literature for Caudatum-race-based hybrids tested under experiment station testing conditions.

The hybrids in this study were confirmed to have levels of photoperiod sensitivity similar to the adapted local check (Table 1). Thus, photoperiod-sensitive sorghum hybrids can deliver high-yield advantages in these environments, as was previously concluded by Andrews (1975) from hybrids in Nigeria based on Nigerian Kaura and Fara Fara germplasm.

Researcher-bred pure-line cultivars to date have not shown 30% yield advantages over well-adapted local sorghum cultivars in farmers' fields in this region, as is exemplified by the limited superiority of the pure-line check cultivar Lata (Table 4). This study gives insight into the potential importance of heterosis for increasing grain yield under farmers' field conditions. Four hybrids in this study (Fadda, Massa, Mona, and Mara) had the check cultivar Lata as their male parent. An average male-parent heterosis, and likely better-parent heterosis, of 26% was computed for these four hybrids with predicted mean yields over 27 test environments. This heterosis level, although less than midparent heterosis exhibited by introduced sorghum germplasm in Eastern (Hausmann et al., 1999) and Southern Africa (Makanda et al., 2010), corresponds to the average level of better-parent heterosis (27.5%) observed over a set of photoperiod-sensitive Guinea-race germplasm accessions assessed over four experiment station environments in Mali and Niger (Dagnoko, 2008). The absolute male-parent heterosis of our four Lata hybrids was 438 kg ha⁻¹ over all trials and 235, 413, and 528 kg ha⁻¹ over the low-, intermediate-, and high-productivity groups of trials, which should be useful for farmers in West and Central Africa.

The average yield advantages 380 kg ha⁻¹ in the less productive, and 660 kg ha⁻¹ in the more productive group of environments shown by the three best hybrids relative to the adapted landrace check represent gains that would benefit farmers' income and food security in the context of national yield averages of approximately 1000 kg ha⁻¹ (FAO, 2010). Further, these hybrids could encourage risk-averse farmers to invest in fertilization with greater assurance of obtaining positive returns on their investment.

The absence of significant yield inferiority relative to the well-adapted local cultivar check across 27 diverse on-farm trials is important for risk-averse farmers. Although farmers often express concern about paying for seed each year (Siart, 2008), the actual yield advantage needed to recoup the seed cost is very low. Assuming double the current price of hybrid seed and a sowing rate of 4 kg ha⁻¹, the quantity of additional grain at a farm-gate market price of US\$0.30 kg⁻¹ to recoup the seed cost would

only be 5.3 g m⁻². The yield superiorities were far higher than this amount in the majority of cases. In fact, the opportunity cost of not sowing hybrid seed appeared to be high, as yield advantages >25 gm⁻² were exhibited by the three highest yielding hybrids in about 75% of all trials.

The hybrids evaluated in this study are based on a very limited number of parental lines, and very low selection intensity (25%), being chosen from a set of 32 short-statured hybrids initially tested on-station. Thus, the hybrid superiorities observed in this study probably represent only the starting point, with even greater yield superiorities possible from a hybrid breeding program using broader genetic diversity to enhance complementary parental pools and with greater resources to scale up the breeding effort.

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