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Yield Stability of Photoperiod Sensitive Sorghum (*Sorghum bicolor* L. Moench) Accessions under Diverse Climatic Environments

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ABSTRACT

Climate variability is a characteristic feature of the tropics where the summer monsoon starts from May/June and ends mostly in October, thus producing an unpredictably variable length of growing season. This results in serious challenges for the mainly substituent small holder farmers in the arid to semi-arid zones of the tropics. A study was conducted to determine the attainable grain yield and yield stability of 10 well characterized and extensively cultivated tropical sorghum accessions across 18 environments comprised of 3 dates of sowing at 3 sites (along a latitudinal gradient covering 3 agro-ecological zones) over 2 years in Mali. For each year and site combination, sorghum accessions and dates of sowing were arranged in a split plot and tested in a Randomized Complete Block (RCB) design. Appropriate cultural practices and timing were used to minimize effects of biotic factors. In addition to Grain yield, yield penalty associated with delayed sowing was determined. Two static and five dynamic indices were used to assess the stability of grain yield for genotypes across environments. Mean grain yield ranged from 0 to 248 g m^{-2} across environments, from 74 to 208 g m^{-2} across the 10 genotypes and generally reduced with delayed sowing. A genotype combining photoperiod sensitivity and stay-green traits was revealed as the most stable. The similarities and differences were observed among the stability indices used in terms of ranking of the genotypes. Implications of these for adaptation to climate change are discussed.

Key words: Climate variability, sorghum, stability indices, yield penalty, yield stability

INTRODUCTION

Climate variability is a characteristic feature of the tropics, particularly West Africa where the summer monsoon starts from May/June and ends mostly in October (Sivakumar, 1988), thus, producing an unpredictably variable length of the growing season. Climate change is a threat to crop productivity in the most vulnerable regions of the world, especially the tropics and particularly the semi-arid regions where higher temperatures and increases in rainfall variability could have substantially negative impacts (Parry *et al.*, 2004). The 21st century is projected to experience a rise of 1.8-4.0°C in surface air temperature with very likely occurrence of unpredictable extreme events such as drought and floods (IPCC, 2007).

Yield stability across different environments is an important consideration in crop breeding programs that target areas with variable climatic patterns (Feizias *et al.*, 2010). For quantitative traits such as yield, for which the relative performances of cultivars often change from one environment to another, extensive testing is required for identifying genotypes with minimal interaction with environments, or that possess greatest yield stability (Bahrami *et al.*, 2008). Accessions among any set of genetic materials being tested that would be adapted to a wide range of growing conditions can be considered as ideal for areas with variable climates. These accessions should produce above average grain yields and have below average variances across environments to be considered stable. Stability can either by static (biological) or dynamic (agronomic) with the most desirable form being dependent on the trait under consideration. Static stability is required when a constant performance (zero variance) of the trait across variable environments is desired (e.g. disease tolerance) whiles dynamic stability is required when predictable responses to variable environments are desirable, examples being yield components and the quantity and quality of yield (Becker, 1981). Indices for determining both types of stability of grain yield exist.

Sorghum (*Sorghum bicolor* L. Moench) plays an important role as a major staple crop of the arid and semi-arid tropics. Sorghum is mainly produced by small holder farmers under rain-fed conditions that have been predicted to be adversely affected by climate change (Folliard *et al.*, 2004; IPCC, 2007). This will have negative impacts on food security and the livelihoods of people in the arid and semi-arid tropics. The characteristics and basis of an ideal sorghum genotype in such ecologies have been stated by several authors (AGRHYMET, 1992; Sultan *et al.*, 2005; Vaksmann *et al.*, 1996; Traore *et al.*, 2007; Andrew *et al.*, 2000). One trait that has so far been shown to facilitate adaptation of sorghum to variable lengths of the growing season in the arid and semi-arid tropics is photoperiod sensitivity (Craufurd *et al.*, 1999; Craufurd and Qi, 2001; Kouressy *et al.*, 2008). This trait has therefore been given attention in the development of improved and higher yielding sorghum cultivars with various degrees of adaptation to different climatic patterns in the arid and semi-arid tropics (Kouressy *et al.*, 2008; Clerget *et al.*, 2004).

For the specific problem of coping with climate change, breeders have to identify and/or develop cultivars with adequate plasticity for adaptation to ecologies with high spatio-temporal variability of rainfall. This could be done by deploying the “ideotype” concept, proposed by Donald (1968) as a biological model. The cultivars currently adapted and widely cultivated in the arid and semi-arid tropics present a gene pool from which appropriate accessions and/or traits for developing new cultivars adapted to variable climates (based on well defined ideotype concepts) can be extracted. However, information on the yield potential and stability of yield for these widely cultivated photoperiod sensitive sorghum accessions, across diverse environments, as well as potential contributions of various traits to these qualities is scanty or nonexistent.

Generally, the study sought to determine if the current gene pool of photoperiod sensitive sorghum in the tropics could be resorted to for developing cultivars for coping with changed and variable climate. Specifically, we sought to determine the attainable yield performance as well as yield stability of an assortment of sorghum genotypes across diverse climate scenarios in the arid and semi-arid tropics.

MATERIALS AND METHODS

Locations and environments: The field studies were conducted under rainfed conditions at three sites along a latitudinal gradient and representative of different tropical agro-ecological zones. These were the agronomic research stations of the Institute d’Economie Rurale (IER) at Cinzana (13°15'N; 5°52'W; 312 masl; Sahel), Sotuba (12°17'N; 7°57'W; 364 masl; Sudan Savannah) and Farako (11°21'N; 5°41'W; 441 mas1; Guinea Savannah) all in Mali. Cinzana, Sotuba and Farako have mean annual rainfall of 600, 900 and 1000 mm, respectively. The sites have a hot, tropical climate with a mean, annual, maximal (minimal) daily temperature of 36.0°C (21.7°C) at Cinzana,

Table 1: Description, code, environment mean yield (E_{mean} (g m^{-2}) value, Rank, total rainfall (mm), mean maximum ($T_{max;\ °C}$) and minimum ($T_{min;\ °C}$) temperature, IPCA1 Scores and the Best 4 AMMI Genotypic Selections per Environment of different climate scenarios used for a study at Mali in 2008 and 2009

		P_{crit}^{d}	P_{crit}								AMMI Genotype^h Selections			
Environment	Code	Date	DAS^e	E_{mean}	Rank	Rain	T_{max}	T_{min}	IPCA1	Rank	1st	2nd	3rd	4th
RS^a at Farako in 2008	F8S1	12/09	98	231	2	931	32.2	21	11.6	1	GRI	IRA	97S	LAK
RS+1^b at Farako in 2008	F8S2	12/09	68	194.3	6	830	32.1	20.6	5.7	3	GRI	IRA	97S	LAK
RS+2^c at Farako 2008	F8S3	12/09	37	114.8	13	514	32.4	20.4	2	7	GRI	97S	IRA	LAK
RS at Sotuba in 2008	S8S1	13/09	84	157.7	9	801	31.1	20.7	-5.5	16	CS3	BOI	LAT	LAK
RS+1 at Sotuba in 2008	S8S2	13/09	54	81.1	15	552	31.1	20.4	-4.8	15	LAT	GRI	CS3	IRA
RS+2 at Sotuba in 2008	S8S3	13/09	23	f	17	332	31.3	20	-4	13	LAT	GRI	CS3	LAK
RS at Cinzana in 2008	C8S1	14/09	68	224.8	3	569	34.7	22.1	2.9	5	GRI	IRA	97S	LAK
RS+1 at Cinzana in 2008	C8S2	14/09	37	119.3	11	367	35	21.7	2.6	6	GRI	IRA	97S	LAK
RS+2 at Cinzana in 2008	C8S3	14/09	6	g	18	39	35.7	21.4	-4	14	LAT	GRI	CS3	LAK
RS at Farako in 2009	F9S1	12/09	93	158.6	8	1173	32.6	18.7	7.6	2	GRI	IRA	97S	LAK
RS+1 at Farako in 2009	F9S2	12/09	63	118.3	12	993	32.5	18.2	0.7	9	GRI	IRA	CS6	LAT
RS+2 at Farako 2009	F9S3	12/09	32	129.2	10	727	33	17.5	-5.6	17	LAT	GRI	CS3	WAS
RS at Sotuba in 2009	S9S1	13/09	79	197.5	5	829	32.4	21.2	-5.7	18	LAT	CS3	GRI	WAS
RS+1 at Sotuba in 2009	S9S2	13/09	54	175	7	702	32.2	20.9	-3	11	GRI	LAT	CS3	IRA
RS+2 at Sotuba 2009	S9S3	13/09	23	113.7	14	456	32.1	20.2	-3.9	12	LAT	GRI	CS3	LAK
RS at Cinzana in 2009	C9S1	14/09	68	248.1	1	527	33.3	22.3	3.3	4	97S	LAK	BOI	GRI
RS+1 at Cinzana in 2009	C9S2	14/09	37	202	4	432	33.5	22	1.5	8	97S	BOI	LAK	CS3
RS+2 at Cinzana in 2009	C9S3	14/09	6	53.8	16	139	34.5	21.6	-1.6	10	97S	GRI	LAK	BOI

a: RS: Regular Sown, a: RS+1: One month delay, c: RS+2: Two month delay; d: Critical photoperiod, e: number of days after sowing; f: Total yield loss due to severe midge infestation; g: Total yield loss due to terminal drought; h: see plant materials section under materials and methods for details on genotypes

34.4°C (21.9°C) at Sotuba and 33.7°C (21.0°C) at Farako. Soil types were Sandy Loam for Farako, Loamy Sand for Sotuba and Silty Clay for Cinzana.

Climate scenarios were created using the different sites and staggered monthly dates of Sowing (S) within sites. Three monthly sowing per site were used for this study. The first date of sowing at each site represents the earliest ideal situation for sowing and was taken as the Regular date of Sowing (RS). The majority of farmers in the study regions will plant at this date. Subsequent dates of sowing were spaced by one month from the previous and designated as one month delayed (RS+1) and two-month delayed (RS+2). Actual dates of sowing at Farako and Sotuba were June (RS), July (RS+1) and August (RS+2) whiles those at Cinzana were July (RS), August (RS+1) and September (RS+2) in both years. Table 1 presents detailed characteristics of the environments used in the study.

Plant materials: Ten well characterized grain sorghum (*Sorghum bicolor* (L) Moench) accessions, from an assortment of races and with differences in traits such as photoperiod sensitivity, height and adaptation to agro-ecology were tested in each environment (i.e., year, site and date of sowing combination). These accessions are representative of the diversity of varieties cultivated in the arid and semi-arid tropics. 97-SB-150 (97 S) is a medium cycled (110-120 days), tall and short-day improved guinea race adapted to areas with 800-1000 mm isohyets; Boiguel (BOI) is a durra type early maturing (100 days) landrace that is adapted to the Sahelian agro-ecology and collected from Bema (15°4’N; 9°19’W; 316 m asl) in Mali; CSM 388 (CS3) is an intermediate maturing (120 days), tall and photoperiod sensitive guinea landrace that is adapted to the Sudan Savannah agro-ecology; CSM 63E (CS6) is an improved early maturing (100 days) and tall guinea landrace, with weak sensitivity to photoperiod, adapted to the Sahelien agro-ecology; Grinkan (GRI) is an improved short-day and dwarf guinea-caudatum Open Pollinated Variety (OPV) with intermediate maturity supplied by the Institut d'Economie Rurale (IER); IRAT 204 (IRA) is an improved early maturing (90 days), dwarf and day-neutral caudatum variety developed by CIRAD; Lakahieri (LAK) is a durra type medium duration (110 days) landrace that is adapted to the Sahelian agro-ecology and collected from Bema; Lata-3 (LAT) is short-day variety from the guinea race with intermediate height and is adapted to zones with 700-900 isohyets. Dancouma (DAN) is a tall photosensitive and late maturing (140 days) guinea landrace native to the Guinea Savannah agro-ecology;. Wassa (WAS) is a medium maturing (105 days), tall and short-day variety adapted to areas with 600-800 mm isohyets.

Experimental procedures and data analysis: The study involved the use of a split plot arrangement in a Randomized Complete Block Design with three replications, with date of sowing as main plot factor and sorghum accessions as subplot factor at each site for 2 years (2008 and 2009). Each experimental plot was 9 m wide (12 ridges spaced 0.75 m apart) and 4 m long and was split into two sub-units of 7 ridges (for regular destructive sampling) and 5 ridges (for yield determination). Hills were spaced 0.25 apart and the seedlings from the 5-10 seeds sown per hill were thinned to 1 plant within 10-14 days after sowing, resulting in a density of 53,333 plants ha^{-1}.

Weed control was done manually with hoes when necessary to minimize competition for resources. Chemical fertilizers were applied at a rate of 30 kg each of N, P and K ha^{-1} using di-ammonium phosphate and muriate of potash at sowing and top dressing with 46 kg N ha^{-1} using urea at 6-8 weeks after sowing to minimize the effect of soil fertility variation. Appropriate pesticides were applied to minimize the effects of biotic stresses. Grain yield of the accessions was evaluated on each and all the plots by sampling from an area of 7.9 m^2, comprising of 3 rows of 3.5 m long spaced 0.75 m apart. This was adjusted to 14% moisture (weight basis) and converted to yield (in g) per m^2 using an appropriate factor.

Data analyses: Hypotheses relating to the effects of treatments on mean grain yield were tested using analysis of variance. A four-way interaction model was applied with year as random effect and location, date of sowing and genotype as fixed effects. This model can be stated as:

$$\begin{gathered}X_{ijkl}= \mu+Y_i+L_j+S_k+G_l+(YL)_{ij}+(YS)_{ik}+(YG)_{il}+(LS)_{jk}+(LG)_{jl} + (SG)_{kl}\\ +(YLS)_{ijk}+(YLG)_{ijl}+(LYG)_{ijl}+(LSG)_{jkl} +(YLSG)_{ijkl} + e_{ijkl}\end{gathered}$$

where, X_{ijkl} = value of treatment in ith Year, jth Location, kth Sowing and lth Genotype; μ = general mean; Yi = ith Year; L_j = jth Location; S_k = kth Sowing; G_l = lth Genotype; $(YL)_{ij}$.... = interactions between Year, Location, Sowing and Genotype etc.; e_{ijkl} = error of X_{ijkl}.

A total of 120 experimental units (40 at each site and 60 for each year) of delayed sowing, covering 10 cultivars at 2 dates of sowing (RS+1 and RS+2) at each of the 3 locations over the 2 years were obtained in the study. Yield penalty due to delayed sowing was estimated using the yield of RS as a reference or bench mark for each site in each year. This was done by expressing the difference between grain yield for RS and that for each of the delayed dates of sowing as a percentage of grain yields for RS at each location in each year.

Assessment of yield stability: Yield stability was assessed using both static and dynamic indices. Seven different ability indices were calculated: Regression coefficient (RC; Finlay and Wilkinson, 1963); Superiority index (SUP; Lin and Binns, 1988); Mean Rank (MR; Nassar and Huhn, 1987); Mean Absolute Difference (MAD; Nassar and Huhn, 1987); Rank Variance (VAR; Nassar and Huhn, 1987); First Interaction Principal Component axes of the AMMI analysis (IPCA1; Purchase, 1997); AMMI Stability Value (ASV; Purchase *et al*., 2000). Spearman's rank correlation was used to establish interrelations both between grain yield and the indices, as well as among the indices. This was done for genotypes across all environments as well as for environments over all genotypes. All computations were done using standard procedures of GENSTAT Twelfth Edition (12.1.0.3278) software (VSN International Ltd., 2009).

RESULTS

Climate: Apart from the regular sowing for both years at the Guinea Savannah agro-ecology, where the seedlings grew under increasing photoperiod for 2 weeks, all other environments presented different ranges of decreasing photoperiod conditions. The trends of temperature and rainfall for the long-term (55 years) and the 2008 and 2009 seasons are presented in Fig. 1a-c.

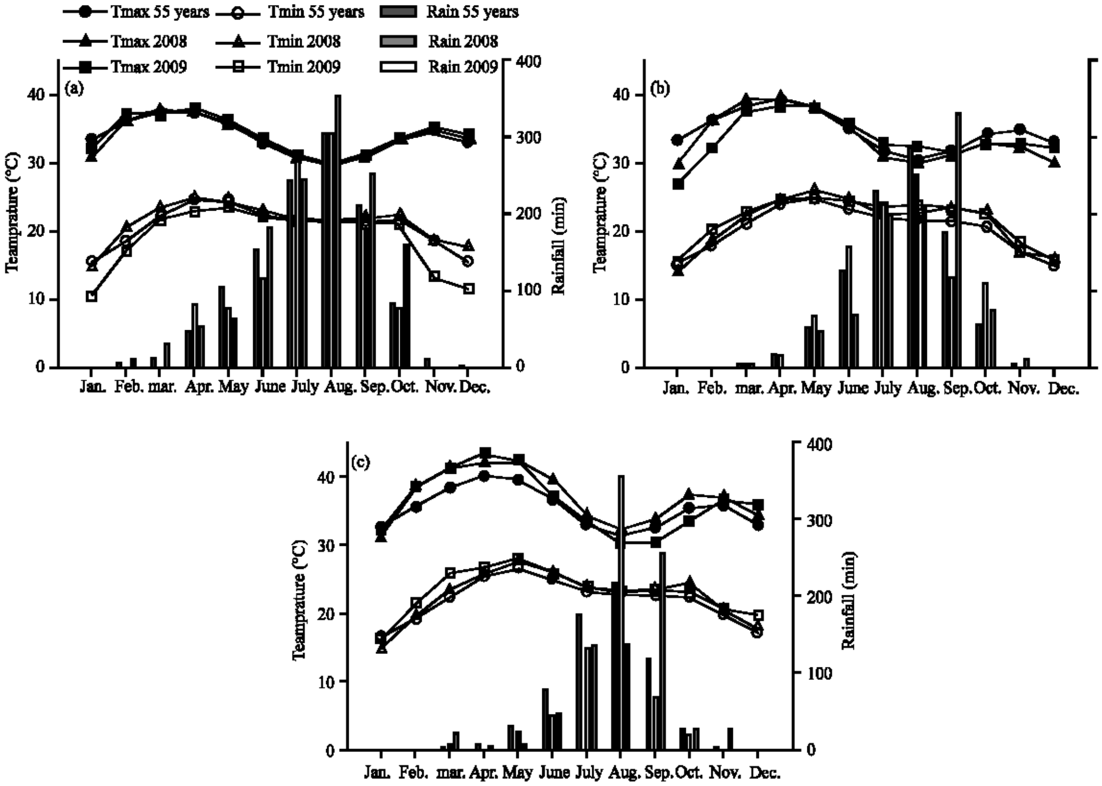

Fig. 1(a-b): Trends of temperature and rainfall for the long-term (55 years) and the growing seasons of 2008 and 2009; (a) Gvinea savannah (b) sudan savannah and (c) Sahel

Table 2: General and Additive main effects and multiplicative interactions (AMMI) Analysis of Variance for grain yield of all the 10 genotypes evaluated 3 dates of sowing at 3 locations in 2008 and 2009 at Mali

General			AMMI (84.4%)^{i}			
Source	df	Mean square	Source	df	Mean square	Variance explained (%)
Year (Y)	1	122372***	Total	539	11009	
Location (L)	2	62671***	Treatments	179	28664***	
Y X L	2	202090***	Genotypes	9	78028***	14
Residual$_a$	12	2129	Environments	17	162375***	54
Sown (S)	2	826271***	Block	36	1684	
Y X S	2	47199***	Interactions	153	10903***	33
L X S	4	76206***	IPCA1	25	22571***	34
Y X L X S	4	14180***	IPCA2	23	13246***	18
Residual$_b$	24	1462***	IPCA3	21	13341***	17
Genotype (G)	9	78028***	IPCA4	19	10672***	12
Y X G	9	7144***	IPCA5	17	7350***	7
L X G	18	28521***	Residuals	48	3986**	
S X G	18	12621***	Error	324	2291	
Y X L X G	18	13721***				
Y X S X G	18	3965***				
L X S X G	36	9416***				
Y X L X S X G	36	5721***				
Residual$_c$	324	2291				
Total	539					

**significant at $p\leq 0.01$ alpha level; ***significant at $p\leq 0.001$ alpha level

The season-long rainfall amount and mean maximum and minimum temperatures for each of the year, site and date of sowing combinations (environments) are presented in Table 1. Comparatively more rainfall was received in 2009 than in 2008 for all, except the RS planting date at Cinzana. Both the onset date and duration of the rainy season did not vary so much among the 2008 and 2009 seasons though 2009 had more rainfall at Farako (245 mm) and Sotuba (7.7 mm) but less rainfall at Cinzana (-16 mm) than 2008. Temperatures were also generally lower in 2009 than in 2008.

Variations in grain yield: Analysis of variance for grain yield revealed all main and interactive effects of year, location, date of sowing and genotype as significant sources of variation. The Additive Main effects and Multiplicative Interaction (AMMI) analysis also showed significant effects for genotype, environment and genotype and environment interaction (Table 2). Environmental effects accounted for 54% of the treatment sum of squares whiles 14 and 33% were attributed to genotype and GXE effects, respectively. Multiplicative effects showed that the first Interaction Principal Component Axis (IPCA1) captured 34% of the interaction SS in 16% of the interaction degrees of freedom (d.f.). Similarly, the IPCA2, IPCA3 and IPCA4 explained a further 18, 17 and 12% of the GXE sums of squares, respectively. In total, the AMMI2 model (G+E+IPCA1 and IPCA2) contained 84% of the treatment sums of squares, indicating that the AMMI model fits the data well and also justifies the use of AMMI2 (Table 2).

Table S1 presents the grain yield response patterns as influenced by the combination of the factors studied. Grain yield performance, pooled over all factors, ranged from 0 to 416 g m^{-2} and the responses for combinations of all other factors ranged from 0 to 416 g m^{-2} and from 0 to

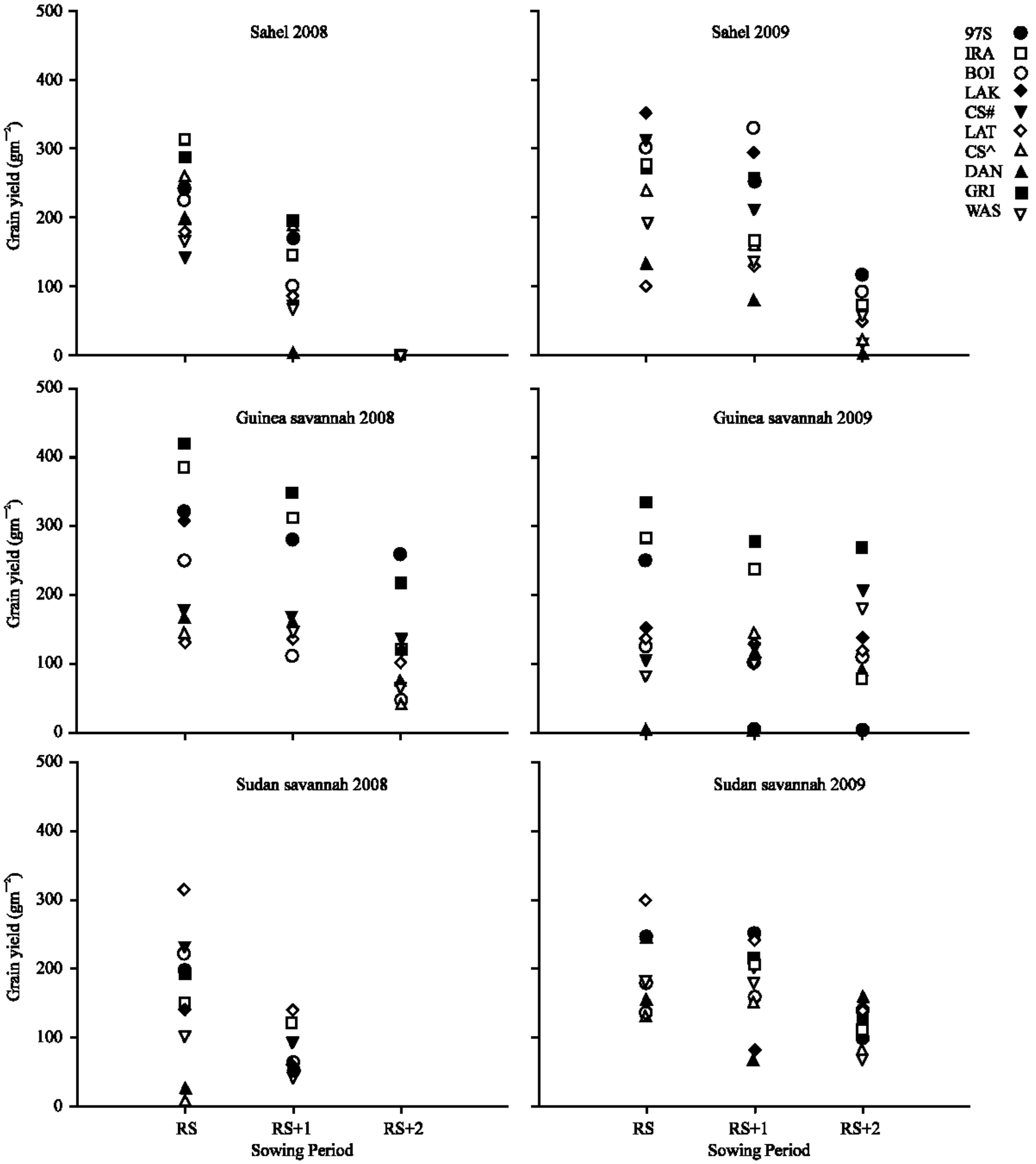

Fig. 2: Grain yield of sorghum, as influenced by the interaction of genotype, date of sowing and location in 2008 and 2009

351 g m^{-2} for 2008 and 2009, respectively. No grain yield was recorded for all cultivars under RS+2 at both Sudan savannah and Sahel zones in 2008. In 2009, 4 plots (97-SB-150 under RS+1 and RS+2 and *Dancouma* under RS and RS+1) at the Guinea Savannah and 1 plot (*Dancouma* under RS+2) at the Sahel did not produce any grains. Grain yields of between 0 and 416 g m^{-2} were recorded across the effects of the full factorial combinations at the Guinea Savannah whiles the respective ranges for the Sudan savannah and Sahel were 0 to 312 and 0 to 351 g m^{-2} (Fig. 2).

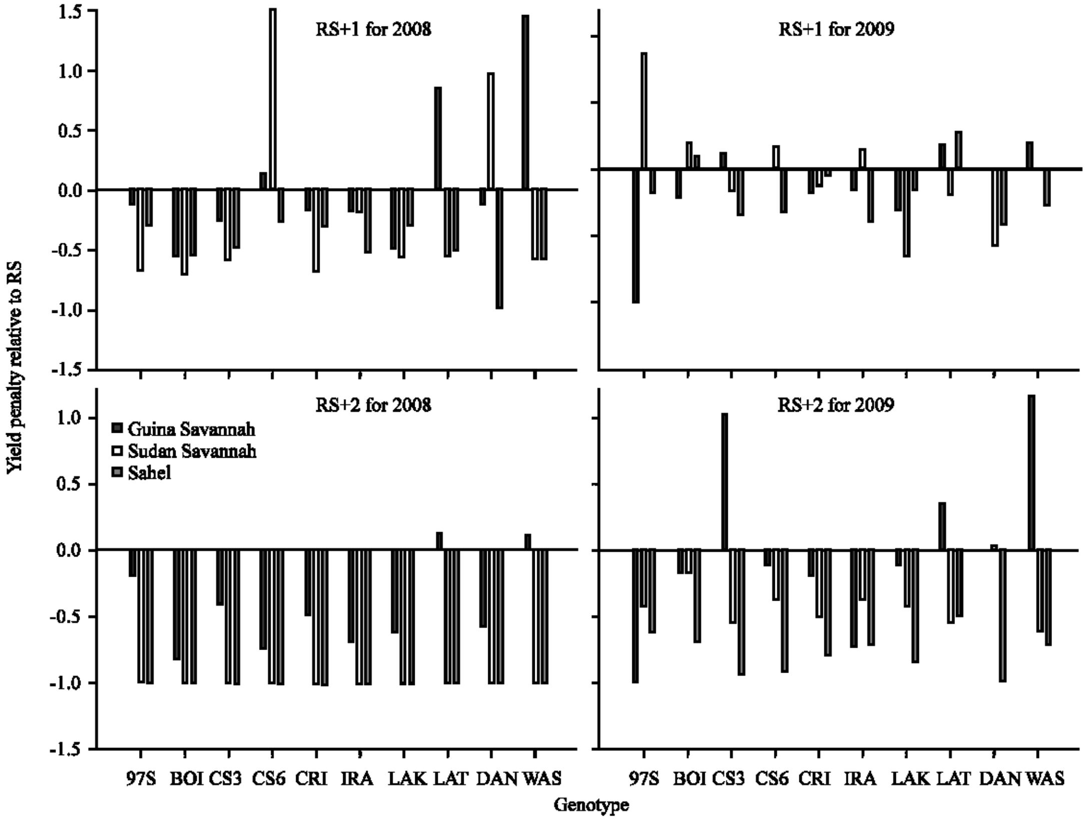

Fig. 3: Yield penalties for delayed sowing relative to RS as influenced by genotypes sown at Farako, Sotuba and Cinzana in Mali during 2008 and 2009 seasons

Yield penalty for delayed sowing: Delayed sowing generally resulted in reduced grain yield at all the sites. Yield penalty was observed in 84% (101 out of 120), ranged from 0.3 to 100% across locations and ranged from 0 to 100% across years. However, yield gains were observed in 16% (9 out of 120) of the experimental units with delayed sowing (Fig. 3).

Yield stability of cultivars: Interactive effects of the factors represented significant ($p<0.01$) sources of variation in mean grain yield (Table 2), suggesting an inconsistency in the performance of the accessions across the environments and necessitated the assessment of stability of performance for each of the ten cultivars in order to identify those with superior and/or stable yields. Of the seven measures of stability used, 2 (IPCA1 and ASV) measured static stability and 5 (RC, SUP, MR, MAD and VAR) measured dynamic stability. Table 3 shows results for grain yield and the stability indices (with ranks in brackets) for the accessions.

Whiles *Dancouma* was not ranked among the 3 most stable by any stability index, each of CSM 388, Lakahieri and Lata-3 were ranked as such by 1 index. Two indices ranked each of Boiguel and Wassa among the 3 most stable, whiles each of 97-SB-150 and CSM 63E were ranked as such by 3 indices. No genotype was ranked among the top 3 by either 4 or 5 indices, but Grinkan and IRAT 204 were each ranked as such by 6 indices. The number of indices that ranked the genotypes among the middle 4 (ranks 4-7) in terms of stability were 0 for CS6 and Grinkan; 1 for IRAT 204;

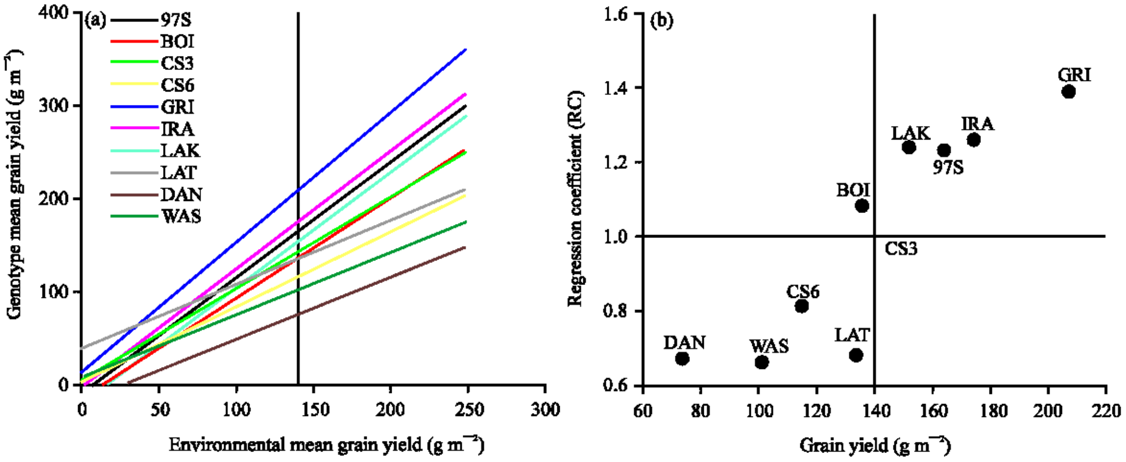

Fig. 4(a-b): Plots of the regression lines for mean grain yields of cultivars on environment mean grain yields (a) and its relationship to cultivar adaptation (regression coefficients) and (b) according to Finlay and Wilkinson (1963)

2 for *Wassa*; 3 for 97-SB-150 and *Dancouma*; 4 for *Lata*-3; 6 for each of *Boiguel* and *Lakahieri*; 7 for *CSM* 388. The number of indices that ranked the genotypes among the 3 least stable were as follows: none for *Boiguel* and *CSM* 388; 1 for each of *IRAT* 204 and *Lakahieri*; 2 for each of *Grinkan* and 97-SB-150; 3 for *Lata*-3; 4 for *Wassa*; 5 for each of *CSM* 63E and *Dancouma* (Table 1).

Coefficients of regression (RC; Finlay and Wilkinson, 1963) as an index of stability considers a genotype with a value closest to 1 as most stable. Genotypic values for this index ranged from 0.65 to 1.39 and *CSM* 388 was ranked as the most stable whiles *Grinkan* with the highest mean grain yield was ranked as the least stable (Table 3). It ranked *Grinkan*, *IRAT* 204, 97-SB-150 and Lakahieri as superior to all the other accessions apart from *Lata*-3 and *Wassa* in all environments. All cross-over interactions were observed between 20 and 133 g m^{-2}. *Lata*-3 crossed over to lower grain yields than *Grinkan*, IRAT 204, *97-SB-150, Lakahieri, Boiguel and CSM* 388 at 34, 66, 87, 106, 133 and 133 g m^{-2}, respectively, but had no cross over interaction with *Wassa, Dancouma and CSM* 63E (over which it was superior in all environments). *Wassa* which had lower grain yield than *Grinkan* in all environments also crossed over from higher to lower yields than *IRAT* 204, 97-SB-150 and *Lakahieri* at 20 g m^{-2} (Fig. 4).

Superiority index (SUP; Lin and Binns, 1988) ranks genotypes with the smallest values (usually with better yields) as more stable. Genotypic values for this index ranged from 2228 to 33520 and it ranked *Grinkan* and *Dancouma* as the most stable and least stable accessions respectively. The 5 most stable accessions including *Grinkan, IRAT 204, 97-SB-150, Lakahieri* and *CSM 388,* produced more than average grain yield whiles the 5 least stable genotypes included *Lata-3, Boiguel, CSM 63E, Wassa and Dancouma,* all lower than average grain yield (Table 3).

Based on MAD, the accession with the lowest value is ranked as most stable (Nassar and Huhn, 1987) and the values for the 10 accessions ranged from 2.37 to 3.46. The index ranked *IRAT 204* as the most stable and *Lata-3* as the least stable. Of the 5 most stable cultivars (*IRAT 204, Grinkan, Wassa, Lakahieri* and *Dancouma*), *Wassa* and *Dancouma* had lower than average mean

Table 3: Mean grain yield (GY) of genotypes across 18 environments and yield stability indices[1] with entry ranks for yield stability indices in brackets

Gen	GY[2]		RC[3]		SUP		MR		MAD		VAR		IPCA1		ASV	
GRI	208a	(1)	1.39	(10)	2228	(1)	3.1	(1)	2.4	(2)	4.4	(2)	-8.94	(8)	14.2	(9)
IRA	175b	(2)	1.26	(6)	7101	(2)	4.2	(2)	2.4	(1)	4.4	(1)	-9	(9)	13.5	(8)
97S	164bc	(3)	1.23	(4)	10926	(3)	4.6	(3)	3.1	(8)	7.3	(9)	-7.31	(7)	12.9	(7)
LAK	152cd	(4)	1.24	(5)	11277	(4)	4.8	(4)	2.5	(4)	4.7	(4)	-2.99	(3)	7.4	(3)
CS3	141de	(5)	0.97	(1)	13413	(5)	5.2	(5)	2.7	(6)	5.3	(5)	5.82	(5)	8.4	(4)
BOI	136de	(6)	1.08	(2)	15111	(6)	5.9	(7)	2.7	(7)	5.7	(6)	0.51	(2)	8.7	(5)
LAT	134e	(7)	0.68	(7)	18476	(7)	5.6	(6)	3.5	(10)	8.8	(10)	10.38	(10)	4.4	(10)
CS6	115f	(8)	0.8	(3)	21362	(8)	6.4	(8)	3.1	(9)	6.9	(8)	0.29	(1)	5	(1)
WAS	101f	(9)	0.65	(9)	24299	(9)	7.4	(9)	2.4	(3)	4.5	(3)	7.23	(6)	10.3	(6)
DAN	74g	(10)	0.67	(8)	33520	(10)	7.8	(10)	2.6	(5)	5.8	(7)	4.02	(4)	5.9	(2)

1: RC: regression coefficient, SUP: superiority, MR: mean rank, MAD: mean absolute difference, VAR: variance; IPCA1: interaction principal component axes, 2: GY figures followed by the same alphabets are not significantly different at $p \leq 0.05$, 3: all values are very highly significant ($p<0.001$)

grain yields, whiles *CSM 388* and *97-SB-150* were the only among the 5 least stable cultivars with more than average mean grain yields (Table 3).

The Mean Rank (MR) stability index was proposed by Nassar and Huhn (1987) and considers the cultivar with the lowest value as the most stable. Values for this index ranged from 3.1 to 7.8, across genotypes, with *Grinkan* and *Dancouma* being ranked as the most stable and least stable cultivars, respectively. For this index, all the 5 most stable accessions including *Grinkan, IRAT 204, 97-SB-150, Lakahieri* and *CSM 388* produced higher than average grain yields, whiles all the 5 least stable accessions including, *Lata-3, Boiguel, CSM 63E, Wassa and Dancouma* had lower than average grain yields (Table 3).

Rank Variance (VAR) is another index used by Nassar and Huhn, 1987 and considers a cultivar with the lowest value as the most stable. Values of the index across the 10 accessions ranged from 4.35 to 8.82. *IRAT 204* was ranked as the most stable cultivar and *Lata-3* was ranked as the least stable. Among the 5 most stable accessions, *Wassa* was the only one that had less grain yield than the grand mean, whiles *97-SB-150* was the only one among the 5 least stable ones with grain yield greater than the grand mean (Table 3).

The first Interaction Principal Component axis of the AMMI analysis (IPCA1; Purchase, 1997) can be taken as a measure of stability that specifically focuses on Genotype X Environment interaction (GXE). The closer the absolute value is to zero, the more stable the cultivar. IPCA1 scores for the 10 accessions ranged from -9.00 to 10.38. *CSM 63E* with a score of 0.29 was ranked the most stable and *Lata-3* with a score of 10.38 was ranked as the least stable by this index. The 4 most stable accessions included *CSM 63E* (0.29), *Boiguel* (0.51), *Lakahieri* (-2.99) and *Dancouma* (4.02), whiles the 3 least stable genotype were *Grinkan* (-8.94), *IRAT 204* (-9.00) and *Lata-3* (10.38) (Table 3).

AMMI stability value (ASV; Purchase *et al*., 2000) ranks the cultivar with the lowest value as the most stable. In this study, the values of ASV ranged from 4.95 to 14.40. The ASV index ranked *CSM 63E* as the most stable and *Lata-3* as the most unstable, though grain yield for *CSM 63E* was lower than for *Lata-3*. The 5 most stable accessions (in decreasing order of stability) were *CSM 63E Dancouma, Lakahieri, CSM 3 88* and *Boiguel* whiles the 5 least stable accessions were *Wassa, 97-SB-150, CSM 388, IRAT 204, Grinkan and Lata-3* (Table 3).

Table 4: Spearman's rank correlation among phenotypic stability parameters after ranking (below diagonal, genotypic parameters correlation; above diagonal, environmental parameters correlation)

	RC	Sup	MR	MAD	VAR	IPCA1	ASV	GY
RC		0.31^{ns}	0.22^{ns}	0.12^{ns}	0.06^{ns}	0.51**	0.50**	0.29^{ns}
Sup	0.03^{ns}		0.96**	-0.11^{ns}	-0.16^{ns}	-0.31^{ns}	-0.43*	0.99**
MR	-0.03^{ns}	0.99**		-0.02^{ns}	-0.08	-0.37*	-0.48*	0.97**
MAD	-0.49*	0.39^{ns}	0.36^{ns}		0.96**	0.39*	0.43*	-0.11^{ns}
VAR	-0.32^{ns}	0.44*	0.39^{ns}	0.95**		0.33*	0.39*	-0.16^{ns}
IPCA1	0.52*	-0.42^{ns}	-0.52*	-0.22^{ns}	-0.14^{ns}		0.57**	-0.33*
ASV	-0.43*	0.52*	0.58*	0.15^{ns}	0.14^{ns}	0.90**		-0.46*
GY	0.03^{ns}	1.00**	0.99**	0.39^{ns}	0.44*	-0.42^{ns}	0.52*	

*,** Significant at $p<0.05$ and $p<0.01$, respectively; ns: Non-significant

Correlations among stability parameters: Close similarities were observed among some of the stability measures for genotypes. As expected of indices for dynamic stability, SUP and MR ranked accessions with higher grain yields as more stable and vice versa, the only exceptions being the ranking of Boiguel and Lata-3 by MR. SUP and MR had same rankings for 8 of the accessions, reversed ranks for the remaining 2 (Table 3), were closely related ($r = 0.96$, $p<0.01$) and their respective relations with grain yield were perfect ($r = 1$; $p<0.01$) and near-perfect ($r = 0.99$; $p<0.01$) (Table 4).

MAD and VAR ranked the same accessions in the same order as the 4 most stable and also the same accession as the least stable, but did not reveal any clear patterns between grain yield levels and phenotypic stability of the genotypes. For example, *Grinkan* with the highest grain yield was ranked as the second most stable by both indices but *Dancouma* with the lowest grain yield as the 5th and 7th most stable by MAD and VAR respectively (Table 3). These indices were revealed as being very closely related ($r = 0.95$, $p<0.01$) (Table 4).

IPCA1 and ASV-the two indices of static stability considered-had similar ranks for 5 of the accessions (CSM 63E, Lakahieri, Wassa, 97-SB-150 and Lata-3), reversed ranks for 2 other accessions (Grinkan and IRAT 204) and did not show any trends or patterns in the rankings of the remaining 3 accessions (Boiguel, CSM 388 and Dancouma) (Table 3). These 2 indices had very high positive and significant correlation ($r = 0.90$, $p<0.01$) (Table 4).

Across environments, significant relations were observed between all the static and dynamic measures of stability, except between IPCA1 and SUP. Across genotypes, ASV was significantly related to RC, MR and SUP, whiles IPCA1 was significantly related to RC and MR but not SUP. Neither MAD nor VAR correlated significantly with any of the static measures of stability-IPCA1 and ASV- (Table 4).

AMMI selections for the environments: The best 4 genotypic selections per environment based on AMMI are shown in Table 1. The analysis revealed that mean grain yield ranged from 74 g m^{-2} (Dancouma) to 208 g m^{-2} (Grinkan) (Table A1 in appendix). The difference in the ranking of genotypes across environments indicated the presence of GXE interaction, which was confirmed by the significant effect of the GXE (explaining 32.41% of the G+E+GE in the AMMI model). *Grinkan* was among the top four ranks in 16 environments and dominated in 8 of them; Lakahieri appeared in the top four ranks in 13 environments but did not dominate in any of them; Lata-3 dominated 6 of the 9 environments in which it was ranked among the top four; 97-SB-150 dominated 3 of the 9 environments in which it was ranked among the top four; CSM 388 appeared within the top four ranks in 11 environments but dominated in 1 only; IRAT 204 and Boiguel appeared among the top four in 9 and 4 environments respectively, but did not dominate in any; *Wassa* did not dominate in any of the 2 environments, in which it appeared among the top four; *CSM 63E* appeared within the top four ranks in only 1 environment, in which *Grinkan* dominated; *Dancouma* neither dominated nor appeared among the top 4 ranks in any of the environments (Table 1).

DISCUSSION

The genotypic differences and variations in environments accounted for the considerable variability in mean grain yield (Fig. 2). Midge (*Contarinia sorghicola* Coquillett) and terminal drought, accounted for total losses in grain yield under RS+2 at Sudan Savannah and Sahel agro-ecologies respectively in 2008. The reduction of grain yield in 84% of plots with delayed sowing is consistent with results obtained by Kouressy *et al.* (2008) but the remaining 16% where grain yield increased with delayed sowing are more of exceptions than the norm and can be attributed to several factors. Norwood (2001) reported yield gains with delayed sowing for maize and attributed it to restriction of root development in the earlier date of sowing by low soil temperature, but this reason is not tenable in the case of this study because temperature and solar radiation (either deficit or excess) did not pose any problems at any of the sites. Occurrence of frequent and heavy rains from panicle initiation to grain development for RS and RS+1 at Farako in 2009, reduced grain yield via poor seed set (wetting of pollen and/or poor anther dehiscence) and a complex of foliar diseases (not sampled for identification). However these conditions abated during such phases of the RS+2 sowing resulting in more efficient use of available resources, especially solar radiation and consequently increased yield. This trend is also attributable to the destruction of panicles by birds in the earlier dates of sowing, especially at the 2 southern most sites of Farako and Sotuba due to asynchrony between grain filling of sorghum and wild flora (main source of food for birds) - a cause previously reported by some authors (Vaksmann *et al.*, 1996; Folliard *et al.*, 2004; Kouressy *et al.*, 2008).

The study showed that SUP and MR can not only be substituted one for the other, but can be more useful as yardsticks of yield performance rather than measures of stability (Table 3). Similar observations were previously reported by Purchase (1997) and Adugna and Labuschagne (2003) for SUP. Information on works with sorghum that concentrate on the use SUP, MR, MAD and VAR for classifying genotypes is very scanty. However, similar relations, between SUP and MR as well as between IPCA1 and ASV, were reported when these were used as measures of stability for sorghum performance under low and high levels of phosphorus in the semi-arid tropics (Leiser, 2010).

Pooling genotypes from all the maturity groups resulted in non-significant positive correlations between RC and yield (Table 3). This is consistent with the findings of Saeed and Francis (1983) who found no relationship between RC and grain yield for a pool of sorghum genotypes and Gama and Hallauer (1980) for maize, but in variance with the findings of Baihaki *et al.* (1975) and Eberhart and Russell (1966) for soybean and sorghum respectively. It appears possible to use medium maturing genotypes to produce higher mean yields and also optimize grain yield in more favorable growing conditions. For example, *Grinkan* is a medium maturing sorghum that combines the photoperiod sensitivity with stay green and is revealed as not only having a higher-than-average grain yield, but also very responsive to improvement in environment. The positive and highly significant correlation between SUP and MR, MAD and VAR as well as IPCA1 and ASV indicate that the relative stability ranking of these sorghum genotypes are consistent when the different pairs of stability indices are used separately, a concept proposed by Langer *et al.* (1979).

Selection of the top 4 accessions for each environment, based on AMMI analysis, revealed that *Grinkan* and *Lata-3* featured in about 78% of the environments (14 of 18 environments). *Grinkan* and *Lata-3* were identified as dominant genotypes in 8 and 6 environments respectively. Individually, Grinkan and Lata-3 appeared in the top four ranks in 16 and 9 environments respectively (Table 1).

Simultaneous assessment of IPCA scores for rice genotypes and environments facilitated the interpretation and identification of specific interactions among them because genotypes with positive IPCA scores were particularly adapted to environments with positive IPCA scores and poorly adapted to environments with a negative IPCA scores (Gauch, 1992), but the reverse applied in this study. Grinkan, 97-SB-150, IRAT 204 and Lakahieri were the only cultivars with negative IPCA1 scores, but were generally adapted to environments with positive IPCA1 scores. Out of the 8 environments in which *Grinkan* dominated, only one had a negative IPCA1 score (Table 1). 97-SB-150 also dominated in 3 environments, but only one had a negative IPCA1 score. IRAT 204 and *Lakahieri* did not dominate in any of the environments.

Grinkan and IRAT 204, with above average grain yield, were ranked among the top 3 most stable cultivars by 6 indices. These can be deployed for tactically adapting to climate change. The superiority of Grinkan across environments seems to be conditioned by a synergy of two traits (stay green and sensitivity to photo-period) that it possesses. Whiles the photoperiod sensitivity allowed the cultivar to delay flowering till when there is little or no risk to bird damage, the stay-green allowed for the supply of current assimilates to fill the growing grains. There was also neither incidence of foliar diseases on this cultivar at Farako, when all the accessions within the guinea race were heavily infected, nor lodging on plots with this cultivar at Cinzana as seen for other cultivars. These therefore resulted in a more efficient use of resources and the subsequent better performance of Grinkan. The benefits of photo-period sensitivity which conditions the length of cycle for the cultivars was not realized in all cases, though the trend suggests some yield advantages to some extent. For example Dancouma, which was latter than all the cultivars for all locations and dates of sowing was the least performing in terms of grain yield (Fig. 2). This shows that some additional traits are required to complement photoperiod sensitivity in ensuring optimum performance under the environments studied.

In conclusion, the study demonstrated that the current gene-pool of sorghum in the arid and semi-arid tropics could be used as a base for extracting cultivars for adapting to climate change if it does occur. Grinkan has a potential for co ping with the effects of climate change in the short-term. Combining photoperiod sensitivity with stay green trait (as in Grinkan) could be a laudable goal for breeders in the environments covered in this study. Further research, involving the use of a greater diversity of accessions and the assessment of physiological and molecular factors that could most likely condition the observations in this study, are required.

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APPENDIX

Table A1: Grain yield of sorghum, as influenced by the interaction of location, date of sowing and genotype in 2008 and 2009

	Genotype[a]									
Envt[b]	97S	BOI	CS3	CS6	GRI	IRA	LAK	LAT	DAN	WAS
					2008					
Farako										
F8S1	317a	247a	176a	138ab	416a	382a	305a	130a	164a	58b
F8S2	276a	107b	165a	156a	344a	309a	153b	135a	157a	142a
F8S3	256a	43b	134a	37b	214b	117b	115b	98a	70b	63ab
Sotuba										
S8S1	194a	220a	235a	6b	193a	149a	141a	312a	25a	102a
S8S2	64b	64b	95b	119a	59b	120a	58b	140b	50a	42ab
S8S3	0b	0b	0c	0b	0b	0b	0b	0c	0a	0b
Cinzana										
C8S1	236a	225a	143a	257a	288a	313a	247a	177a	196a	166a
F8S2	166a	100b	73a	186a	195b	147b	170a	87b	0b	69b
F8S3	0b	0c	0b	0b	0c	0c	0b	0c	0b	0b
					2009					
Farako										
F9S1	245a	123a	103b	139a	331a	280a	149a	205a	0b	83b
F9S2	0b	97a	115b	139a	272a	232a	103a	239a	0b	99ab
F9S3	0b	103a	206a	128a	265a	76b	133a	274a	86a	178a
Sotuba										
S9S1	175ab	134a	241a	128a	243a	180ab	242a	299a	152a	181a
S9S2	250a	159a	203a	149a	214a	205a	81b	242a	66b	181a
S9S3	102b	111a	110b	79a	123b	112b	141b	136b	155a	68b
Cinzana										
C9S1	307a	299a	313a	238a	270a	277a	351a	101ab	132a	193a
C9S2	253a	328a	215b	160b	256a	167b	296a	130a	78a	139a
C9S3	117b	91b	20c	19c	53b	74c	53b	50b	0b	60b

a: see plant materials section under materials and methods for details on genotypes, b: see table 1 for details on the environments, particularly the dates of sowing

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