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Combined agronomic and climatic approaches for sorghum adaptation in Mali

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In Sub-Saharan Africa, Genotype-Environment interaction plays a key role in formulating strategies for crop improvement. Multi-location trials have created enabling structure to determine varieties yield performance and stability. Crop modeling led to prediction of long-term and spatial effects of climate variability. Three improved varieties were compared to three landraces. Optimum cultivation areas minimizing the risk of crop failure were delineated by comparing predicted flowering dates and end of rainy seasons. Agronomic values were determined in trials from three climatically different zones in 27 farms. Yield stability was determined using linear regression depending on each environmental mean and the AMMI model. Photoperiod sensitive varieties have wider optimal cultivation areas whereas early-maturing varieties (photoperiod insensitive) are subjected to strong constraints on sowing date. In low productivity conditions, landraces and improved varieties are not distinct. As the environmental cropping conditions increase, improved lines become significantly superior to landraces. Photoperiod insensitive landrace is subservient to climate conditions of its area of origin and its productivity drops sharply when moved to a wetter area. Varieties studied combined productivity and stability traits. These findings are important steps toward breeding climate resilient varieties for meeting the challenges of climate smart agriculture and sustainable intensification.

Key words: Mali, sorghum, GxE, photoperiodism, climate change, yield stability.

INTRODUCTION

Population growth in Mali will lead to a short term food demand increase for both rural and urban populations. Dryland cereals production needs to follow population demand. So far, cereal production increase in Sub-

Saharan zones has mainly been achieved through cultivated surfaces expansion. However, the gradual saturation of rural are due to cropping and pastoral pressures requires increasing the productivity of cropping systems, in a sustainable way.

Mali has a dry tropical climate influenced by the monsoon, from May to October, during the onset of rainy season; thus growing season duration is varies from year to year which strongly impacts the potential of agricultural production (Sivakumar, 1988; Traoré et al., 2001; Lodoun et al., 2013).

Effects of climate change on agricultural production are difficult to analyze because climate change is accompanied by significant socio-economic change. Thus, despite climate change and recurrent droughts, cereals production increases in Mali; showing the capacity of African countries to achieve food self-sufficiency through intensification of agricultural production (van Ittersum et al., 2016).

As a result of climate change, rain distribution modifications can potentially affect drought occurrence. Droughts of the 1970s and 1980s in the Sahel caused a significant decrease in rainfall, but the consequences for rainy seasons onset and ending were lower (Le Barbé and Lebel, 1997; Traoré et al., 2001). Even if climate models are unclear in predicting the future distribution of African rainfall, an increase in climate variability and a succession of drought and flooding periods are expected (Thornton et al., 2010).

Recently developed high yielding sorghum varieties for the Malian Sudano-Sahelian zone poorly adapt to both environmental and population food requirements. Conversely, landraces are specifically well adapted to local biotic and abiotic stresses and have acquired excellent grain qualities with low yield potential.

These landraces have been selected by farmers over generations and they contribute to environmental constraints mitigation through sensitivity to photoperiod which is a very widespread trait among African sorghum varieties (Kouressy et al., 2008a; Sissoko et al., 2008). Photoperiod sensitivity naturally synchronizes flowering date with the end of rainy season, regardless of the sowing date (Cochemé et al., 1967; Andrews, 1973; Vaksmann et al., 1996).

Farmers define adapted sorghum cultivars as "landraces with grouped maturity" regardless of their sowing dates: u be nyogon konô in Bambara language (Sissoko et al., 2008). A variety is seen as adapted if flowering occurs within 20 days before the end of the rainy season (Traoré et al., 2007; Kouressy et al., 2008b) for a given zone.

This condition ensures a balance between satisfaction of water needs and avoidance of many biotic constraints. Yield and grain quality are closely related to the flowering date. Grain of early maturing varieties is attacked by birds and altered by mold and insects, while late maturing varieties deplete soil moisture before the end of grain filling.

In the wake of the Green Revolution, photoperiod sensitivity has been eliminated by breeders in order to develop early maturing varieties with a broader geographic adaptation (Swaminathan, 2006; Morris et al., 2013). However, the rate of adoption of new early maturing varieties is very low (Sissoko et al., 2008). African farmers, especially Malians, still predominantly grow photoperiod sensitive landraces maturing later than modern varieties (Lambert, 1983; Kouressy et al., 2008a). Nowadays, development of high yielding photoperiod-sensitive varieties adapted to the Sudano-Sahelian climate has become a priority of dryland cereals breeding programs in West-Africa (Kouressy et al., 1998; Vaksmann et al., 2008; Haussmann et al., 2012). In addition, photoperiod sensitivity recently drew breeders attention to increase biomass yield for biofuels production (Olson et al., 2012).

A molecular marker assisted recurrent selection (MARS) program cumulated components of grain yield, grain and fodder quality and climate adaptation (Guindo et al., 2016; Guitton et al., 2018). An on-farm participatory selection program was implemented to develop varieties based on farmer practices and preferences (Leroy et al., 2014). MARS program was undertaken in Mali from 2008 to 2015. A bi-parental population was derived from the cross between two contrasting elite lines from IER (Institut d'Economie Rurale).

Both parents were medium height (<200 cm), well adapted to Sub-Saharan conditions and photoperiod sensitive. Furthermore, parents were interesting combiners based on grain yield and quality. Quantitative Traits Loci (QTLs) identified for target traits and positive alleles were aggregated in recurrent generations. Elite varieties from MARS program are being investigated on station and on farm as well as for seeds registered in Mali. This work intends to determine agronomic performances and genotype-environment interactions of new varieties compared to the most common landraces of the study areas. Multi-location trials were used to analyze genotypes' yield stability in conjunction with a simple crop model to interpret and understand agroclimatic long-term effects.

MATERIALS AND METHODS

Study area

Phenology data collections were carried out at Sotuba Research

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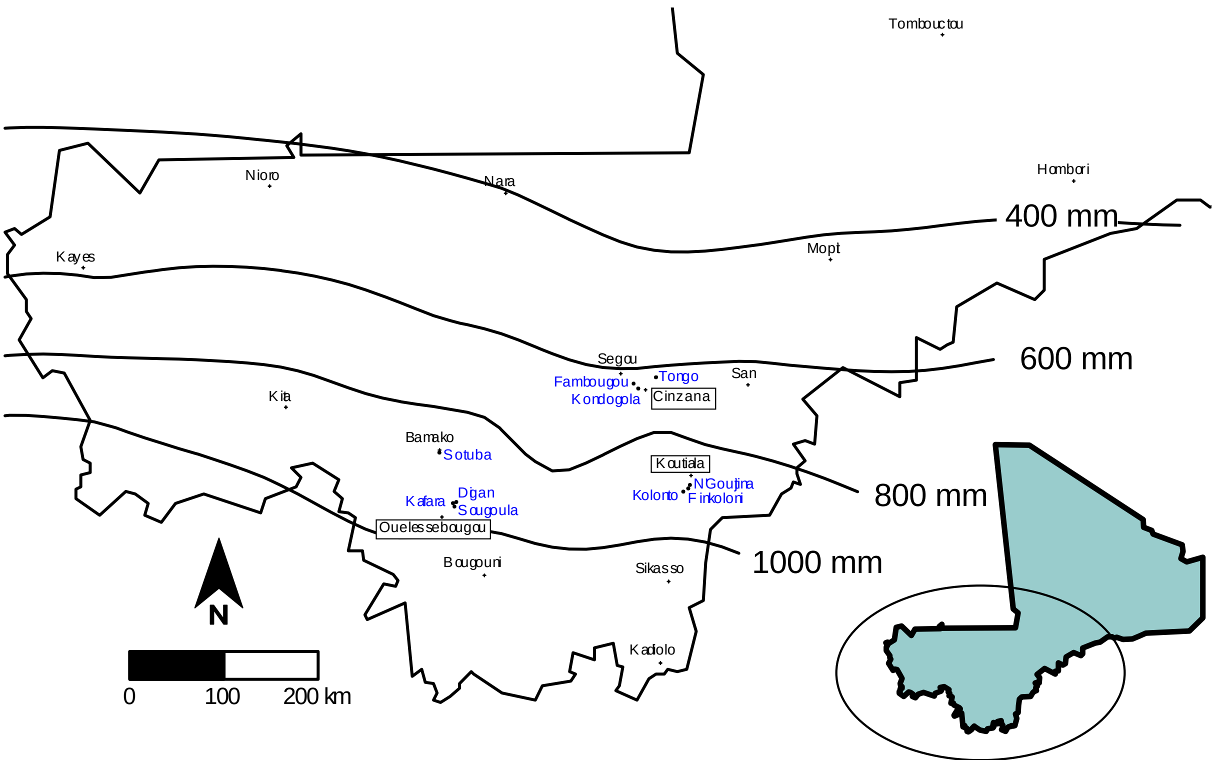

Figure 1. Location of Sotuba station and study areas in farmer fields. Average rainfall over the period of 1981-2010 for each location is indicated. Villages of Kondogola, Fambougou and Tongo are in Cinzana zone; villages of Kafara, Digan and Sougoula in the Ouélessébougou region; villages of Finkoloni, N'Gountjina and Kolonto are in the Koutiala region.

Station (12°39'N, 7°56'E, 381 m) in Mali. Agronomical studies were conducted in three contrasting climatic zones of the Malian Sudano-Sahelian band (Figure 1): Ouélessébougou, Segou and Koutiala. The multi-locational trial network consisted of 27 producers (three villages per zone with three farmers per village) (Figure 1). Villages from Kondogola, Fambougou and Tongo are in the Cinzana zone (40 km from Ségou); villages from Kafara, Digan and Sougoula arein the Ouélessébougou zone; while villages from Finkoloni, N'Gountjina and Kolonto are in the Koutiala zone.

All locations have mono-modal patterns of rainfall in summer (May to November) accounting on average 690 mm at Cinzana, 850 mm at Koutiala, 890 mm at Sotuba and 950 mm at Ouélessébougou. Koutiala and Ouélessébougou are located in upper southern Mali, the major Malian cotton and maize region. Cinzana is located further north (drier zone), where millet and sorghum dominate its cropping system. The soils are clay, silt clay, sandy loam and gravel types according to the toposequence position.

Plant material

Six varieties were tested in 2016 (Table 1), three improved lines and three landraces. Elite lines C2_075-16, C2_099-08 and C2_099-12 are photoperiod sensitive, medium height (<2 m height) with loose to semi-compact panicles. In partner villages, the most common landraces were selected as controls. Varieties Kalagnigue, Folomba and Jacumbe respectively come from Ouélessébougou, Koutiala and Cinzana. Jacumbe is an improved landrace (Teme et al., 2017) which is from a drier zone than Cinzana. This latter variety is fairly well adopted in central Mali due to its earliness. Landraces are tall (> 3 m height), guinea botanical type, with loose panicles.

GxE interaction and crop modeling

Environmental parameter calculation

Thermal time after emergence was computed using an algorithm developed by Jones et al. (1986), considering that growth speed increases as a linear function of temperature between a base and an optimal temperature, and then decreases linearly between optimal and maximal temperature. Cardinal temperatures were 11°C for base temperature (Lafarge et al., 2002), 34°C for optimum temperature and 44°C for maximum temperature (Abdulai et al., 2012). The resulting thermal time per day was used to calculate the progress of developmental processes. The Thermal Time from emergence to flag leaf ligulation (TTFL) was computed for each variety and each sowing date, expressed in degree days (°Cd). Thermal time to panicle initiation was derived from TTFL using the linear formula proposed by Folliard et al. (2004). Day length used is not astronomical day length but civil day length (sunrise to sunset plus civil twilight), which includes periods when the sun is 6° below the horizon, to account for photoperiod effect during dawn and twilight (Aitken, 1974).

CERES model adjustment

A trial with three sowing dates was used to study the phenology of varieties under different photoperiod conditions and to calculate CERES model coefficients (Ritchie et al., 1989; Guitton et al., 2018). This trial was replicated in 2015 and 2016. A split-plot design in two replicates was used. The main factor was three dates of sowing and the secondary factor was six varieties. In 2015, planting dates were June 21, July 20 and September 15. In 2016, planting

Table 1. List of varieties studied in 2015, 2016 in nine villages in Mali.

Name	Origin	Traits of interest
C2_075-16	Marker assisted Recurrent Selection	Productivity and stability, dual purpose value (grain and fodder).
C2_099-12	Marker assisted Recurrent Selection	
C2_099-08	Marker assisted Recurrent Selection	
Kalagnigue	Koutiala (Finkoloni)	Landraces adapted to their area of origin. Good grain quality.
Jacumbe	This variety is released in Cinzana but its area of origin is further north (Chegue) near Nara in the 400 mm rainfall zone.	
Folomba	Ouélessébougou (Kafara)	

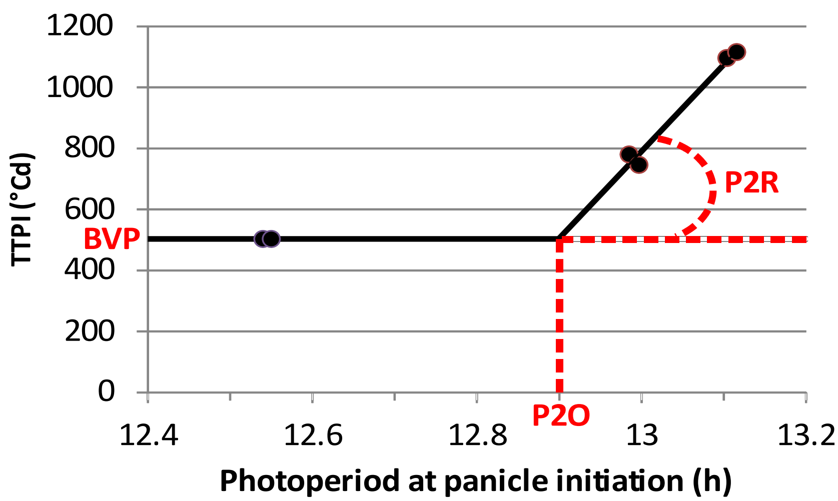

Figure 2. Thermal Time for Panicle Initiation (TTPI) depends on photoperiod according to CERES model. Three parameters, BVP, P2O and P2R, are derived from this modeling. Data from C2_099-08 were used to establish the figure.

dates were June 17, July 18 and September 14. Each year, the first two sowing dates were used to determine varieties behavior in farmer normal period of sowing conditions (long and intermediate photoperiod), while the third date (off-season planting) was to study short photoperiod effect. An irrigation system was used to ensure plant development without water shortage. The varietal response to photoperiod was modeled using the sorghum linear CERES model (Major et al., 1975; Major et al., 1990; Alagarswamy et al., 1991). This model (Figure 2) is based on a linear adjustment between photoperiod and the length of the vegetative phase (Chantereau et al., 2001; Sanon et al., 2014). After emergence, the shortest thermal time required to reach panicle initiation is known as the Basic Vegetative Phase (BVP). During this phase, floral induction cannot occur no matter what the photoperiod conditions are. The CERES model considers that below a critical photoperiod (P2O), the duration of the vegetative stage is constant and is equal to BVP. Above P2O, the duration of the vegetative stage increases as a linear function of photoperiod whose slope, P2R, defines photoperiod-sensitivity in degree days per hour of photoperiod increase (°Cd/h). A modified CERES model version was used (Folliard et al., 2004). Photothermal time accumulation was replaced by a critical photoperiod threshold (varying on plant age) below which sorghum panicle initiation occurs. The three model parameters (P2O, P2R and BVP) were calculated using a method presented by Guitton et al. (2018). For each family, the thermal time for panicle initiation was plotted for the three sowing dates against the photoperiod at panicle initiation date (Figure 2). In practice, BVP was calculated from the minimal duration of the vegetative phase observed at Sotuba in short day length conditions. The photoperiod sensitivity P2R was estimated as the slope of the line drawn between the points related to the sowing dates of June and July. The critical photoperiod P2O, corresponds to photoperiod at the intersection of this line and the BVP base line.

Delineating optimal cultivation areas

The method used comprises identifying the areas for which a variety can be sown during normal planting period to minimize biotic and abiotic risks. The optimum cultivation area of a variety is determined by combining information on photoperiod sensitivity, climatic variability and farmer practices (early and staggering sowing dates) (Soumaré et al., 2008). For each rainfall station in Mali, onset and end of rainy season was established using a simplified water balance model (Traoré et al., 2001). Flowering date is predicted using the CERES model. The difference (in days) between the predicted flowering date and the end of the rainy season gives an adaptation index. This adaptation index was calculated for each variety based on 1981-2010 Malian weather stations data. A geographical information system (Surfer® 14, Golden Software, LLC) was used to delineate areas for which the adaptation index is between -20 and 0 because an adapted variety flowers in the 20 days preceding the end of the rainy season was considered (Kouressy et al., 2008b). Spatial distribution of adaptation index uses a model of linear interpolation by kriging. This action was repeated for each variety considering two sowing dates. A first sowing date was simulated immediately after the installation of the rainy season and a second sowing date was delayed by one month. This duration corresponds to the general practice observed in farmer's fields.

Multi-location trials

Trials were conducted in 27 farms in randomized complete block designs (RCBD) with 2 replicates. Experimental plot consisted of 4 rows of 6 m long. The distance was 0.75 m between lines and 0.40 m between hills on the row. Thinning was done at two plants per hill, corresponding to a maximum density of 66 666 plants/ha. Chemical fertilizers (73 kg N, 30 kg P /ha) were applied.

ANOVA

An analysis of variance (ANOVA) was performed for each environment and trait separately as a RCBD (data and results not presented). A combined ANOVA was undertaken for all environments. Before pooling trials, Hartley test of homogeneity of residual variance for each trait was conducted. The model for the combined analysis across locations was:

$$Y_{ijk} = m + E_i + g_j + (gE)_{ij} + b_{ik} + e_{ijk}$$

Yijk is the observation in the ith environment of the jth genotype, in the kth block of the experimental design.
m is the grand mean
Ei is the effect of the ith environment
gj is the effect of the jth genotype
(gE)ij is the interaction of the jth genotype with the ith environment
bik is the effect of kth block in ith environment
eijk is the residual error.

Interaction GxE

In case of Variety x Environment significant interaction, several statistical methods are available for analysis of adaptation, ranging from univariate parametric models, such as linear regression of each genotype on the average yield of all genotypes in the studied environments (Finlay et al., 1963), to multivariate models such as the additive main effect and multiplicative interaction (AMMI) analysis (Gauch et al., 1988; Sabaghnia et al., 2008).

Regression slope approach

The Finlay-Wilkinson approach (Finlay et al., 1963) is designated to investigate GxE (Figure 4a). The method is to fit, for each genotype, a regression of the mean yields on the average environmental yield (the mean response of all varieties in each environment). The two important indices are the regression coefficient (slope) and the variety mean yield over all environments. Regression coefficients approximating to 1.0 indicate average stability. When this is associated with high mean yield, varieties have general adaptability; when associated with low mean yield, varieties poorly adapt to all the environments.

Regression coefficients increasing above 1.0 describe varieties with increasing sensitivity to environmental change (below average stability) specifically adapted to high-yielding environments. Regression coefficients decreasing below 1.0 provide a measure of greater resistance to environmental change (above average stability), and therefore increasing adaptation to low-yielding environments. The response of varieties to environments may be summarized by plotting the variety sensitivity coefficients (slope), against their means (Figure 4b).

The performance of the varieties may be predicted from the particular quadrant in which they appear on the plot (Kempton, 1984). Those in the bottom right-hand quadrant are relatively stable high-yielding varieties which should yield well consistently in all environments. Those in the top right-hand quadrant are high-yielding varieties.

Similarly, the two left-hand quadrants include lower-yielding varieties.

Additive main effect and multiplicative interaction (AMMI) model

The AMMI analysis fits a model which involves the Additive Main effects of ANOVA with the Multiplicative Interaction effects of principal components analysis (Sabaghnia et al., 2008). GxE scores can be used to construct biplots to help interpret GxE interaction. In the biplot, genotypes that are similar to each other are closer.

Likewise, environments that are similar were grouped together as well. When environment scores are connected to the origin of the plot, an acute angle between lines indicate a positive correlation between environments. A right angle between lines indicates low or no correlation between environments, and an obtuse angle indicates negative correlation. To estimate varieties stability, two indexes were used (Farshadfar et al., 2011).

The AMMI Stability Value (ASV) index was proposed to quantify and rank genotypes according to their yield stability (Purchase et al., 2000; Adugna et al., 2002; Farshadfar et al., 2011). Stability per se should not be the only parameter for selection, because the most stable genotypes would not necessarily give the best yield performance. Yield Stability Index (YSI) incorporates both mean yield and stability in a single index. YSI gives the most stable genotype with high grain yield (Farshadfar et al., 2011). Genotype x Environment interaction was studied using the AMMI function (package 'agricolae') in the R environment (R_Development_ Core_Team, 2008).

RESULTS

Phenological study - CERES model

Ceres model parameters calculation

Sowing delay caused a sharp reduction in the time from sowing to flag-leaf ligulation (SFD) for all varieties except Jacumbe whose SFD duration had little change between sowing dates (Table 2). For June sowing (in long days length), SFD of Jacumbe is short (56 days) compared to those of other landraces (Kalagnigue = 88 days and Folomba = 93 days). SFD of improved varieties are quite similar (98 days on average).

Photoperiod sensitivity is expressed by the reduction of SFD between June and July sowings. SFD of photoperiodic varieties is reduced by an average of 23 days for a staggered 30 day sowing (from June 17 to July 18). For the same period, the Jacumbe variety SFD is only reduced by 3 days. SFD was further reduced by 20 days between July and October sowings for other varieties, except for Jacumbe whose SFD was only reduced by 9 days. Parameters of CERES model was calculated (Table 2).

Table 2. Results of the 2015 and 2016 "sowing date" trials and adjustment of the CERES model parameters for the six studied varieties. SFD: duration from sowing to flag leaf appearance, BVP: Basic Vegetative Phase, P2O: critical photoperiod and P2R: photoperiod sensitivity.

Variety	SFD/Sowing dates						CERES model coefficients		
	2015 sowings			2016 sowings			BVP	P2O	P2R
	June 21	July 20	Sept. 15	June 17	July 18	Sept. 14	(°C.d)	(h)	(°C.d/h)
Jacumbe	56.6	49.0	44.2	56.2	53.6	44.6	432	12.94	319
Kalagnigue	90.0	69.5	57.9	87.9	67.2	52.6	573	12.91	1692
Folomba	95.7	71.8	57.1	92.7	70.8	50.5	539	12.86	2053
C2_099-08	93.9	69.8	49.0	97.3	72.3	48.0	503	12.90	2840
C2_099-12	92.8	71.3	54.1	97.8	73.7	48.4	503	12.86	2441
C2_075-16	93.3	72.4	55.2	98.4	80.2	54.2	590	12.77	1452

The photoperiod sensitivity of Jacumbe (P2R = 190°Cd/h) is much lower than that of the other varieties (2216°Cd/h on average). Differences on BVP and P2O values are weaker, the lowest and the highest BVP (469°Cd for Jacumbe and 591°Cd for C2_075-16) correspond approximately 7 days apart for the basic vegetative phase.

Delineating optimal cultivation areas

Adaptation areas of the 6 varieties studied are shown in Figure 3. The adaptation zone corresponds to an early sowing colored in blue; while adaptation zone corresponds to a late sowing is colored in red. The delay of sowing caused a shift in the adaptation zones towards the south. The adaptation zones of photoperiod-sensitive varieties are characterized by an overlap (colored in purple) which corresponds to the optimal cultivation area, the area in which cultivation of the variety is possible regardless of the sowing date. The two photoperiod-sensitive landraces, Folomba and Kalagnigue, delineate optimal area including or close to their region of origin. The optimal adaptation area of Kalagnigue (intermediate maturity) is located slightly further north of Bamako; whereas, Folomba optimal cultivation area is centered around Bamako. Improved varieties have optimal cultivation areas centered around Bamako and slightly similar to those of local varieties. The marker assisted breeding program has thus succeeded in preserving this character of landraces into the new varieties. Optimal cultivation areas of the most photoperiodic improved varieties (C2_099-08 and C2_099-12) are wider than that of C2_075-16. Conversely, Jacumbe optimal cultivation area is typical of photoperiod-insensitive varieties. Areas corresponding to early and late sowing do not overlap, so there is no place where this variety can be sown safely over a period of one month after the onset of rains. In case of early sowing, Jacumbe is adapted to the Sahelian band which is its zone of origin (>500 mm isohyet) and in case of late sowing, the optimal cultivation area moves towards the south in the Sudano-Sahelian band (isohyet 700 mm). In practice, the date of sowing of Jacumbe must be modulated according to the end of rainy season in the target zone.

Multi-location trials

In each climatic zone, the average yields of improved varieties are very similar from those of landraces (Figure 4). The landrace is still among the best varieties in its area of origin but its performance decreases if grown elsewhere. This is especially true for the variety Jacumbe which does not tolerate being grown further south (<700 mm). The flowering of Jacumbe in Koutiala and Ouélessébougou occurs before the end of the rains so that many constraints contribute to its lower yield (mold, birds ...). The performance of the other two landraces also decreases outside their area of origin but to a lesser extent. Conversely, the improved varieties have remarkable stability since they present good yield performances in the three zones. Four trials out of 27 were eliminated based on heterogeneity of variance. The ANOVA results for grain yield across locations are given in Table 3. Significant interaction GxE ($p<0.001$) in grain yield demonstrated that genotypes responded differently to variations in environmental conditions and necessitated the assessment of stability of performance for each of the six cultivars in order to identify those with superior and/or stable yields.

Regression analysis

Population mean yields and regression lines for the 6 varieties are shown in Figure 5, which illustrates different types of responses to the range of environments. With the exception of Jacumbe, a highly significant linear relationship is obtained between the site mean yield of the 23 farmers (environments) and the individual yields of varieties. Pairwise comparison of the regression lines

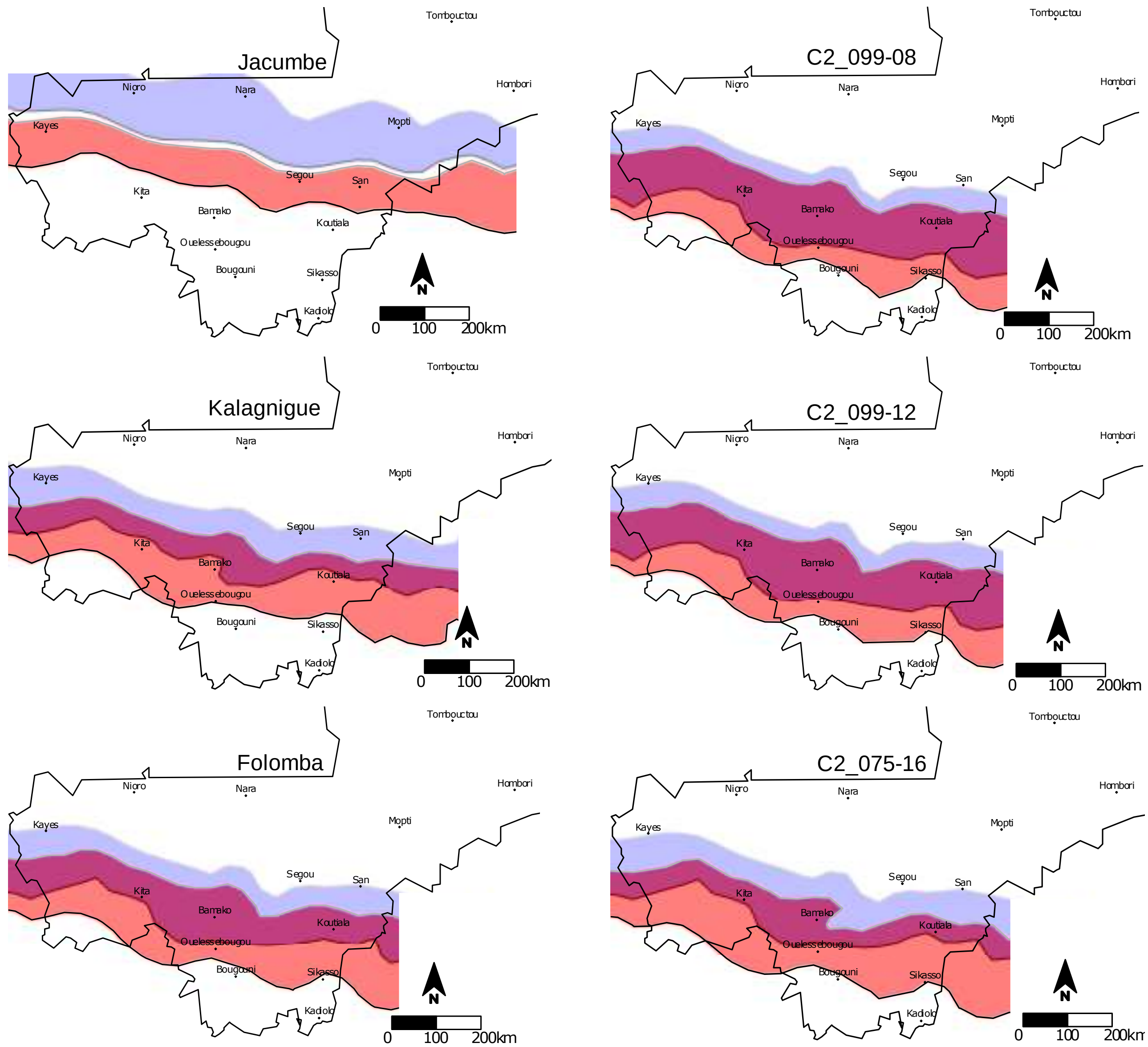

Figure 3. Delineation of optimal cultivation areas for the six studied varieties. The adaptation zone is in blue for an early sowing and in red for a late sowing. The optimal cultivation area (the overlap of the two zones) is in violet.

showed that the slopes of C2_075-16 and C2_099-08 are significantly different from those of the 3 landraces. Variety C2_099-12 has an intermediate behavior between improved lines and landraces (Figure 5a) Regression coefficients from 1.27 to 1.49, C2_075-16 and C2_099-08 are more sensitive to changes in the environment. These two varieties appear in top right-hand quadrant (Figure 4b) and could be described as being specifically adapted to high-yielding environments. It would be tempting to say that these varieties fail to adapt to poor environments. However, since all regression lines intersect for low-yielding environments (average yield around 500 kg / ha), it can be concluded that all varieties are the same in low-yielding environments. Folomba, Kalagnigue and C2_099-12 varieties, with regression coefficients closest to 1 (Table 4). are most stable over all environments. These three varieties appear in Figure 5b at the intersection of quadrants (slope of 1 and average yield). Jacumbe's yield regression slope is around 0.2 with a low coefficient of determination (R^2=0.21) showing that there is no linear relationship between the yield of this variety and the productivity of the environment. This resulted from numerous bird attacks that have been observed in the south (Ouéléssébougou and Koutiala). Bird problem results from the early maturity of Jacumbe, which does not happen in its area of origin (dry area).

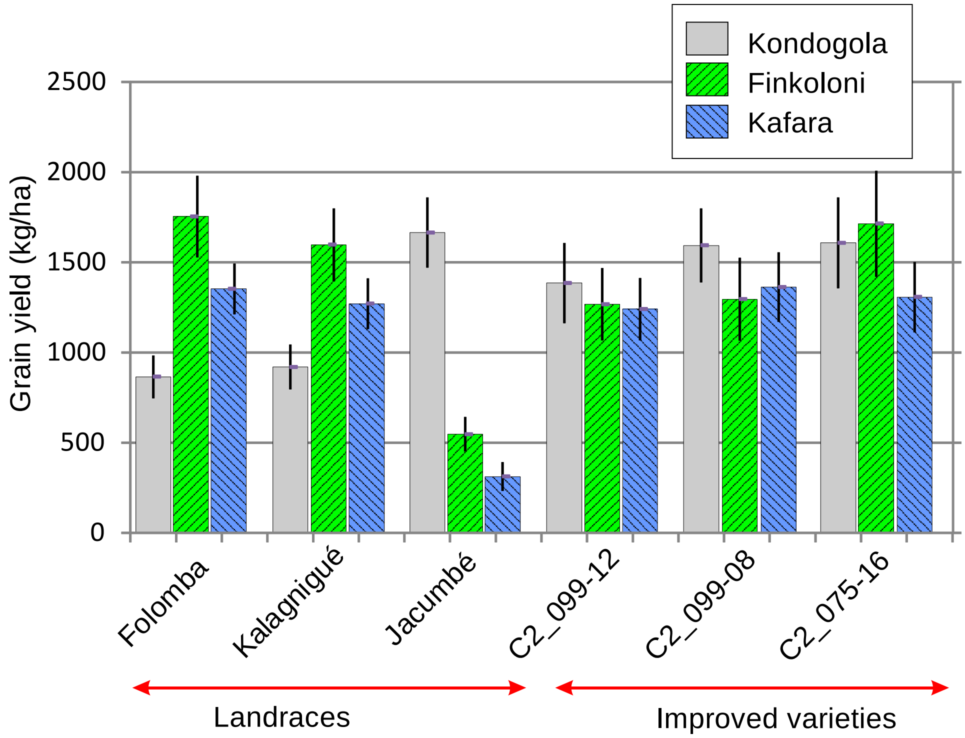

Figure 4. Average grain yields (kg/ha) of the six varieties in the three environments. The vertical bars represent the standard error.

Table 3. Analysis of variance for grain yield of 6 sorghum varieties tested in 23 environments.

Source	Df	Sum of squares	Mean squares	F value	
Genotype (g)	5	14628463	2925693	59.97	***
Environment (E)	22	112143433	5097429	127.02	***
Interaction (gE)	110	56002246	509111	10.44	***
Block (b)	23	923000	40130	0.82	
Residual (e)	115	5610363	48786		

*** Significant at p=0.001.

Table 4. Mean yield, regression slope and determination coefficient (R^2) of six varieties tested in 23 villages in Mali.

Variety	Mean yield (kg/ha)	Regression coefficient	R^2
C2_075-16	1480	1.487	0.91
C2_099-08	1336	1.265	0.92
C2_099-12	1216	1.044	0.86
Folomba	1300	1.061	0.74
Jacumbe	741	0.207	0.21
Kalagnigue	1250	0.935	0.75

AMMI results

On the biplot (Figure 6), landraces and improved varieties are positioned along the second axis with the exception of Jacumbe which contributes to the first axis. The presence of GxE interaction as seen in the north (Cinzana) and South (Ouélessébougou and Koutiala) are separated into (mega) environments on axe 1. The AMMI

Table 5. Mean grain yields in kg/ha (Y), AMMI Stability value (ASV) and yield stability index (YSI) for six sorghum genotypes tested in 23 environments and corresponding ranks (rASV and rYSI).

Variety	ASV	YSI	rASV	rYSI	Y
C2_075-16	40.3	5	4	1	1480
C2_099-08	24.7	4	2	2	1336
Folomba	41.0	8	5	3	1300
Kalagnigue	33.4	7	3	4	1251
C2_099-12	4.2	6	1	5	1216
Jacumbe	98.6	12	6	6	741

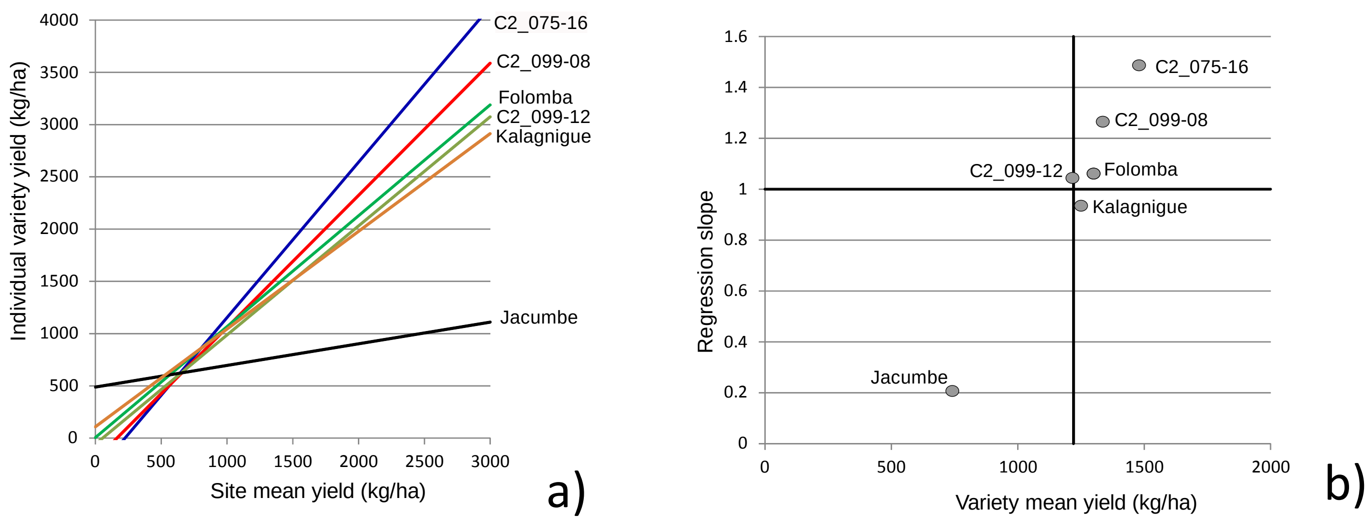

Figure 5. Stability analysis according to Finlay and Wilkinson (1963). (a). Plot of regression lines for grain yields of cultivars on average yields from 23 farmers in Mali. (b). Plots of the varietal regression slope on mean grain yield. The vertical line is the grand mean, whereas the horizontal line is the slope =1.

stability value (ASV) and the yield stability index (YSI) are given in Table 5. The most stable variety in the ASV index is C2_099-12, while Jacumbe variety is unstable and ranked last. The results for YSI are similar to those obtained by the regression method since the varieties C2_075-16 and C2_099-08 are the most stable with high grain yield.

DISCUSSION

The predictive value of multi-location trials is limited to the range of environments studied. It would be risky to generalize these results to other locations or other climatic situations. The two GxE study methods discussed here are complementary. Using agroclimatic maps facilitates rural planning, as well as ecological and economic decision-making (Cetin et al., 2018). Such maps, delineating optimal cultivation area, enable, in particular, avoidance of unsuitable varieties release. Conversely, multi-location trials provide an evaluation of cultivars response to soil fertility rather than an evaluation of their climatic adaptation.

The first sorghum breeding programs in Africa have shown that the choice of new varieties for any area is restricted to those which flower at the same time as the local varieties (Curtis, 1968). These climate adaptation rules may seem simple but early planting and matching flowering period to end of rainy season are limiting factors that account for much yield, yield stability and grain quality far above fertilizer inputs or tillage. For this reason, we decided to address climatic and agronomic approaches separately. It should be stressed that methods combining these approaches have been developed using a crop model to evaluate the expected genotype performance in a large sample of environments and to interpret the long-term and spatial effects of environment (Chapman et al., 2002; Dieng et al., 2006).

Furthermore, the use of crop models for generalization in space of photoperiod response should be done with caution since it has been shown that photoperiod sensitivity assessment becomes imprecise when one

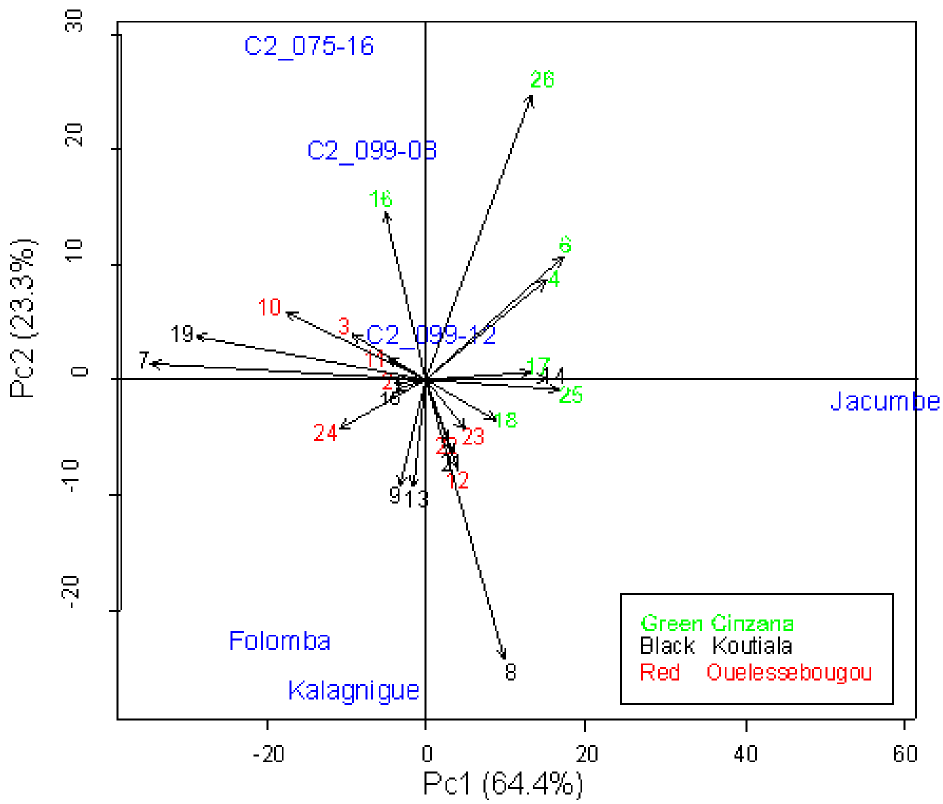

Figure 6. Genotype x Environment biplot of grain yield assessed in 23 environments (red) for six varieties (blue). Environment labels are colored to identify the region.

moves too far away, in latitude, from the area where the model was calibrated (Abdulai et al., 2012). Climatic and agronomic approaches show that Jacumbe, the early maturing variety, is specifically adapted to the dry (northern) part of the studied area. Its yield decreases rapidly if grown outside its area of origin. This finding contrasts with green revolution paradigms that opines that non-photoperiod sensitive varieties have a broad geographical adaptation (Bonneuil et al., 2009).

In reality, thanks to a large sowing window and good maturing conditions, photoperiod sensitive varieties have the widest cultivation area. Release of early maturing varieties is necessarily accompanied by a strong constraint on the sowing date that needs to be adapted to each target zone. However, delaying sowing after the onset of the rainy season is a risky advice. Sowing as of the first rains is always a race for Malian farmers (Viguier, 1947) because planting delayed after the installation of the rains lead to a considerable risk increase in crop failure (Andrews, 1973; de Rouw, 2004). Late planting produces lower yields for many reasons: damages and parasites, leaching of nitrogen and mineral elements, lower amount of radiation, low temperatures, flooding, weeds competition and aggressiveness of heavy rains.

In addition, all fields are rarely sown simultaneously, erratic precipitation at the beginning of the season leads to successive waves of sowing. It is not unusual for farmers to reseed two or three times, either because of low rate of emergence, loss of seedling due to early drought or because of pest attacks. The constraints of exploitation, lack of labor or farm equipment, often force farmers to stagger sowings.

Moreover, by grouping flowering, photoperiod sensitivity considerably limits the development of pests such as midge that benefits staggered flowerings to multiply (Etasse, 1977). There are concerns that the recent release of early maturing varieties in Mali will result in an outbreak of midge, which until recently was a minor problem in Mali (Kouressy et al., 2014). It has long been thought that combining photoperiod sensitivity of landraces with the productivity of modern varieties would not be possible (Sapin, 1983; Haussmann et al., 2012).

The findings of this research show that photoperiod-sensitivity is not an obstacle to the development of productive varieties that has been facilitated by the implementation of molecular marker-assisted recurrent breeding techniques, which lead to rapid accumulation of positive alleles.

In favorable environmental conditions, improved varieties yield exceeds 3700 kg/ha, significantly higher than landraces yield. Conversely, at low productivity (average yield 500 kg/ha), it is difficult to distinguish the varieties among them. In low yielding conditions, average yield of landraces is as good (if not better) than that of improved varieties. This result explains the weak release of improved varieties in farmers' fields. Farmers often prefer their landraces which, under traditional cultivation conditions present a more stable yield, almost systematically associated with a better grain quality (Luce, 1994).

On the other hand, new improved varieties would be useful to intensify farmer's production. So far, given the lack of high-yielding photoperiod sensitive sorghum varieties, farmers who wish to increase cereal production are turning to corn, which values higher fertilizer application. The challenge is therefore to improve sorghum productivity to make it a better option in more intensive production systems where it can even or beat corn.

Conclusion

In Sub-Saharan Africa, Genotype × Environment interactions in multi-location and/or multi-year trials are important. The only statistical consideration of interactions is that it does not always predict the responses of genotypes particularly with regard to climate change. The use of crop models effectively complements multi-location trials. Delineation of optimum cultivation areas can save considerable time for the release of new genotypes. Given the cost of a multi-location trial, modeling approach is much less expensive and would avoid experimentation outside target area. Rapid increase in African population (especially in towns) and the gradual saturation of rural areas will force African farmers to intensify agricultural production. Fertilizers and manure are being used more commonly by farmers, especially in the southern zone of Mali. Molecular marker-assisted recurrent selection allows combining the traits of interest in productivity and stability. It is therefore possible to sustainably raise the productivity of sorghum to make it a plausible alternative crop in an intensified cropping system. These findings are thus an important step toward breeding climate resilient varieties for meeting the challenges of climate smart agriculture and sustainable intensification. These two concepts are closely interlinked (Campbell et al., 2014). Climate smart agriculture lays emphasis on improving risk management which provides the foundations for enabling sustainable intensification.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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