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Genotypic responses of Rainfed Sorghum to a Latitude Gradient

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Preface

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Summary

Climate change poses various challenges to crop production systems. Coping with the changing climate requires adaptation strategies that will enhance the resilience of crop production systems to the resultant aberrant weather. However, the impacts of the changing climate are extremely difficult to predict because the associated extreme events result in a complex of abiotic stresses. These stresses act singly or in synergy with others to affect physiological processes at the different growth and development stages of crop plants. Currently, the physiological and phenological (developmental) response mechanisms of crops, as well as adaptation of cultivars to these stresses are not very clear and well understood. The complex interactions between crops and abiotic stresses make it difficult to accurately predict crop responses to climate change using the available crop growth models that have been parameterized and validated using some climate scenarios. While prediction of the complex ideotype-trait combinations may benefit breeders, physiological models that are well validated for target environments are equally important. Therefore, this study investigated elite grain sorghum genotypes from three races (Caudatum, Durra, and Guinea) and a Guinea-Caudatum composite, with different degrees of sensitivity to photoperiod and adaptation to a wide range of latitude locations, for their grain yield and yield stability responses to different environments. The aim was to calibrate growth models in for use in quantifying climate change effects on rainfed sorghum production systems. Field experiments were established to investigate the yield performance and yield stability of ten genotypes in eighteen environments created from a factorial combination of three locations (along a latitudinal gradient) and three monthly-staggered dates of sowing within years in 2008 and 2009. Field trials to study the phenology of seven of the ten genotypes were also established in a similar fashion in 2009 and 2010. Data were also collected on yield and other traits for the first two dates of sowing on six of the genotypes used for the yield performance trial to analyze the relations between grain yield and the selected traits and also evaluate the potential of path analysis in improving understanding of trait yield relations of grain sorghum. Mean grain yields of 0 to 248 g m² were recorded across environments and from 74 to 208 g m⁻² across the 10 genotypes and generally reduced with delayed sowing. Grain yield was significantly influenced by the main and interactive effects of location, year, sowing date, and genotype, necessitating the assessment of yield superiority and stability for each of the ten cultivars. The only two Caudatum

cultivars (Grinkan and IRAT 204) were ranked among the top three by six of the indices. The study also brought to the fore that some yield stability indices correlate perfectly or very highly and could be substituted one for the other when assessing yield stability of sorghum. Very strong correlations were found between grain yield and each of shoot biomass, panicle weight, the number of grains per panicle, and threshing ability across environments, but path coefficient analysis confirmed that these traits are auto-correlated, with grains per panicle being the major mediating trait in all the relationships. Relationships between grain yield and the remaining traits were weak to medium and very inconsistent across the environments. This study brings to the fore, the location- and / or environment-specific adaptation of existing genotypes which should be exploited for tactical adaptation to changed climates, while genotypes with general or wider adaptations to environments are being sought. The phenology study showed that for photoperiod sensitive (PPS) genotypes, the number of days from emergence to panicle initiation and the number of leaves increased with latitude and decreased with sowing date, a day-length difference between locations of < 8 minutes increasing crop duration of some varieties by up to 3 weeks and decreasing number of leaves by up to 11 for the same sowing date. Some varieties exhibited photoperiod-insensitivity at one location and photoperiod-sensitivity at another location, indicating the complex nature of photoperiod responses. The study also showed that existing models do not accurately simulate the effect of latitude on the phenology of PPS sorghum, and latitude has to be taken into account in adjusting coefficients to improve the accuracy of such simulations. We conclude that genotypic response of rainfed sorghum is influenced by latitude, sowing date, and their interactions, but very little by years. Some existing cultivars could be deployed as tactical adaptive measures, while efforts are intensified to develop strategic adaptive measures. If changes in rainfall and temperature reduce the length of growing seasons, genotypes which are currently adapted to higher latitudes could easily be shifted southwards to lower latitudes, while those at lower latitudes may fit poorly into the new environments. A large potential for contributing to food security exist for the low latitudes if climates change in the direction predicted in future. It is absolutely necessary to develop new models that will be able to accurately simulate effects of sowing date and latitude on phenology. More research is needed to understand physiological response mechanisms of the pronounced latitude effects on sorghum phenology.

Zusammenfassung

Der Klimawandel stellt heutige Produktionssysteme vor eine Vielzahl von Herausforderungen. Der Umgang mit dem Klimawandel erfordert Anpassungsstrategien um die Widerstandsfähigkeit der Anbausysteme gegen sich wandelnde Wettergegebenheiten zu erhöhen. Allerdings sind die Auswirkungen des Klimawandels äußerst schwierig vorherzusagen. Die damit verbundenen Extremereignisse resultieren in einem Komplex von abiotischen Stressfaktoren, die einzeln oder im Zusammenwirken mit anderen, unterschiedliche Auswirkungen auf die physiologischen Prozesse in den verschiedenen Wachstums- und Entwicklungsstadien der Kulturpflanzen haben können. Derzeit sind die physiologischen und phänologischen Reaktionsmechanismen von Nutzpflanzenarten, sowie die Anpassung der verschiedenen Sorten auf diese Belastungen nicht sehr klar oder eindeutig verstanden. Die komplexen Wechselwirkungen zwischen Pflanzen und abiotische Stressfaktoren machen es schwierig deren Reaktionsweise auf den Klimawandel vorherzusagen, selbst unter Verwendung der verfügbaren Pflanzenwachstumsmodelle, obwohl die parametrisiert und für einige Aspekte der prognostizierten Klimaszenarien validiert sind. Obwohl die Vorhersage der komplexen „Ideotype-Trait-Kombinationen“ den Züchter bei ihrer Arbeit helfen kann sind physiologische Modelle, die für die Zielumgebungen validiert sind, ebenso wichtig. Daher untersucht diese Studie Elite Sorghum-Genotypen (Caudatum, Durra, Guinea), mit unterschiedlichen Graden der Empfindlichkeit gegenüber Aspekten der Lichtperiode, die an eine breiten Palette Standorte angepasst sind, hinsichtlich ihres Kornertrags und Ertragsstabilität unter verschiedene Umwelten, um die Wachstumsmodelle zu kalibrieren die die Quantifizierung der Auswirkungen des Klimawandels auf niederschlagsgespeiste Sorghum Produktionssysteme erleichtern sollen. Zwei Feldversuche wurden etabliert, insgesamt wurden dafür achtzehn Umwelten aus einer faktoriellen Kombination der drei Standorte (entlang eines Breiten Gradienten) sowie dreier monatlich gestaffelter Aussattermine über zwei Jahre hinweg untersucht. Ziel war es die Stabilität der Ertragsleistung der zehn Genotypen im Jahr 2008 und 2009 zu untersuchen, sowie für die Jahre 2009 und 2010 Phänologische Aspekte von sieben Genotypen zu erfassen. Von sechs der untersuchten Genotypen wurden zudem Ertragsdaten und zusätzliche phenologische Merkmale detailliert erhoben, um die Beziehungen zwischen Kornertrag und selektierten traits zu analysieren sowie das Potenzial der Pfadanalyse für ein

besseres Verständnis der Trait-Ausbeute Beziehungen von Sorghum zu klären. Mittlere Kornerträge von 0 bis 248 g m⁻² wurden in den verschiedenen Umwelten erfasst, ebenso Erträge von 74 bis 208 g m⁻² für die Versuche zu den 10 selektierten Genotypen; diese reduzierten sich als Faustregel mit verzögerter Aussaat. Die wichtigsten (signifikanten und interaktiven) Effekte auf den Kornertrag hatten die Faktoren Lage, Jahr, Datum der Aussaat sowie Genotyp, was eine detailliertere Untersuchung der Ertragsstabilität und Ertragsleistung für die selektierten Kultivare nötig machte. Die einzigen beiden caudatum Sorten (Grinkan und IRAT 204) wurden unter den Top Drei für sechs der Indizes einsortiert. Die Studie zeigt außerdem dass einige der Indices zur Ertragsstabilität zueinander korreliert sind und deswegen für eine Beurteilung der Erträge von Sorghum wechselseitig austauschbar sind. Es wurden sehr starke Korrelationen zwischen Kornertrag und den folgenden Faktoren festgestellt: Sprossbiomasse, Gewicht der Rispe und Anzahl der Körner pro Rispe. Eine Analyse der Pfadkoeffizienten bestätigte, dass diese Charakteristika Auto-korreliert sind, wobei aber Körner pro Rispe das Hauptvermittlungsmerkmal in allen Beziehungen darstellt. Beziehungen zwischen Kornertrag und den restlichen Charakteristika waren schwach bis mittelgroß und sehr uneinheitlich über die für die Studie verwendeten Umwelten. In dieser Studie konnten die Orts-Umweltbedingten Anpassungen der Genotypen aufgezeigt werden, die für eine taktische Anpassung an veränderte Klimabedingungen ausgenutzt werden sollen, während weitere Genotypen mit allgemeinen oder größeren Anpassungen an sich verschiedene Umgebungen gesucht werden. Die phenologische Studie zeigte, dass bei photoperiodisch sensitiven Genotypen die Anzahl der Tage vom Auflauf bis zur Initiierung der Rispe sowie die Anzahl der Blätter sich stark erhöht mit dem Breitengrad und verringert mit dem Datum der Aussaat. Die Studie zeigte auch, dass die Unterschiede in der Breite, trotz eines Unterschieds in der maximalem Tageslängendifferenz zwischen Standorten von weniger als <8 min, für einige Sorten eine deutlich (bis zu 3 Wochen) verlängerte Anbauperiode ergab. Einige Sorten wiesen an einem Standort eine Unempfindlichkeit gegenüber der Photoperiode auf, während sie an anderer Stelle empfindlich auf die Photoperiode reagierten. Dies verdeutlicht die Komplexität von Fragestellung in Bezug auf die Photoperiode. Die Studie zeigte auch, dass die vorhandenen Modelle die Auswirkung der Breite auf die Phänologie von Sorghum nicht korrekt einschätzen. Um die Bestimmung der optimalen Bereiche für die Sorten in Westafrika zu erleichtern und die Auswirkungen des Klimawandels prognostizieren zu können wird eine Korrektur der

Simulationskoeffizienten unter Berücksichtigung des Breitengrades vorgeschlagen. Abschließend folgere ich aus dieser Studie dass die genotypische Antwort von Sorghum durch den Breitengrad, den Zeitpunkt der Aussaat und deren Wechselwirkungen, aber sehr wenig von interannuellen Schwankungen beeinflusst wird. Einige der existierenden Sorten sollten für taktische Anpassungsstrategien auf lokale umwelt-spezifische Bedingungen genutzt werden, während gleichzeitig die Zuchtbemühungen intensiviert werden müssen um geeignete Sorten für die strategische Anpassung an veränderte Klimabedingungen zu entwickeln. Bei sinkenden Niederschlagsmengen und steigenden Temperaturen, könnten Genotypen aus höheren Breitengraden, bedingt durch eine Verkürzungen der Anbauperiode neue optimale Anbaubedingungen in niedrigeren Breiten finden . Gleichzeitig würden Genotypen die derzeit niedrige Breitegrade angepasst sind schlecht in höhere Breiten passen, hauptsächlich wegen ihrer langen Anbaudauer und des Phänomens der mit dem Breitengrad ansteigenden Anbaudauer aus dieser Studie. Ein großes Potenzial für einen Beitrag zur Ernährungssicherheit besteht in den niedrigen Breitengraden, vor allem unter Berücksichtigung der zukünftigen Klimaszenarien. Es ist absolut notwendig neue Modelle zu entwickeln, die in der Lage sind die Auswirkungen der beiden Faktoren „Tag der Aussaat“ und „Breitengrad“ vorherzusagen. Mehr Forschung ist notwendig, um die physiologischen Reaktionsmechanismen der ausgeprägten Auswirkungen des Breitengrades auf die Sorghum Phänologie zu verstehen.

1 General introduction

1.1 Sorghum (*Sorghum bicolor* L. Moench)

The genus *Sorghum* is incredibly diverse with members of the genus present throughout the semi-arid tropics. The center of origin is in Eastern Africa; a significant amount of diversity still exists in this region today (Dahlberg, 2001). Based on phenology and genetics, Garber (1950) and Celarier (1959) subdivided the genus into five subgenera: *Sorghum*, *Chaetosorghum*, *Heterosorghum*, *Parasorghum*, and *Stiposorghum*. The cultivated sorghums are included in the *Sorghum* subgenera and Snowden (1936) completed the classification of this subgenera. Celarier (1959) reported that the base chromosome number in the *Sorghum* subgenera is $n = 10$ and most members of the subgenera were diploid ($2n = 2x = 20$); but several members were polyploid ($2n = 4x = 40$). de Wet (1978) further classified the *Sorghum* subgenera by recognizing three distinct species: *S. propinquum*, *S. halepense*, and *S. bicolor*. Furthermore, *S. bicolor* was divided into three sub-species: *drumondii*, *bicolor*, and *verticilliflorum*. All of the cultivated sorghums are classified as *S. bicolor* subsp. *bicolor*. Finally, the primary gene pool of *S. bicolor* L. Moench was finally partitioned into five basic races (designated Bicolor, Guinea, Caudatum, Kafir, and Durra) and 10 intermediate races from the combinations of the five basic races (Harlan and de Wet, 1972) that have different but overlapping geographic distributions (House, 1985). These races are used today for the classification of sorghum germplasm collections. In addition, these races are reflective of different patterns of production and utilization in specific geographic regions.

Sorghum [*Sorghum bicolor* (L.) Moench] is an important and widely cultivated small-grain cereal grown between 40°N and 40°S of the equator (Doggett, 1988). It is mainly a rainfed crop of lowland, semi-arid areas of the Tropics and Sub-Tropics and a post-rainy season crop grown on residual soil moisture, particularly in India. Depending on the location, sorghum is grown for many different purposes. The grain is used for food, feed, and industrial purposes, while the stalk is used as forage in many production systems. The specific type of sorghum grown depends on the ultimate end use which varies with location. For example, in many regions of Africa, sorghum is a vital food grain and the stalk and leaves are valued as forage and building materials. In these production systems, the farmers demand pure-line cultivars that are tall with specific

food quality parameters and stable production under stress. Farmers grow Bicolor throughout much of Africa, Durra predominantly in East Africa, Kafir primarily in Southern Africa, Caudatum in East Africa to Nigeria, and Guinea in West and Southern Africa (Dahlberg, 2000). However, in the developed world, sorghum is grown as a feed grain with high input and management. The production system is mechanized and demands sorghum hybrids with high yield potential, relatively short, lodging resistant, and responsive to favorable environmental conditions.

In 2014, sorghum was grown on more than 44 million hectares globally with an average yield of 1536 kg ha⁻¹ to produce a total of more than 67 million metric tons (Figure 1.1). In the same year, Africa accounted for 65% of the global area cropped to sorghum (more than 29 million hectares) to produce nearly 29 million metric tons, representing more than 40% of global production, with a mean yield of 999 kg ha⁻¹ (FAO, 2016). The area cultivated to sorghum in West Africa was more than 12.5 million hectares in 2014. With an average yield of more than 900 kg ha⁻¹, West Africa produced more than 12 million metric tons of sorghum in 2014 (FAO, 2016). From 1979 to 2001, sorghum production in West Africa increased from 5.1 to 13 million tons, but declined to 12 million tons in 2014, and mean yields are stagnant (890 kg ha⁻¹ in 1979; 780 kg ha⁻¹ in 1992-94; 830 kg ha⁻¹ in 2001; 900 kg ha⁻¹ in 2014) (FAO, 2016).

More than 70% of the world's total production of sorghum comes from developing countries in Asia and Africa where the crop is the mainstay of resource and technology poor farmers and is grown with limited inputs of water and nutrients. As a result of being relatively tolerant of heat and drought, sorghum constitutes an integral component of agricultural production throughout Africa (House *et al.*, 2000) and plays a pivotal role in the economies of nations within the semi-arid and sub-humid regions of tropical Africa, contributing substantially to total cereal production in these areas. In West Africa, sorghum is grown mainly as a rainfed crop between May and November, so climatic factors play a significant role in its productivity. The sorghum plants grow mostly under progressively decreasing day length resulting in a shortening of crop duration for photoperiod sensitive cultivars, particularly when sowing is delayed.

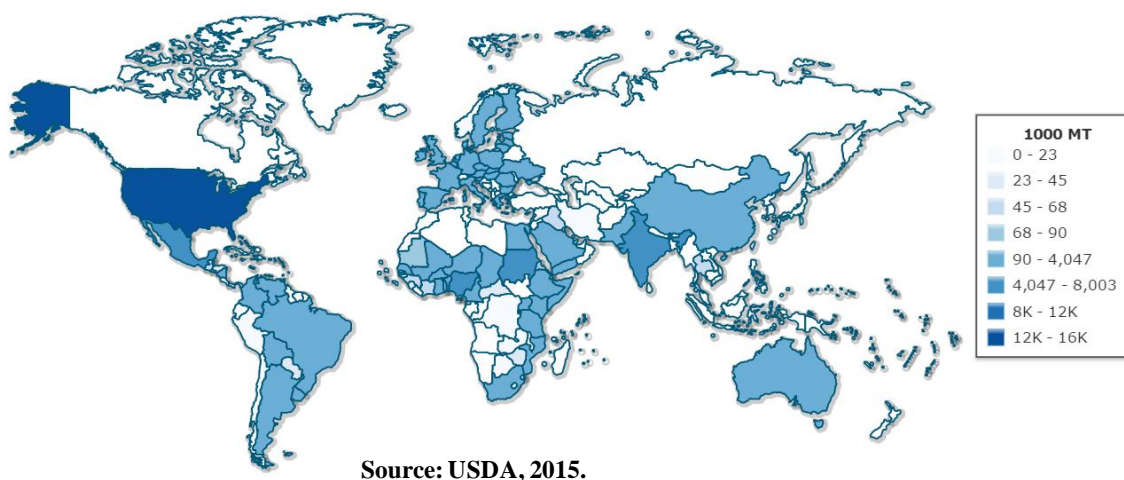


Figure 1.1: Global sorghum production. MT = Metric tons

1.2 Climate change, abiotic stresses, and sorghum

The Inter-governmental Panel on Climate Change (IPCC) projects a 1.8-4.0°C rise in surface air temperature together with the very likely occurrence of frequent extreme weather (heat waves, drought, floods) in the 21st century (IPCC, 2007). Increased concentration of CO₂ in the atmosphere, rising temperature, and increased variability in the onset, amount, distribution, and cessation of rainfall are the major climate change related phenomena with potential impact on sorghum production. These phenomena threaten crop productivity in the most vulnerable regions of the world and could have substantial negative impacts (Nelson, 2009; Parry *et al.*, 2004).

The potential benefits of increased CO₂ concentration in the atmosphere are negated through a reduction in grain yield due to the shortening of the growth cycle, the increase in maintenance respiration and the decrease in sink size resulting from the increase in temperature (Matthews and Wassmann, 2003). No significant yield increases in sorghum were found by von Caemmerer and Furbank (2003) under carbon dioxide fertilization because in C₄ crops photosynthesis is CO₂ saturated. However, some experiments have conclusively shown the stimulation of carbon assimilation under elevated CO₂ during drought or short-term water stress conditions because of a reduction in stomatal conductance which improved water use efficiency (Ghannoum *et al.*, 2000; Vu and Leon, 2009).

Sorghum and other C₄ plants have a higher optimum temperature for photosynthesis than C₃ plants, and Maiti (1996) published the mean optimum temperature ranges for sorghum as 21-35°C for germination; 26-34°C for vegetative growth and development; and 25-28°C for

reproductive growth. Attri and Rathore (2003) found that higher temperatures reduced yield by triggering a rapid accumulation of growing degree days which hastened growth and development of the crop and resulted in the reduction of pheno-phase duration. Others found that high temperatures decreased the rate of biomass accumulation, pollen viability, seed setting and duration of seed-filling (Schoper *et al.*, 1986; Fuhrer, 2003;), resulting in smaller seeds and lower seed weights (Chowdhury and Wardlaw, 1978; Kiniry and Musser, 1988; Abrol and Ingran, 1996). Physiologically, higher than optimum temperatures reduce the activity of Rubisco (the enzyme responsible for CO₂ assimilation in plants), its specificity for CO₂, and the solubility of CO₂ relative to O₂ (Jordan and Ogren, 1984; Brooks and Farquhar, 1985; Holiday *et al.*, 1992), thus resulting in a net loss of carbon assimilates.

In sorghum, drought stress at either pre-flowering or post-flowering stage can result in heavy yield loss. Traits such as greater leaf photosynthetic rates, greater canopy temperature depression, improved panicle exertion, and increased pollen viability have been cited as being associated with pre-flowering drought tolerance (Ayeneh *et al.*, 2002; Lawlor and Cornic, 2002). For tolerance to post-flowering drought, improved rooting depth, stay-green, longer seed filling duration, increased seed filling rate, and increased individual seed weight have been cited (Tuinstra *et al.*, 1997; Rajcan and Tollenaar, 1999; Borrell *et al.*, 2000; Hoad *et al.*, 2001; Sharp *et al.*, 2004; Harris *et al.*, 2007). Mild drought stress accelerated flowering of sorghum, while severe drought stress resulted in delayed flowering of sorghum (Seetharama *et al.*, 1984). Matthews *et al.* (1990) found that moisture stress delayed panicle initiation and suggested that if drought occurs before panicle initiation, sorghum plants tend to delay switching to the reproductive phase in order to wait for favorable weather conditions, but hastens maturity when drought stress occurs after panicle initiation.

1.3 Climate variability and sorghum production

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). But this has been increased by climate change to create challenges for farmers in the form of unpredictably variable onset of rains and length of growing seasons. Cooper *et al.* (2008) showed for Eastern and Southern Africa that variability of rainfall increases with decreasing amount of

rain. So, the most vulnerable farmers face the stiffest challenges posed by climate change and variability.

Sorghum panicles are affected by grain mold if flowering coincides with high atmospheric humidity (Ratnadass *et al.*, 2003). Birds damage sorghum panicles if the crop sets grain at a time wild flora and crops on neighboring cultivated plots have not set grain (Cochemé and Franquin, 1967; Curtis, 1968). To reduce bird damage and grain mold infection, farmers have to combine cultivars and sowing dates in such a manner that flowering occurs during the last 20 days of the rainy season, so that the grain filling process will not be perturbed (Kouressy *et al.*, 2008; Traoré *et al.*, 2000; Vaksman *et al.*, 1996) and the risk of terminal drought (detrimental to grain filling), due to flowering later than this time, is averted (Borrell *et al.*, 2000).

Sensitivity to photoperiod is a trait that effectively synchronizes the final developmental stages with the end of the rainy season. Photoperiod-sensitive varieties are, therefore, very important for African farmers (Soumaré *et al.*, 2008) who have to contend with the conditions mentioned above.

Accurate prediction of phenology is highly relevant for coping with such conditions. Under optimal moisture and fertility conditions, the phenology of day-neutral varieties can be easily predicted, because panicle initiation occurs after a constant thermal time, but is more complex for photoperiod-sensitive varieties in which day length and/or temperature modify the duration of the vegetative phase. For these cultivars, panicle initiation occurs when photoperiod drops below a cultivar-specific and age-dependent threshold (Folliard *et al.*, 2004). Jarvis *et al.* (2011) stated that the projected increase in climate variability will intensify the cycle of poverty, natural resource degradation, vulnerability and dependence on external assistance if effective interventions are not made.

1.4 Genotypic Adaptability and Stability

Adaptability of a genotype is conditioned by both major and minor genes. For example, some major genes for vernalization requirement, photoperiod insensitivity and semi-dwarfism have played major roles in adapting wheat and rice to new environments. Minor genes for adaptability have been discovered using quantitative traits locus (QTL) analysis. For example, QTLs conditioning both general adaptability and also specific adaptability to rain-fed conditions have

been found in wheat (Farshadfar and Sutka, 2003; Kato *et al.*, 2000). Separate Amplified fragment length polymorphism (AFLP) markers for grain yield, stability and adaptability were identified in spring barley by Kraakman *et al.*, in 2004. Traits that ensure phenotypic plasticity, diversity for adaptation within a genetically heterogeneous variety or plant stand, and direct conferment of tolerance or resistance to abiotic and biotic stresses, could help attain yield stability of sorghum in unpredictably variable environments (Hausmann *et al.*, 2012).

Natural factors such as geography, climate, season and relief as well as human factors such as agronomy determine environments (Dencic *et al.*, 2000; Farshadfar and Sutka, 2003; Chloupek *et al.*, 2004) and associated biotic and abiotic conditions. Matching phenology to given abiotic and biotic conditions is a prerequisite for good varietal adaptation within a given environment. That is particularly important in the context of climate change because the temperature increase is likely to modify the precocity of the varieties (Craufurd and Wheeler, 2009). Agricultural crops are considered to originate from nine homelands but became adapted to new environments as they advanced across the world (Chloupek and Hrstkova, 2005), and were exposed to selection pressures, which were absent from their origins. Human selection favored characteristics of low selective value in the wild and a dependence on man-made habitats (Harlan, 1992).

Modern plant breeding programs aim to develop genotypes with high and stable yields because yield stability has become more important for sustainable plant production. Farmers feel more secure with cultivars that have stable yields than with cultivars with high potential yield in favorable environments (Dawson *et al.*, 2007). Yield stability could either be static or dynamic (Becker and Léon, 1988). A genotype has static stability if its performance is constant across different environments and this is desired for qualitative traits, such as resistance to certain stress characters. A genotype is said to have dynamic stability if its performance at any given environment is near the expected yield potential of that environment. Dynamic stability is more appropriate for yield measures since static stability tends to favor low yielding genotypes (Becker and Léon, 1988). Genotypes with greater stability show weak GxE interactions (GEI). The aim of genotypic stability, therefore, is to minimize GEI.

Understanding and exploiting GEI is important for setting up new breeding programs. At both the species and variety levels, variations in adaptability to different environments have been observed (e.g. Dencic *et al.*, 2000; Banziger and Cooper, 2001). The ability to perform at

acceptable levels in a range of environments is general adaptability, while specific adaptability refers to an ability to perform well only in particular environments (Dencic *et al.*, 2000; Chloupek *et al.*, 2003; Farshadfar and Sutka, 2003).

1.5 Adaptability Traits of Sorghum

Crop cultivars targeted at adaptation to climate change and variability can be developed through direct selection for performance in the target stress environments or indirect selection through specific morphological, phenological or physiological characteristics. However, the use of indirect selection should involve traits that are easy to identify, cheap and fast to measure and / or have a strong genetic correlation with yield performance under the target condition (Falconer, 1989). Combining multi-locations, multi-years, and staggered sowing dates within a year can be used to create an array of environments for testing and / or selecting cultivars for adaptation to each of the environments.

Photoperiod sensitivity is among the most important escape traits for a multitude of abiotic and biotic stresses, as it allows the plant to complete its reproductive stage under environmentally optimal conditions (Dingkuhn and Asch, 1999; Dingkuhn *et al.*, 2007; Kouressy *et al.*, 2007a). For a long time, photoperiod sensitivity was believed to be a genetic constant that needed to be broken via breeding to better fit genotypes to the requirements of modern agriculture (Khush, 1977). A number of authors have shown that photoperiod sensitivity also depends on environmental factors, such as water availability and radiation (Shresta, 2007; Dingkuhn and Asch, 1999). Photoperiod sensitivity allows cultivars sown on different dates to mature at the same time, and could be used indirectly for selecting cultivars targeted at situations where the onset of the cropping season requires the use of varied sowing dates (Curtis, 1968). Flowering patterns of a single early sowing date can be used to indirectly measure photoperiod sensitivity because a strong relationship has been found between later maturity and photoperiod sensitivity in sorghum (Clerget *et al.*, 2007). Haussmann *et al.* (2012), have presented a list of potential traits for adaptation to climate change to include the following: photoperiod sensitivity for matching vegetative the crop cycle to available growing period despite variable sowing dates and to reduce risks of biotic (damage by birds, grain moulds) and abiotic (terminal drought) stress because of variable sowing dates; plastic tillering for spreading flowering/maturity period, reducing exposure to severe stress at a single point in time and inherent capacity to respond to

improved conditions; very early maturity for completion of grain filling in more predictably short growing period; flood tolerance for plant survival under temporary flooding. The authors also tagged phosphorus efficiency, stay green, drought-induced senescence, and root architecture as traits that still need to be investigated for their usefulness to sorghum cultivars cultivated in Africa.

The highly variable sowing dates, due in part to erratic onset of the rainy season, present great challenges to farmers who generally want their grains to mature during a more fixed calendar window to ensure successful grain filling and pest avoidance (Niangado, 2001), as well as minimal loss of quantity and quality of grain to bird damage and grain mold complex.

The duration of a crop is one other trait that can influence its adaptability to a given environment. The time a crop takes to flower influences its duration, while the transition of plant growth from the vegetative to the reproductive stage is the primary determinant of flowering time of determinate crops such as sorghum. Sorghum as a short-day plant will, therefore, initiate panicles when the appropriate day-length which serves as a trigger is sensed. Therefore, under conditions of climate change, sensitivity to photoperiod will be a useful trait for adapting flowering time to temperature and water requirements of the crop (Vaksmann *et al.*, 1996), since it will allow batches of sorghum crops sown at different times to initiate panicles at almost the same time, thus widening the window for sowing. Thus, photoperiod-sensitive flowering responses of sorghum in West and Central Africa (WCA) enhance adaptation by enabling more or less fixed maturity dates despite variable sowing dates (Vaksmann *et al.*, 1996; Haussmann *et al.*, 2007; Clerget *et al.*, 2008).

A better understanding of the mechanisms of coping with current climate variability is not only essential but is a prerequisite for adaptation to future climate change (Cooper *et al.*, 2008). Climatologists, breeders, and agronomists need tools to translate variable climatic conditions into probable crop performance, and to identify suitable genotypic characteristics that can enhance adaptation to the different agro-ecological zones. Crop adaptation strategies such as the introduction of new crop varieties, adjustment of planting dates to fit the new cropping calendars, and development of appropriate component technologies are required for coping with the changing climate. However, significant gaps in knowledge on how the performance of specific crop plants respond to latitude, shifting planting dates and their complex interactions exist and need to be filled.

1.6 Research hypothesis

Rainfed sorghum is influenced to a large extent by spatiotemporal variability in climatic conditions determined mostly by the availability of water and nutrients, and the length of the growing season. Water is a major limiting factor to rainfed sorghum production because sorghum is cultivated in arid to semi-arid areas with very high production potentials due to the lack of cloud cover and the consequent high solar radiation input. Climate change influences the onset and cessation of rainfall which determines the length of the growing season and the type of cultivar to grow for any given year.

The hypothesis of this study is that phenology, yield, and yield stability of grain sorghum are influenced by the effect of latitude and staggered monthly sowing dates since the microclimate at different development phases of genotypes will depend on the environments. Differences in latitude will differentially influence the phenology of sorghum cultivars because the amplitude of photoperiod increases with latitude.

1.7 Research objectives

The main objective of this study was to investigate genotypic responses of tropical grain sorghum to different environments with the sole aim of combining crop responses with models to facilitate the evaluation of adaptation mechanisms of genotypes under climate change scenarios. This should make it possible to propose crop ideotypes that will enhance the resilience of production systems via appropriate adaptation to specific changes in the environment, and thus contribute to the development of tools that can be used for tactical and strategic decisions to ensure adaptation of agriculture to the changing climates.

Field trials that combine the assessment of phenology, yield, and yield stability as well as how grain yield relates with other plant characters of rainfed sorghum along a latitudinal gradient have not been given much attention so far. This study was initiated based on the following specific objectives:

- to determine the attainable yield and yield stability of various grain sorghum genotypes across diverse climate scenarios in the arid and semi-arid Tropics.

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- to measure the effect of latitude on the development of selected sorghum varieties in order to determine the precision with which available models predict the phenological responses of short-day sorghum varieties to photo-thermal regimes at different latitudes.
 - to evaluate the effect of genotype by environment interactions on plant characters in order to identify specific genotypic characters that significantly contribute to stabilizing grain yield across locations along a latitude gradient.

1.8 References

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

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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 be 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) while 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; Vaksman *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 masl; 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,

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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

Environment	Code	Date	P_{crit}^d	P_{crit}	DAS ^e	E_{mean}	Rank	Rain	T_{max}	T_{min}	IPCA1	Rank	AMMI Genotype ^b Selections			
													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) while 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 Sahelian 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 m², 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 m² 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:

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

where, X_{ijkl} = value of treatment in i th Year, j th Location, k th Sowing and l th Genotype; μ = general mean; Y_i = i th Year; L_j = j th Location; S_k = k th Sowing; G_l = l th Genotype; $(YL)_{ij}, \dots$ = 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.

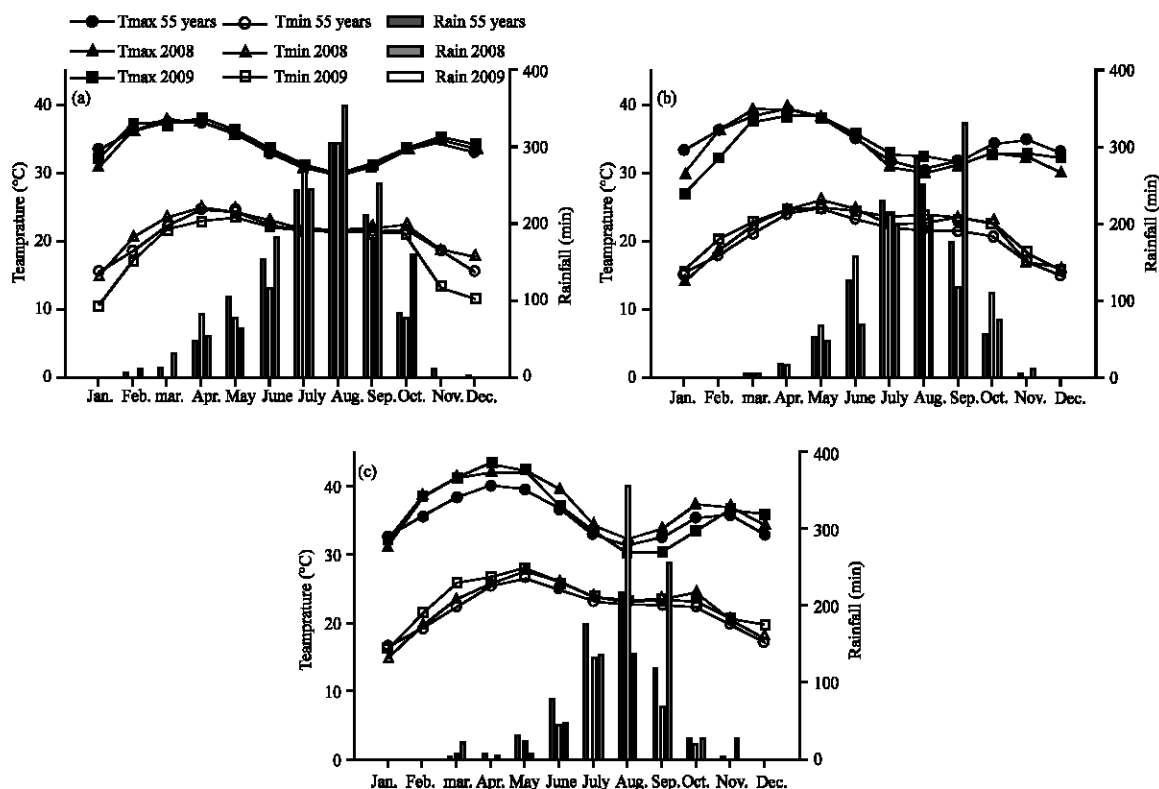


Fig. 1(a-b): Trends of temperature and rainfall for the long-term (55 years) and the growing seasons of 2008 and 2009; (a) Guinea savannah (b) Sudan savannah and (c) Sahel

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%) ^j			
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 while 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

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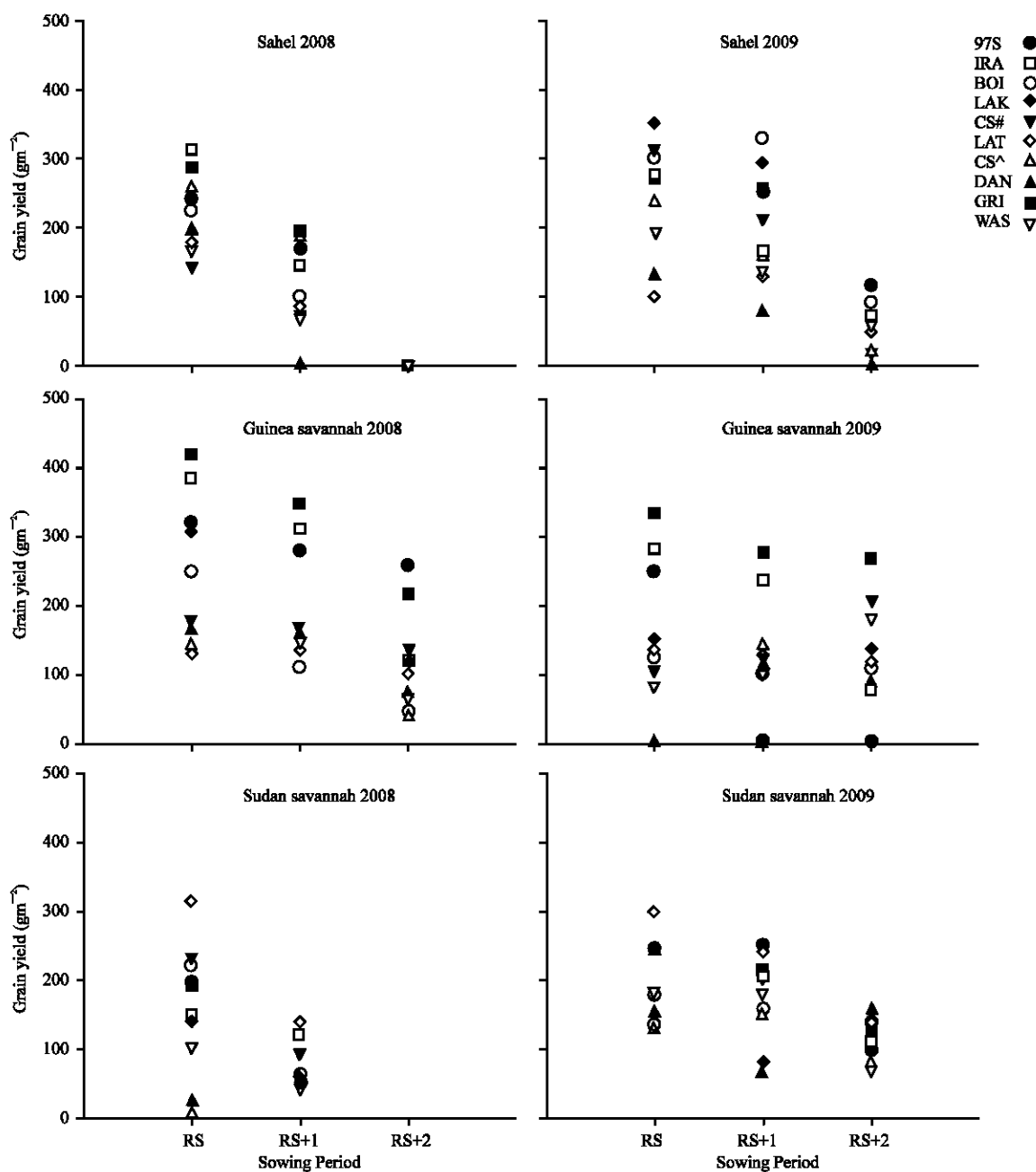


Fig. 2: Grain yield of sorghum, as influenced by the interaction of genotype, date of sowing and location in 2008 and 2009

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).

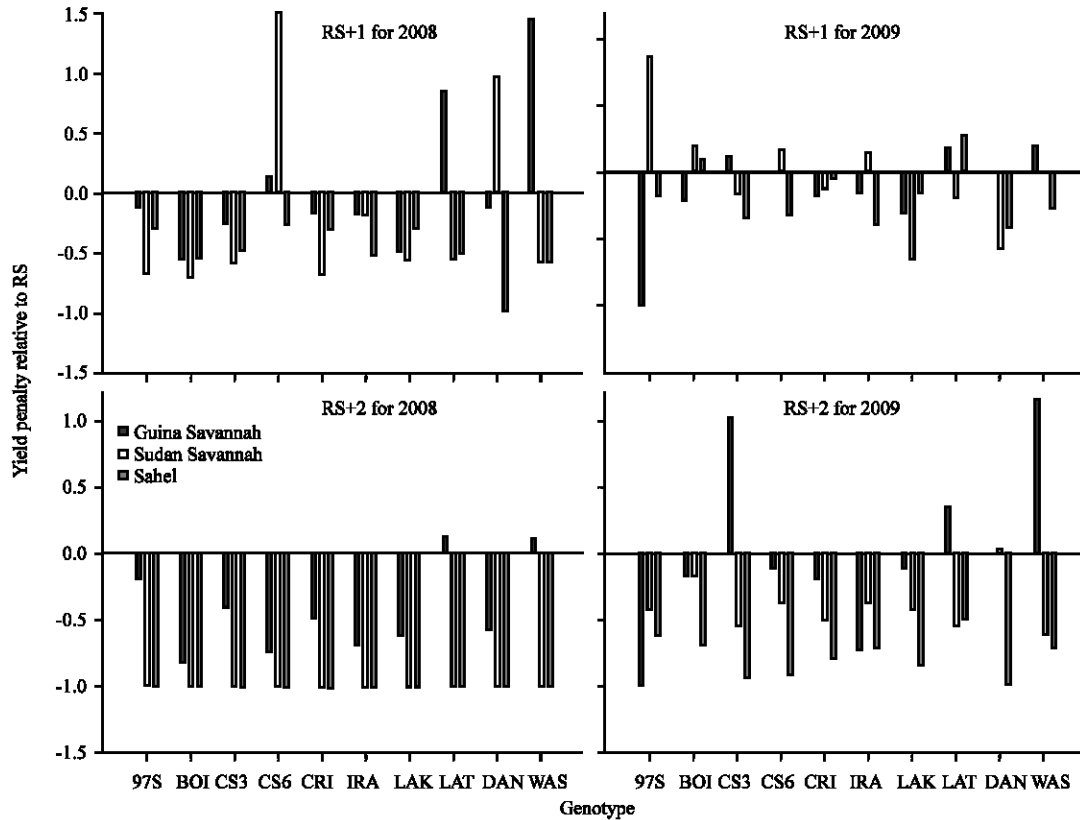


Fig. 3: Yield penalties for delayed sowing relative to RS as influenced by genotypes sown at Farako, Sotuba and Cinzana in Mali during 2008 and 2009 seasons

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;

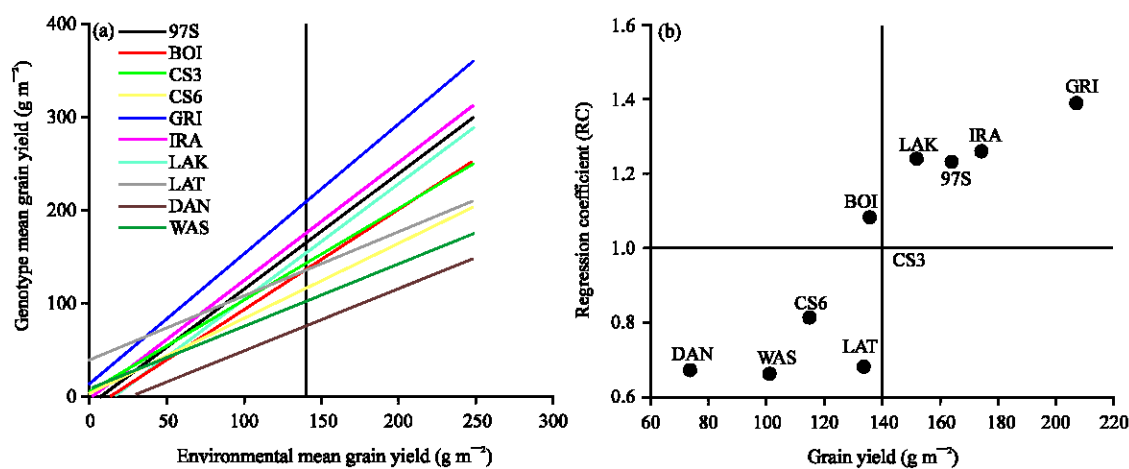


Fig. 4(a-b): Plots of the regression lines for mean grain yields of cultivars on environment mean grain yields (a) and its relationship to cultivar adaptation (regression coefficients) and (b) according to Finlay and Wilkinson (1963)

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 while *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 while 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 indices¹ 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, while *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, while 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, while *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), while 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 388* and *Boiguel* while 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								
Sup	0.03 ^{ns}							
MR	-0.03 ^{ns}	0.99 ^{**}						
MAD	-0.49 [*]	0.39 ^{ns}	0.36 ^{ns}					
VAR	-0.32 ^{ns}	0.44 [*]	0.39 ^{ns}	0.95 ^{**}				
IPCA1	0.52 [*]	-0.42 ^{ns}	-0.52 [*]	-0.22 ^{ns}	-0.14 ^{ns}			
ASV	-0.43 [*]	0.52 [*]	0.58 [*]	0.15 ^{ns}	0.14 ^{ns}	0.90 ^{**}		
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, while 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 coping 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

Envt ^b	Genotype ^a									
	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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3 Latitude and Date of Sowing Influences Phenology of Photoperiod-Sensitive Sorghums

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MISCELLANEOUS

Latitude and Date of Sowing Influences Phenology of Photoperiod-Sensitive SorghumsA. L. Abdulai^{1,2}, M. Kouressy³, M. Vaksman⁴, F. Asch¹, M. Giese¹ & B. Holger¹¹ University of Hohenheim Stuttgart, Germany² CSIR-SARI Ghana³ IER Bamako, Mali⁴ CIRAD Bamako, Mali**Keywords**

latitude; phenology; photoperiodism; sorghum; sowing date

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Abstract

Matching phenology with prevalent abiotic and biotic conditions is a prerequisite for varietal adaptation to the environment. That is particularly important in the context of climate change because an increase in temperature is most likely to modify the precocity of the varieties. The forecast of flowering time in photoperiod-sensitive sorghum is complex as flowering depends on temperature, day length and soil fertility. The objectives of this work were to quantify effects of latitude on the development of selected sorghum varieties and to verify the precision of our models to predict sorghum maturity. A field experiment at three locations along the latitudinal gradient in Mali with staggered sowing dates (SDs) was conducted. Seven sorghum cultivars covering a wide range of the diversity of cultivated sorghums in Mali were sown on the 10 of June, July and August in 2009 and 2010. Duration of the vegetative phase strongly decreased with latitude. Although the maximum day length difference between locations was < 8 min, for some varieties, we observed a reduction in crop duration of up to 3 weeks. Some varieties were photoperiod insensitive at one location but became photoperiod sensitive at another. The effect of latitude on the phenology is underestimated by the existing models. To determine the optimal areas for the varieties in West Africa and to forecast the effects of climate change, a correction of the simulation coefficients taking account of latitude is proposed. But, in the end, it will be necessary to develop a new model that will be able to predict the effects of both SD and latitude. More research is needed to understand physiological response mechanisms of the pronounced latitude effects on sorghum phenology.

Introduction

Matching phenology to given abiotic and biotic conditions is a prerequisite for good varietal adaptation within a given environment. That is particularly important in the context of climate change because the temperature increase is likely to modify the precocity of the varieties (Craufurd and Wheeler 2009).

In West Africa, favourable conditions for sorghum cultivation usually extend from May to November and most of the plant growth of photoperiod-sensitive sorghum, thus, takes place under decreasing day length with the cycle duration of photoperiod-sensitive varieties shortening when sowing is delayed. Sorghum panicles are extremely

susceptible to grain mold when exposed to excess moisture (occurring when flowering occurs too early in the season; Ratnadass et al. 2003) and bird damage (occurring predominantly when the crop's grain set is out of phase with that of the neighbouring cultivated and wild flora; Andrews 1973, Cochemé and Franquin 1967, Curtis 1968). It was thus recommended that choice of cultivar and sowing date (SD) should be combined in such a way that flowering occurs during the last 20 days of the rainy season to ensure an unperturbed grain filling process (Kouressy et al. 2008a, b, Traoré et al. 2000, Vaksman et al. 1996). Flowering at a later date incurs risks of terminal drought that is detrimental to grain filling (Borrell et al. 2000). Photoperiod-sensitive varieties that are very important for African farmers

(Soumaré et al. 2008) can cope with variation in SD, as triggering of flowering by day length effectively serves to synchronize final developmental stages with the end of the rainy season.

Farmers choose which crop varieties to grow where, and in what proportions, allocating them to a range of biophysical and social environments over both space and time. Farmers' preference for varieties depends mainly on their knowledge of the crop's phenology in relation to the local characteristics of the wet season (Lacy et al. 2006). Such knowledge and the requisite skills are often acquired through ancestral transmission and are not always easy to express scientifically (Sissoko et al. 2008). Climatologists, breeders and agronomists need tools to translate variable climatic conditions into probable crop performance and to identify suitable genotypic characteristics for adapting to the different agro-ecological zones. Prediction of phenology is highly relevant for the reasons mentioned previously. Under optimal moisture and fertility conditions, the phenology of day-neutral varieties can be easily predicted, because panicle initiation (PI) occurs after a constant thermal time (TT), but is more complex for photoperiod-sensitive varieties in which day length and/or temperature modify the duration of the vegetative phase. For these cultivars, PI occurs when photoperiod drops below a cultivar-specific and age-dependent threshold (Folliard et al. 2004).

Model-assisted analyses of agricultural production systems are required for upscaling from plot and field data to regional and larger scales. The impatience model integrated into the simulation software SARRA-H (Dingkuhn et al. 2008) takes photoperiod sensitivity into account to delineate SD effects on phenology. Coupling this model with a climatic database within a geographical information system could allow delineation of suitable areas for sorghum varieties in West Africa and the forecast of these under various climate change scenarios.

Multi-location field trials (e.g. along latitudinal or altitudinal gradients) in combination with staggered SDs can be employed for creating a range of environments allowing for the assessment of varietal differences in phenology. However, depending on the climatic variability along the gradient or between SDs, effects of photoperiod can be masked by interactions with temperature (Bonhomme et al. 1991) as well as soil fertility levels.

Relations between photothermal environments and phenology have been studied by some authors to improve understanding of the phenological basis of adaptation to environment in sorghum (Craufurd et al. 1999, Kouressy et al. 2008b), culminating in the subsequent use of models to successfully simulate the effects of temperature and/or photoperiod on the phenology of sorghum (Folliard et al. 2004, Dingkuhn et al. 2008, Kouressy et al. 2008a). The impatience version of SARRA-H has been reported as the

most appropriate for short-day varieties (Kouressy et al. 2008a). The extent to which latitude modifies or influences photothermal effects on phenology of photoperiod-sensitive sorghum varieties as well as the precision with which available simulation models predicts the phenology of photoperiod-sensitive varieties under different latitudes have not been investigated.

The objectives of this work were to (i) measure the effect of latitude on the development of selected sorghum varieties and to (ii) determine the precision with which the SARRA-H model is able to predict the phenological responses of short-day sorghum varieties to photothermal regimes at different latitudes.

Materials and Methods

Three sites in Mali representative of different agro-climatic zones were used: Cinzana station (13°15'N, 5°58'E, 265 m; Sahel), Sotuba station (12°39'N, 7°56'E, 381 m, Sudano-sahelian savannah) and Farako station (11°13'N, 5°29'E, 375 m, Sudano-Guinean savannah). All sites have a mono-modal pattern of rainfall with a distinct rainy season in summer (Fig. 1), accounting on average for 690 mm at Cinzana, 890 mm at Sotuba and 1060 mm at Farako and mean annual maximal (minimal) daily temperatures of 35.6 °C (19.3 °C) at Cinzana, 34.7 °C (20.6 °C) at Sotuba and 33.7 °C (21.0 °C) at Farako. Maximum day length is 12:47' at Cinzana, 12:45' at Sotuba and 12:39' at Farako (Fig. 2), increasing from South to North by 8 min. Details on the soil and patterns of rainfall at the locations are reported in an earlier paper (Abdulai et al. 2012).

Seven sorghum cultivars (*Sorghum bicolor* (L) [Moench]) were selected to represent a wide diversity of the varieties cultivated in West Africa. They are composed of both landraces and improved varieties (Table 1). Trials comprising three SDs were established on each of the three research stations during the rainy seasons of 2009 and 2010. At each site, a split-plot arrangement was fitted into a randomized

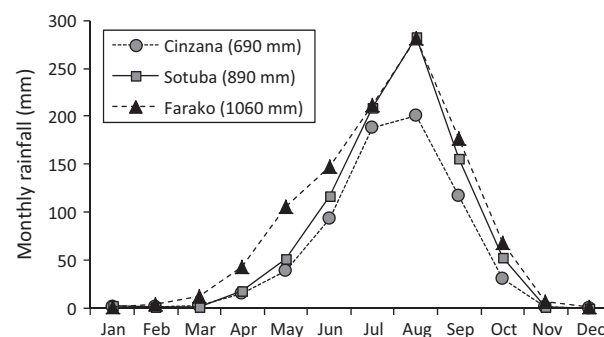


Fig. 1 Monthly rainfall at Cinzana, Sotuba and Farako (1971–2000 period).

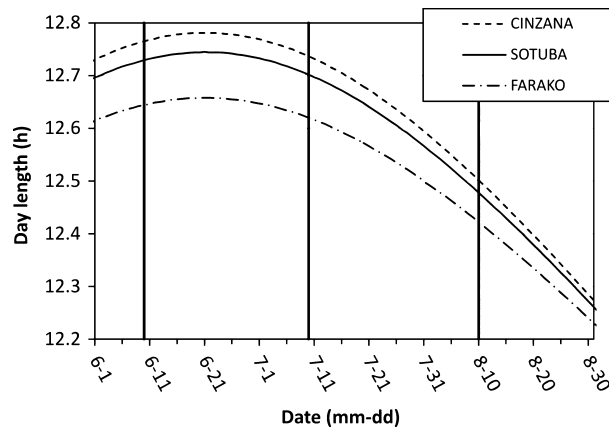


Fig. 2 Comparison of astronomical day length around the summer solstice for the three studied sites. The three sowing dates are indicated by a vertical line.

complete block design (RCBD) with two replications. The three dates of sowing (June 10; July 10 and August 10) were the main plot treatments and the seven varieties formed the subplots. Each experimental unit comprised 12 plants sown in two ridges of 3 m length, with a spacing of 0.5 m between plants and 0.75 m between ridges. To ensure non-limiting conditions, supplemental irrigation (provided from sowing until the moment when the rains became sufficiently stable and regular) and chemical fertilizers (76 kg N, 30 kg P and 30 kg K per hectare) were applied at all the sites. Flooding was not observed in any of the sites because the experimental plots were well drained. No phyto-pathological problems were encountered before flowering.

Eight plants on each plot were studied by recording date of flag leaf appearance and total leaf number. A leaf was considered fully expanded when its' ligule became visible above the enclosing sheath of the previous leaf. Date of PI was recorded on the sorghum variety Keninkeni which was sown in additional plots. Three plants were harvested two times a week, dissected and panicle development observed under a light microscope. PI was defined as the time when the panicle had attained a length of 2 mm (Borrell et al. 2000). The average standard error of time to flowering for

the 2009 and 2010 was < 2 days. Therefore, for each variety and date of sowing combination, phenology was calculated using averages of the 2-year data.

For 'short day' plants such as sorghum, the most visible expression of photoperiodism is the reduction in the vegetative phase when sowing is delayed. This reduction between two sowings is usually used to compare the varieties (Clerget et al. 2007). The mean coefficient of photoperiodism, K_p , was calculated according to Clerget et al. (2007) by dividing the difference in days to flag leaf emergence (FL_i) of the first and third SD by the number of days between these two SDs as presented below:

$$K_p = \frac{FL_1 - FL_3}{SD_3 - SD_1}$$

K_p varies between 0 and 1, and K_p is equal to 0 if FL_i is not influenced by SD (photoperiod-insensitive varieties) or close to 1 when shortening of the vegetative growth phase compensates exactly for the difference of SDs (photoperiod-sensitive varieties).

For the calculation of TT, the broken-stick model was implemented (Dingkuhn and Miezán 1995) using hourly temperature values estimated from daily, observed minimal and maximal temperatures. Cardinal temperatures were 11 °C for base temperature (T_b) (Clerget et al. 2004, Lafarge et al. 2002), 34.8 °C for optimum temperature (T_{opt}) and 44 °C for maximum temperature (T_{max}) (Ritchie and Alagarwamy 1989). The resulting TT per time step (day) served, on an additive basis, to calculate the progress of developmental processes.

$$\delta TT = 0 \quad T < T_b \text{ or } T > T_{max}$$

$$\delta TT = T - T_b \quad T_b < T < T_{opt}$$

$$\delta TT = (T_{opt} - T_b) \left[1 - \frac{(T - T_{opt})}{(T_{max} - T_{opt})} \right] \quad T_{opt} < T < T_{max}$$

The crop model used in this study is SARRA-H (<http://ecotop.cirad.fr/sommaire.php3>). This model is particularly suited for the analysis of climate impacts on cereal growth and yield in dry, tropical environments (Sultan

Table 1 Description of the varieties studied

Name	Improved/Landrace	Botanical type	Adaptation	Maturity type	Height
Boiguel	Malian landrace	Durra	Sahelian zone	Early (100 days)	Tall
CSM 63E	Improved Malian landrace	Guinea	Sahelian zone	Early (90 days)	Tall
CSM 388	Malian Landrace	Guinea	Sudano-Sahelian zone	Intermediate (120 days)	Tall
Dancouma	Malian Landrace	Guinea	Sudano-Guinean zone	Late (140 days)	Tall
Grinkan	Improved variety	Composite	Not yet determined	Intermediate (110 days)	Dwarf
Keninkeni	Improved variety	Composite	Not yet determined	Intermediate (110 days)	Dwarf
IRAT 204	Improved variety	Caudatum	Supplied by CIRAD	Early (90 days)	Dwarf

et al. 2005). The version used here was equipped with the phenological sub-model 'Impatience' specifically developed to simulate effects of temperature and day length on sorghum crop duration (Dingkuhn et al. 2008).

The originality of the Impatience model resides in the calculation of the photoperiod-sensitive phase (PSP). The underlying hypothesis is that the short-day requirements for floral induction diminish as the PSP or wait state for the inducing signal advances. In other words, older plants are less demanding of short days to flower. The TT history (degree days elapsed since end of basic vegetative phase; BVP) and the current astronomic day length (P_i) are combined in a single state variable. For PI to occur, this state variable has to become equal or smaller than a genotypic threshold parameter (P_{sens}). Panicle initiation occurs when the following condition is met:

$$\left(\frac{1000}{\sum_{i=BVP} dtti} \right)^{P_{exp}} \frac{P_i - 11}{13.5 - 11} \leq P_{sens}$$

Where P_{exp} is a coefficient that provides for a curvilinear effect of $\sum dtti$, $dtti$ is the daily TT, P_i is the current photoperiod, P_{sens} is a genotypic parameter, while 13.5 and 11 are the upper limit and critical photoperiods, respectively. P_{exp} generally is smaller than 1, typically between 0.05 and 0.2 (Kouressy et al. 2008a). The model is most sensitive to variation of P_{sens} , which may assume values around 0.4 in highly photoperiod-sensitive genotypes and >1 in insensitive genotypes. Genotype-specific coefficients were calculated from results of the SD trials. BVP was estimated from the shortest duration of the vegetative phase observed on each variety. Genotype-specific values of P_{sens} and P_{exp} were determined using all possible combinations of P_{sens} and P_{exp} . For every pair of values, date of PI was simulated for the three planting dates of each site and compared with observations. The set of values that minimized the root mean square deviation, RMSD, was selected as the best estimate for the parameters (Kobayashi and Salam 2000). RMSD is defined here as follows:

$$RMSD = \sqrt{\frac{\sum (EFL_{calc} - EFL_{obs})^2}{n}}$$

where n is the number of SDs, EFL the number of days from emergence to flag leaf and the subscripts calc and obs stand for calculated and observed, respectively. Although the model operates with four parameters, only one (P_{sens}) or two (P_{sens} and P_{exp}) were adjusted to fit the model to observations (Dingkuhn et al. 2008). To compare the adjustment of the model on the three sites, P_{sens} and P_{exp}

were fitted at Sotuba station (the mid-latitude location). We then regarded P_{exp} as fixed for each variety and adjusted only P_{sens} for the two other sites.

Results and Discussion

Panicle initiation and total number of leaves

The TT (in GDD) from emergence to panicle initiation (EPI) and total number of leaves (TLN) were substantially influenced by latitude and date of sowing. The TT for EPI generally reduced with delayed sowing and increased with latitude, except for the day-neutral cultivar 'IRAT 204' which recorded increases in TT for EPI with delayed sowing from July to August at Cinzana and Farako and from June to July at Sotuba. For a given date of sowing, TT s for EPI increased with latitude except for IRAT 204 that recorded more TT for EPI at Sotuba the mid-latitude site than at Cinzana the northern site (Fig. 3). A similar trend, as for TT for EPI, was observed for TLN.

The phenotyping procedure used in this study is economical because it requires only one observation (date of flag leaf ligulation for this study) on three specific SDs, backed by daily atmospheric temperature records. It is also based on some simplifications that have the potential of masking component traits of phenology that are not considered by the model. For example, it does not distinguish PSP from the juvenile phase (because the latter cannot be measured in the field) and estimates PSP on the assumption that the thermal duration from PI to flag leaf ligulation is constant (Dingkuhn et al. 2008).

In this study, it was found that duration of PI to flag leaf appearance of 22 days was most appropriate. This value is slightly higher than the 18 days used in SARRA-H (Kouressy et al. 2008a) but coherent with the formula presented by Folliard et al. (2004). The date of PI can therefore be estimated by simply deducting 22 days from the date on which the ligule on the flag leaf has appeared.

Effect of latitude and sowing dates on precocity of the varieties

Latitude and SDs had substantial effects on the duration of the vegetative phase expressed in days (EPI) as well as the TLN produced (Table 2). Except for the day-neutral variety (IRAT 204), duration of the vegetative phase decreased with delayed sowing, indicating that they are photoperiod-sensitive varieties. For the same date of sowing, the duration of the vegetative period increases with latitude, with the effects being most pronounced between the most northern and southern sites. Latitude effects on phenology became smaller at later SDs. In sharp contrast to other varieties, IRAT 204 had a longer duration of vegetative phase at

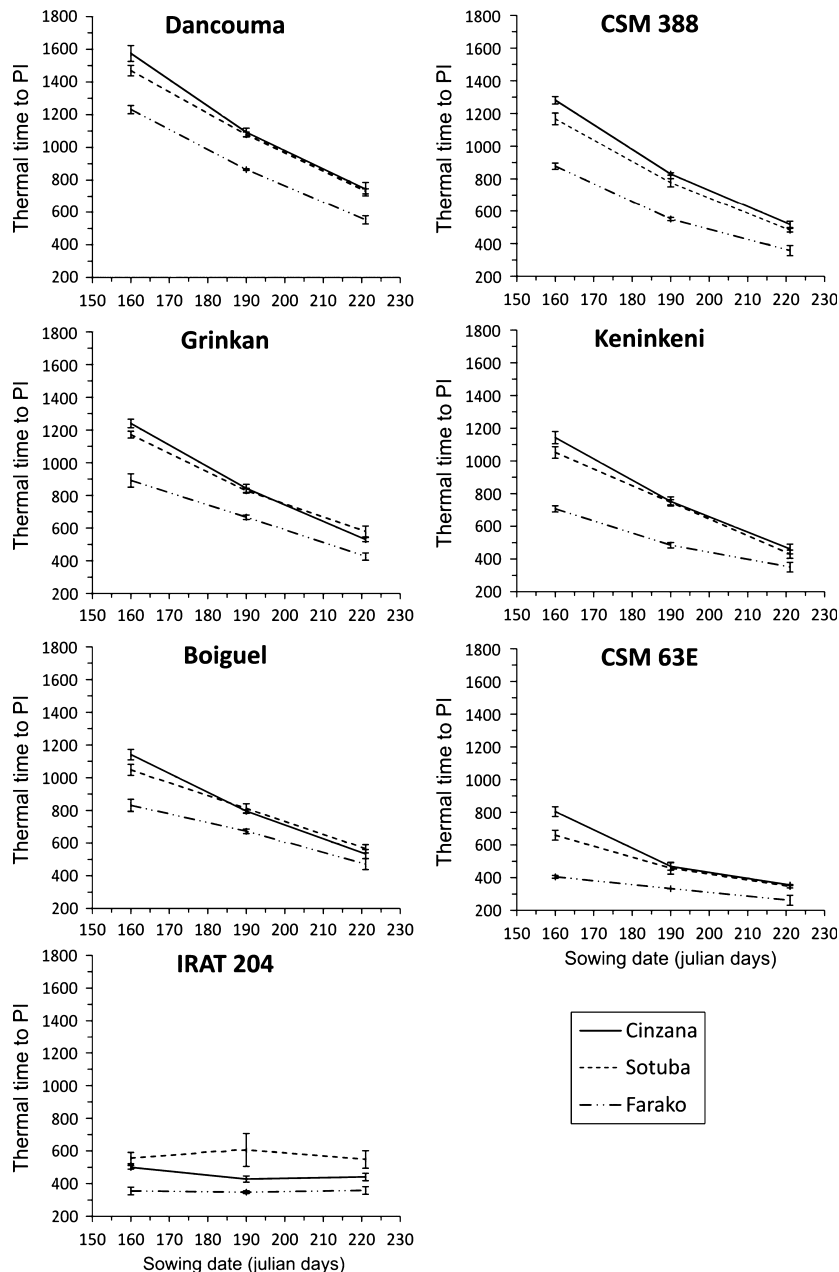


Fig. 3 Effect of sowing date on thermal time to panicle initiation (PI) in seven sorghum cultivars evaluated at three locations (Cinzana, Sotuba and Farako) along a North–South latitude gradient in Mali. Error bars represent the standard error of the means calculated for the 2 years of experimentation.

Sotuba, the mid-latitude location compared with Cinzana the northern site (Table 2). For the short-day varieties, the coefficient of photoperiodism K_p increased with latitude (Fig. 4). Taking the June sowings at Sotuba and Farako as an example (Table 2), the reduction in the vegetative phase does not seem to depend only on the degree of photoperiodism as this phase is reduced more for the slightly photoperiodic variety CSM 63E (13 days) than for the highly

photoperiodic variety *Dancouma* (7 days). Variety CSM 63E, for example, appears photoperiod insensitive at Farako ($K_p = 0.1$) but fairly sensitive to photoperiod at Cinzana ($K_p = 0.4$). Total leaf number decreased almost linearly when sowing was delayed from June to August (Table 2). This reduction was more important for the June sowing when the photoperiod difference between the sites was highest (Table 2).

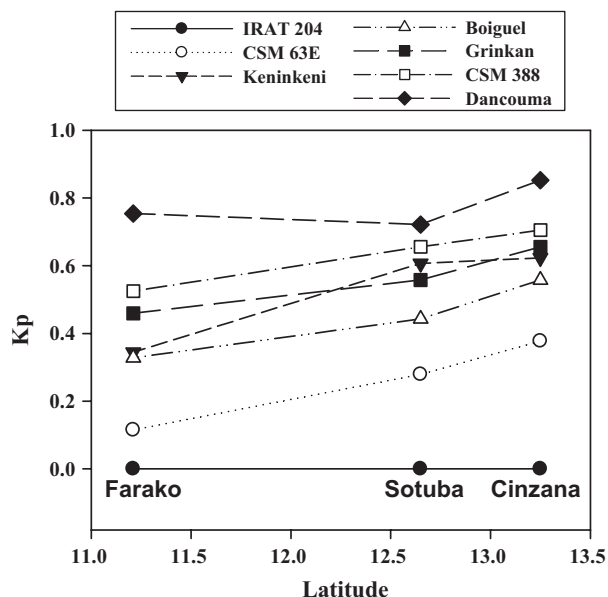


Fig. 4 Latitude effect on the photoperiodism coefficient (Kp) of seven sorghum cultivars evaluated at three locations (Cinzana, Sotuba and Farako) along a North–South latitude gradient in Mali.

There are not many crop models developed for sorghum cultivars adapted to the conditions found in the semi-arid

tropics where low-input agricultural production systems are found. The few models that exist for these scenarios have focused mainly on depicting phenology based on photothermal responses of genotypes (Folliard et al. 2004, Dingkuhn et al. 2008, Kouressy et al. 2008a). To the best of our knowledge, no model has considered latitude effects in the simulation of phenology of photoperiod-sensitive sorghums so far. The current study demonstrates that it is possible, when working on photoperiod-sensitive sorghum genotypes, to accurately estimate genotypic coefficients for a location by applying latitude correction to the coefficients from another location. This approach presents or reveals one major means by which laborious experiments and associated high costs could be minimized while scouting for appropriate cultivars for specific locations, especially also in view of climate change in West Africa.

'Impatience' model adjustment

To determine the accuracy with which the model predicts parameters for a location, using those determined for another location and adjusting for latitude, the genetic coefficients of the Impatience model were calculated and used to compare observed and simulated days from emergence to flag leaf ligulation for the three SDs. To carry out this adjustment, we eliminated IRAT 204 from calculations because the Impatience model is unable to perform

Table 2 Duration from emergence to panicle initiation (EPI; expressed in days) and total leaf number of seven sorghum varieties evaluated at three sowing dates at three Malian locations with different latitude (Cinzana, Sotuba and Farako), averaged across two test years and two replications. The \pm symbol precedes the standard error of measurement

Varieties	Sowing	Days to panicle initiation			Total leaf number		
		Cinzana	Sotuba	Farako	Cinzana	Sotuba	Farako
Boiguel	June 10	70 \pm 2.1	65 \pm 1.3	56 \pm 2.1	38.8	36.3	27.8
	July 10	52 \pm 0.3	53 \pm 2.8	49 \pm 1.3	32.3	27	24.5
	August 10	36 \pm 1.5	38 \pm 1.3	36 \pm 2.5	21	23.5	18
CSM 388	June 10	79 \pm 1.9	73 \pm 0.3	60 \pm 0.9	34.3	32.8	24.5
	July 10	53 \pm 0.9	50 \pm 1.2	40 \pm 0.6	28	23.8	19.8
	August 10	36 \pm 1.2	33 \pm 2.0	28 \pm 2.4	18.5	18	15
CSM 63E	June 10	49 \pm 1.3	41 \pm 1.5	28 \pm 0.7	26	23.3	17.5
	July 10	31 \pm 1.0	30 \pm 2.4	25 \pm 0.5	19.8	17.3	14.5
	August 10	26 \pm 0.5	24 \pm 1.5	21 \pm 2.2	15.5	15.8	12
Grinkan	June 10	76 \pm 1.1	73 \pm 0.4	61 \pm 2.4	36.5	34.5	26.5
	July 10	55 \pm 0.9	54 \pm 1.1	47 \pm 0.3	30.3	25.8	22.3
	August 10	36 \pm 1.1	39 \pm 3.1	33 \pm 1.6	20	19.3	15.5
IRAT 204	June 10	31 \pm 0.5	35 \pm 1.8	24 \pm 1.2	19.8	21	17.3
	July 10	28 \pm 0.9	40 \pm 6.1	26 \pm 0.3	17.8	19.5	15
	August 10	31 \pm 1.9	35 \pm 3.0	28 \pm 1.7	17.3	17.8	14.3
Keninkeni	June 10	70 \pm 2.0	66 \pm 1.2	49 \pm 1.0	33	31.8	22
	July 10	48 \pm 1.1	48 \pm 1.7	35 \pm 1.2	26.8	22.5	18
	August 10	32 \pm 2.3	29 \pm 2.5	28 \pm 2.6	17.3	16.3	13.3
Dancouma	June 10	98 \pm 2.1	92 \pm 1.0	85 \pm 1.2	39.5	37	32.5
	July 10	71 \pm 0.8	71 \pm 1.8	62 \pm 0.8	32	28.8	25
	August 10	46 \pm 1.7	48 \pm 1.8	39 \pm 0.3	23	22.5	18.3

adjustments on strictly day-neutral varieties. We obtained a set of 12 data points (six varieties at two sites) which makes it possible to establish a regression equation for correcting Psens by taking latitude into account. By comparing the coefficients established at Cinzana and Farako with those established at Sotuba, we obtained the following regression equation for correcting Psens via adjustment for latitude:

$$Psens = 2.022.PsensSot - 0.063 - .PsensSot.Lat R^2 = 0.987,$$

Where Psens is the photoperiod sensitivity, PsensSot is the value of Psens obtained at Sotuba and PsensSot.Lat expresses the interaction between photoperiod sensitivity and latitude.

Validation of the model with data collected at Cinzana and Farako (Fig. 5a) indicates a high predictive power of the model with a RMSD of 3.11 days when site-specific parameters were used. Contrarily, if coefficients determined at Sotuba were directly used to forecast the phenology at the two other sites (Fig. 5b), the RMSD becomes twice as large (6.8 days). However, the application of latitude correction to the coefficients of Sotuba improved the performance of the model (Fig. 5c). The RMSD of 2.8 days was

similar to that obtained using coefficients from site-specific data for each location (Fig. 5a). It must be kept in mind that experimental data were obtained between latitudes 10 and 14°N, and it remains open if extrapolation to other latitudes is justified.

The model parameters for data from Sotuba, when adjusted for latitude, always over-estimated the duration of the vegetative period at Farako.

For example, for the June sowing (EFL1), EFL observed for the cultivar Keninkeni was 92 days at Cinzana and 71 days at Farako (Fig. 5). The reduction in the vegetative phase between these two sites is thus 21 days. The model, based on the established coefficients at Sotuba, simulated EFLs of 90 and 84 days for these same scenarios. The predicted reduction was 6 days only. In this case, the model predicts less than a third of the observed reduction in the duration of vegetative phase owing to the latitude. This indicates that the genetic coefficients of the Impatience model were not stable across latitude. We also tried adjustments with other models like CERES-sorghum (Alagarswamy and Ritchie 1991) and DSSAT (Folliard et al. 2004), but none of them improved the forecast of phenology.

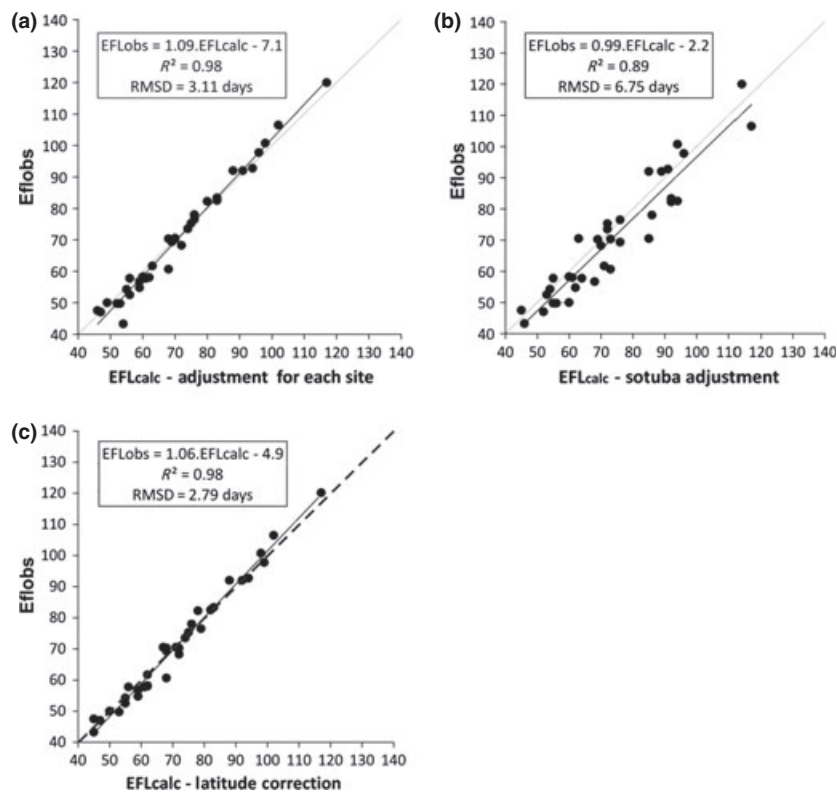


Fig. 5 Model validation. Scatterplots of calculated emergence–flag leaf expansion durations (EFLcalc) against observations from the Cinzana and Farako experiments (EFLobs). Dashes identify the 1 : 1 line, solid line identify the linear adjustment line with R2 for determination coefficient; RMSD is the root mean square deviation: (a) Coefficient calculated for each site; (b) Coefficient calculated at Sotuba station; (c) Coefficient calculated at Sotuba station and corrected for latitude of other sites.

Conclusion

The effect of latitude on the phenology has been definitely more important than portrayed by existing crop growth models. The largest difference in day length was 8 min; however, this caused a variation in the duration of the vegetative phase of up to 3 weeks. Photoperiod sensitivity is therefore influenced by the latitude in a subtle manner. CSM 63E behaved as a photoperiod-insensitive cultivar at the lowest latitude site and as a photoperiod-sensitive cultivar at the highest latitude site.

Existing models do not sufficiently take into account this phenomenon. The Impatience model allows for the calculation of genetic coefficients for each site to forecast the SD effect on phenology, but the genetic parameters obtained were not stable with latitude. The model established for Sotuba always over-estimates the duration of the vegetative period at Farako. This result could explain the failure of photoperiodism studies based on trials with various latitudes or with artificial light.

Integrating photoperiod sensitivity into a crop model and using a geographic information system (GIS) makes it possible to identify optimum growing areas for different cultivars by combining varietal traits, length of the growing season, climatic uncertainty and farmers' practices (Soumaré et al. 2008). Adaptation maps derived can help plant breeders in determining areas of cultivar adaptation especially under climate change in West Africa, with its potential displacement of isohyets from North to South and the concomitant movement of varieties from one zone to another (Traoré et al. 2000).

The latitude correction should not yet be extrapolated beyond the range of latitude explored by our experiments. Further studies are required to test the behaviour of the varieties on a broader range of latitudes. The statistical fitting of Psens with latitude, as suggested here, helps in depicting the improved forecast of phenology along latitudinal gradients in the Sudano-Saharan zone, but does not offer any physiological explanations for this phenomenon. It will be first necessary to decipher the physiological basis for the strong effect of latitude observed.

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4 Grain yield and its relations with some characters of grain sorghum under diverse environments

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Title: Grain yield and its relations with some characters of grain sorghum under diverse environments

Article Type: Research Paper

Keywords: Climate change. Sorghum, AMMI Analysis, Correlation Analysis, Path analysis

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Abstract:

Genotypic options for coping with climate variability as well as tactical and strategic adaptation to climate change entail the introduction, development and deployment of genotypes with adequate plasticity of phenology together with component technologies that will optimize yield. Such genotypes should be based on ideotype concepts that assemble the most appropriate traits selected based on a comprehensive understanding of the relationship among characters and their individual and joint contribution to grain yield as well as their responses to various environments. Six sorghum cultivars, drawn from three races, were evaluated in twelve environments created from a factorial combination of two monthly sowing dates, three locations (along a latitudinal gradient) and two years (2008 and 2009) in Mali. Data were collected on twelve (12) plant characters and grain yield. Analysis of Variance (for individual and general environments), AMMI analysis, AMMI1 AMMI2 biplots were performed for grain yield. Correlations were used to determine relations between grain yield and the twelve characters as well as among the characters. Path analysis was used to determine direct coefficients to grain yield and indirect coefficients through other characters to grain yield for six of the characters that had strong correlations with grain yield. Genotypic differences for grain yield were significant at eight of the twelve environments and the general ANOVA showed significant differences for genotypes, environments and interaction. The proportion of total variance explained by each of

31 environment and interaction was more than twice that of genotype. Majority of the high potential
32 environments were found at the highest latitude location. Grinkan and IRAT 204 were found to
33 have high minimum yields and good responsiveness to environments. Strong positive
34 correlations were found between grain yield and each of shoot biomass, panicle weight, number
35 of grains per panicle and threshing ability, but path analysis showed that the relations of the other
36 characters to grain yield was influenced to a large extent by their relations to number of grains
37 per panicle. The implications of the findings for plant breeders are discussed.

38 Highlights of manuscript:

- 39 • Environments and interaction each contributed more than twice the contribution of
40 cultivars to total variance.
- 41 • Cultivars showed specific adaptation for particular environments
- 42 • Grain yield correlated strongly with shoot biomass, panicle weight, number of grains
43 per panicle and threshing ability.
- 44 • Number of grains per panicle played an important mediatory role in relations between
45 grain yield and most of the characters
- 46 • Path analysis complement correlation in improving understanding of relations between
47 sorghum grain yield and other characters

48 **4.1 Introduction**

49 Grain sorghum (*Sorghum bicolor* L. (Moench)) is one of the main staple foods for the world's
50 poorest and most food insecure people (El Naim *et al.*, 2012). Globally, it is the fifth most
51 important cereal crop following rice, maize, wheat and barley (FAO, 2006), and is cultivated
52 mainly under rain-fed conditions in the arid to semi-arid regions of West Africa (House, 1985).
53 Genetically, it is suited to hot and dry agro-ecologies where occasional extreme events (flood
54 and drought) make it difficult to profitably grow other food grains, and have many traits that
55 enhance phenotypic plasticity and/or tolerance to particular stresses created by particular
56 environments (Ezeaku *et al.*, 1997; Haussmann *et al.*, 2012).

57 In the semi-arid tropics, especially West Africa, sorghum production systems are highly
58 vulnerable because the bulk of sorghum production is by poor and subsistent small-holder
59 farmers having very low adaptive capacity for climate-related challenges.

60 IPCC (2007) predicted that climate change will adversely affect crop production systems of the
61 semi-arid tropics where the majority of the world's poorest and least food secure people reside.
62 The realization of these predictions will further worsen the global food security problem since
63 many more of the small-holder farmers in such areas will become food insecure.

64 Currently, the majority of farmers in the semi-arid tropics use diverse well adapted but
65 unimproved, tall, and photoperiod sensitive sorghum genotypes with low yield potentials. Major
66 reasons adduced for the preference for these genotypes include their ability to mature uniformly
67 (at the end of the rainy season) irrespective of time of sowing (due to photoperiod sensitivity),
68 the reduced risk of damage from birds, and the production of grains with good quality (with no
69 grain mold contamination). Improving the yield potential of these preferred genotypes is one
70 major way by which the problem can be addressed.

71 Grain yield and yield-associated traits are complex quantitative traits controlled by multiple
72 genes and are highly influenced by environmental conditions and thus have low heritability
73 estimates (Grafius, 1959; Shi *et al.*, 2009), so indirect selection through other traits with high
74 heritability could simplify the task of yield improvement. Currently, information on the
75 responses of individual traits and yield to changes in the environment, and whether it is possible
76 as well as how to exploit these for crop improvement purposes is very scanty. Adequate
77 knowledge of relations between the various traits and their linkage to grain yield (especially
78 under different climatic conditions) is required for effectively using these traits in improving
79 grain yield. Fadlalla and Abdalla (1994) found the weight of 1000-grains and number of
80 grains/spike to be the most reliable traits for improving yield. Other authors have shown that
81 early senescence under stress, number of panicles, panicle size, harvest index, grain number, and
82 seed weight correlate positively with grain yield in sorghum (Heinrich *et al.*, 1983; Saeed and
83 Francis, 1983; Craufurd and Peacock, 1993; Can and Yoshida, 1999; Hausmann *et al.*, 1999;
84 Soltani *et al.*, 2001; Kouresy *et al.*, 2008).

85 We took advantage of the wide range of different latitudes across Mali and staggered sowing
86 dates to create a large number of diverse sorghum growing environments. The environments so
87 created were used to investigate responses of selected traits and yield performance to different
88 environmental conditions using a set of sorghum cultivars sampled to represent a share of the
89 global genetic variation of rain-fed grain sorghum.

90 Specifically, we sought to (i) to determine environmental influences on yield performance of
91 selected sorghum cultivars; (ii) to analyze the relation between selected traits and grain yield in
92 the sorghum cultivars; (iii) to determine if and how environment affects the relations among
93 traits and grain yield; (iv) to evaluate the potential of path analysis in improving understanding
94 of trait-yield relations for sorghum cultivars.

95 **4.2. Materials and Methods**

96 **4.2.1 Characteristics of experiment and the study sites**

97 Three sites located on different latitudes and with obvious differences in amplitude of
98 photoperiod were selected in Mali for field trials. The research fields of the Institute d'Economie
99 Rurale (IER) at Cinzana (13°15'N; 5°52'W; 312 m asl; Sahel) with a sandy clay loam, Sotuba
100 (12°17'N; 7°57'W; 364 m asl; Sudan Savannah) with a sandy loam soil, and Farako (11°21'N,
101 5°41'W; 441 m asl, Guinea Savannah) with a loamy sand soil, were used for the experiments.
102 Details on the physicochemical properties of soils at each of the sites are presented in Table 4.1.
103 All the sites have a hot, tropical climate and the decadal means for rainfall and temperature for
104 the 2008 and 2009 seasons are presented in Figure 4.1.

105 **4.2.2 Experimental units and Cultivars**

106 Experimental units for this study were sampled from a bigger experiment designed to study the
107 yield performance of 10-grain sorghum cultivars under three monthly sowing dates in 2008 and
108 2009 at the afore mentioned locations. The full details on experimental units and design, cultural
109 practices as well as grain yield and yield stability performance for the bigger experiment are
110 reported by Abdulai *et al.*, 2012. For this study, only the first two sowing dates (because of zero
111 yields recorded for the third sowing date at one location due to a complex of stressors) were
112 used. The two dates of sowing were combined with the three locations and two years to create 12
113 environments. Six of the ten sorghum cultivars, including 3 races (Guinea, Durra, and
114 Caudatum), with different degrees of sensitivity to photoperiod, were also used for this study.
115 Details on these cultivars are presented in Appendix 1.

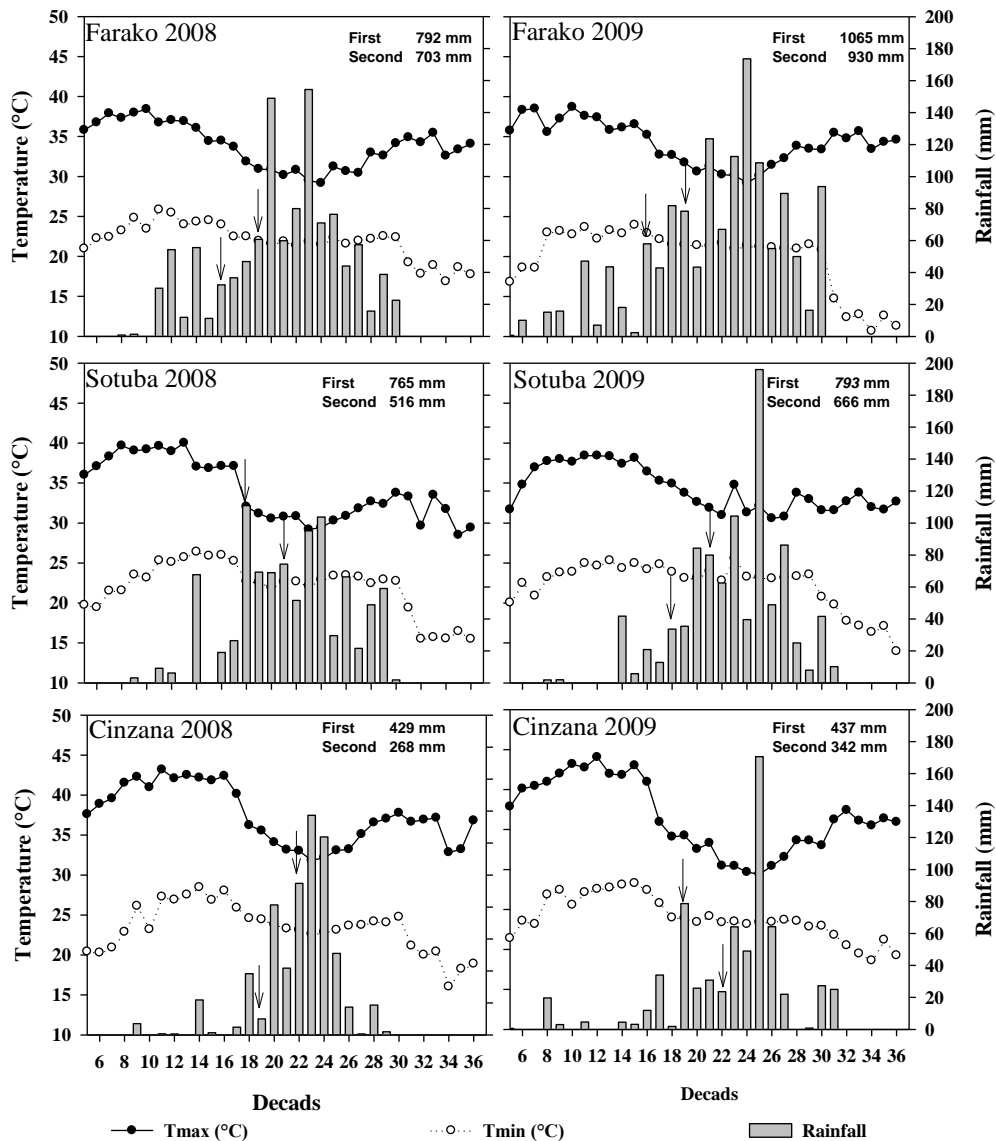
116 **4.2.3 Data collection and analysis**

117 Parameters evaluated were number of days from sowing to ligulation of the flag leaf (FDD), total
 118 number of leaves (TLN) produced, area of the largest leaf (LLA), maximum leaf area index
 119 (LAI), leaf area duration (LAD; calculated according to Power *et al.*, 1967), plant height at
 120 maturity (PHT), shoot biomass (SBM) as total dry weight at maturity, panicle weight (PWT),
 121 grain yield (GRY), harvest index (HAI) expressing grain yield as a percentage of total shoot
 122 biomass), number of grains per panicle (GPP), threshing ability (TRS), and weight of 1000
 123 grains (TGW). Number of stands and number of panicles are important components of yield, but
 124 were not recorded because every net plot had the complete plant stands (5 plants and panicles m⁻²)
 125 at harvest, and none of the six genotypes developed tillers.

126

127 **Table 4.1: Physico-chemical properties of soils at the experimental sites**

Soil Property	Farako		Sotuba		Cinzana	
	0-15	15-30	0-15	15-30	0-15	15-30
	cm	cm	cm	cm	cm	cm
pH (water)	5.5	5.4	4.7	5.0	5.2	5.6
pH (KCl)	4.6	4.4	4.2	4.4	4.4	4.3
Organic matter (% C)	0.04	0.03	0.36	0.24	0.13	0.12
Nitrogen (% N)	0.01	0.01	0.05	0.02	0.03	0.02
Available P (Bray) II (ppm)	5.4	4.57	13.52	5.87	7.47	2.91
pF 2.5	7.25	11.46	7.13	10.82	14.6	19.12
pF 3	5.86	8.2	6.24	9.76	9.02	15.14
pF 4.2	4.33	7.61	5.01	8.04	7.37	14.08
CEC ammonium acetate (meq/100g)	2.8	2.74	4.64	7.89	7.08	7.15
Exchangeable Ca (meq/100g)	1.08	1.38	1.87	2.67	3.74	4.53
Exchangeable Mg (meq/100g)	0.65	0.7	0.95	1.43	1.97	2.3
Exchangeable K (meq/100g)	0.2	0.16	0.16	0.16	0.2	0.16
Exchangeable Na (meq/100g)	0.1	0.06	0.06	0.06	0.17	0.03
Sand (%)	84	76	52	46	67	51
Silt (%)	14	14	32	30	19	20
Clay (%)	2	10	16	24	14	29



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Figure 4.2: 10-day averages for rainfall and temperature for the growing seasons of 2008 and 2009 at the locations used for the study in Mali. Vertical arrows indicate dekads within which the sowings were done.

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The data collected on GRY were subjected to analysis of variance (ANOVA) for individual environments and a combined ANOVA based on the AMMI model using GENSTAT Twelfth Edition; Version 12.1.0.3278 (VSN International Ltd., 2009). AMMI1 and AMMI2 biplots for GRY were also plotted. Phenotypic correlation coefficients (r) between GRY and each of the traits studied were computed for sowing date (data pooled over locations and years), locations (data pooled over sowing date and years) and environments (genotypic means across environments). However, correlation coefficients for all possible pairs of traits were computed for the environment data only. Path analysis was used to partition relations between each trait

139 and GRY into direct effects and indirect effects through other traits to grain yield. Figure 4.2
 140 shows an example of a schematic diagram for computing path coefficients based on six traits.
 141 Path coefficients (P) were calculated for seven yield component traits using the simultaneous
 142 solutions based on the work of Wright (1921) and Dewey and Lu (1959). The equations used
 143 were as below.

144 1: $r_{17} = P_{17} + r_{12}P_{27} + r_{13}P_{37} + r_{14}P_{47} + r_{15}P_{57} + r_{16}P_{67}$

145 2: $r_{27} = P_{27} + r_{12}P_{17} + r_{23}P_{37} + r_{24}P_{47} + r_{25}P_{57} + r_{26}P_{67}$

146 3: $r_{37} = P_{37} + r_{13}P_{17} + r_{23}P_{27} + r_{34}P_{47} + r_{35}P_{57} + r_{36}P_{67}$

147 4: $r_{47} = P_{47} + r_{14}P_{17} + r_{24}P_{27} + r_{34}P_{37} + r_{45}P_{57} + r_{46}P_{67}$

148 5: $r_{57} = P_{57} + r_{15}P_{17} + r_{25}P_{27} + r_{35}P_{37} + r_{45}P_{47} + r_{56}P_{67}$

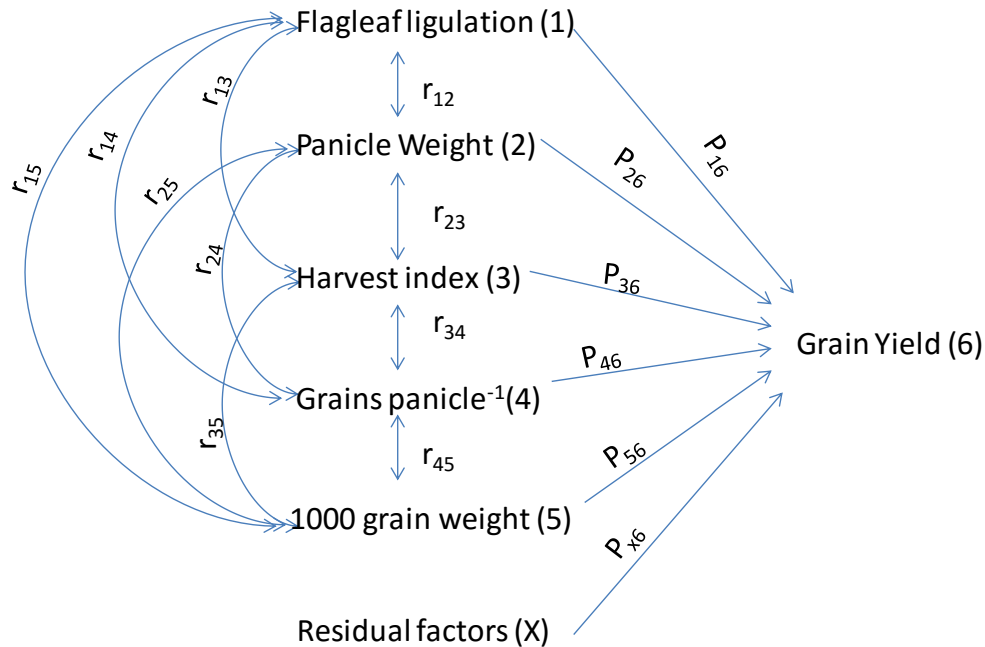
149 6: $r_{67} = P_{67} + r_{16}P_{17} + r_{26}P_{27} + r_{36}P_{37} + r_{46}P_{47} + r_{56}P_{57}$

150 7: $1 = P^2_{X7} + P^2_{17} + P^2_{27} + P^2_{37} + P^2_{47} + P^2_{57} + P^2_{67} + 2P_{17}r_{12}P_{27} + 2P_{17}r_{13}P_{37} + 2P_{17}r_{14}P_{47} +$
 151 $2P_{17}r_{15}P_{57} + 2P_{17}r_{16}P_{67} + 2P_{27}r_{23}P_{37} + 2P_{27}r_{24}P_{47} + 2P_{27}r_{25}P_{57} + 2P_{27}r_{26}P_{67} + 2P_{37}r_{34}P_{47} +$
 152 $2P_{37}r_{35}P_{57} + 2P_{37}r_{36}P_{67} + 2P_{47}r_{45}P_{57} + 2P_{47}r_{46}P_{67} + 2P_{57}r_{56}P_{67}$

153 Where 1 = number of days from sowing to ligulation of flagleaf (FDD); 2 = Panicle weight
 154 (PWT); 3 = Harvest Index (HAI); 4 = Grains per panicle (GPP); 5 = weight of 1000 grains
 155 (TGW); 6 = Threshing ability (TRS); 7 = Grain yield (GRY); X = Residual factor representing
 156 unaccounted variation which was calculated by making X the subject of the formula in equation
 157 7. Taking equation (1) above for example, r_{17} is the correlation coefficient between 1 (FDD) and
 158 7 (GRY); P_{17} is the direct effect of FDD upon GRY; $r_{12}P_{27}$ is the indirect effect of FDD upon
 159 GRY through PWT; $r_{13}P_{37}$ is the indirect effect of FDD upon GRY through HAI; $r_{14}P_{47}$ is the
 160 indirect effect of FDD upon GRY through GPP; $r_{15}P_{57}$ is the indirect effect of FDD upon GRY
 161 through TGW; and $r_{16}P_{67}$ is the indirect effect of FDD upon GRY through TRS.

162 GENSTAT Twelfth Edition; Version 12.1.0.3278 (VSN International Ltd., 2009) was used for the
 163 analysis of variance and computation of correlation coefficients, while all other analyses were
 164 conducted using SPSS.

165



166

167 Figure 4.3: Schematic diagram for path coefficient computations involving five sorghum traits and grain yield as the
168 response variable

169 4.3 Results

170 4.3.1 Analysis of Variance, AMMI Analysis, and Biplots

171 The yield performance of the six genotypes considered for this study is presented in Appendix
172 Table 1. The Individual analyses of variance for each of the environments revealed significant
173 differences ($p \leq 0.05$) among genotypes in all except four (4) environments (E5, E8, E11, and
174 E12), but the analysis revealed that there was sufficient genetic variability to be exploited by
175 selection (Table 4.2)

176 Table 4.2: Means sum of squares of individual analysis of variance, means, and coefficients of variation (CV) for grain
177 yield (GRY) of 6 genotypes in twelve environments in Mali in the crop seasons of 2008 and 2009

Source	d.f.	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
Rep.	2	3191	10616	868	1440	3231	1386.1	2348	228	254	124	14673	227
Genotype	5	36912**	27829**	26606**	16484*	6647 ^{ns}	2566.6**	9024*	7590 ^{ns}	10510**	7214*	4956 ^{ns}	14041 ^{ns}
Error	10	4173	2758	1809	3779	2706	372.5	2559	3360	1580	1630	7018	5375
Mean (g/m ²)		227	206	187	160	176	85.7	195	169	245.4	145.2	291	237
Cv (%)		23.3	25.5	22.7	38.5	29.6	22.5	26.0	34.4	16.2	27.8	28.8	31.0

178 ns = non-significant; * = significant at $p \leq 0.05$; ** = significant at $p \leq 0.01$

179 The combined analysis of variance also showed highly significant differences ($p \leq 0.01$) for
 180 environments (E), genotypes (G) and the Genotype and Environment interaction (GEI) (Table
 181 4.3). AMMI analysis of variance for GRY across the twelve environments showed significant (p
 182 ≤ 0.05) effects of genotypes, environments, and GEI. It was observed that 44.0 % of the total
 183 sum of squares (SST) was attributable to environmental effects, 16.8 % to genotypic effects and
 184 39.2 % to GEI effects (Table 4.3). The AMMI analysis also showed that 5 IPCAs accounted for
 185 100% of the sum of squares for interaction (SSI), but only the first 3 IPCAs were significant ($p \leq$
 186 0.01), and explained a total of 89.6% of the SSI. The respective contributions of IPCA1, IPCA2,
 187 and IPCA3 to SSI were 54.6%, 20.8%, and 14.2%.

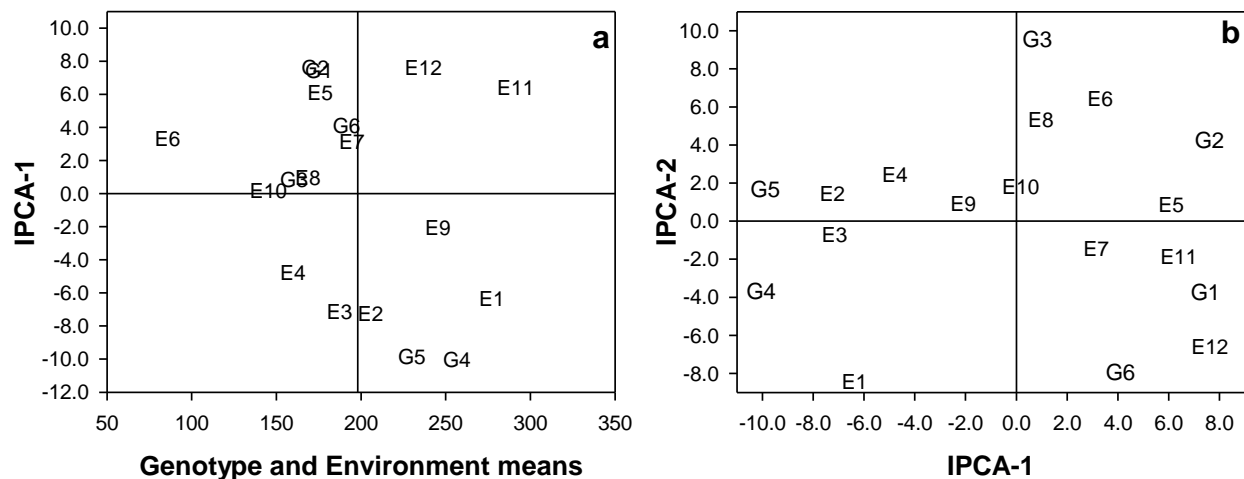
188 **Table 4.3: Summary of analysis of variance and partitioning of the $G \times E$ interaction by the AMMI method and the**
 189 **percentage of the sum of squares explained (singly and cumulatively) for grain yield in 12 environments.**

Source	df	SS	MS	SS Explained (%)	
				Singly	cumulative
Total	215	1966971	9149		
Treatments	71	1518611	21389**		
Block	24	77168	3215 ^{ns}		
Genotypes	5	254728	50946**	16.8	16.77
Environments	11	668510	60774**	44.0	60.8
Interactions	55	595372	10825**	39.2	100.0
IPCA1	15	325231	21682**	54.6	54.6
IPCA2	13	123539	9503**	20.8	75.4
IPCA3	11	84885	7717**	14.2	89.6
IPCA4	9	42893	4766 ^{ns}	7.2	96.8
IPCA5	7	18825	2689 ^{ns}	3.2	100.0
Error	120	371193	3093		

190 **, and ns significant at P value ≤ 0.01 and non-significant respectively. Abbreviation: df, degree of freedom; SS, sum of squares;
 191 MS, mean sum of squares

192 AMMI1 (IPCA1 vs. means) and AMMI2 (IPCA2 vs. IPCA1) biplots were used to decipher the
 193 effects of each genotype and environment on the variation of GRY (Figure 3). For the AMMI1
 194 biplot, the main effects (means) of environments and genotypes constituted the abscissa while
 195 the IPCA1 constituted the ordinate (Figure 3a). The IPCA1 score of 0.82 for CSM 63E (G3) was

196 the closest to zero while the IPCA1 score of -10.06 for Grinkan (G4) was the furthest from zero.
 197 G4 produced the highest mean GRY (256.6 g m⁻²) while CSM 63E produced the lowest mean
 198 GRY (160.4 g m⁻²). Among the genotypes, only G4 and IRAT 204 (G5) produced above the
 199 average mean GRY recorded for the study. Boiguel (G1) and CSM 388 (G2) had more or less
 200 similar average GRY as G3, but their IPCA1 scores were respectively, the fourth and third
 201 furthest away from zero. GRY for Lakahieri (G6) was very close to the average for the study,
 202 and its IPCA1 score was the second closest to zero (Figure 4.3a).
 203 The environment with the highest mean for GRY was E1, while E6 had the lowest mean for
 204 GRY. Mean GRY for five of the twelve environments (E1, E2, E9, E11 and E12) were above the
 205 average GRY recorded for the study (Figure 4.3a). The IPCA1 score for E10 (0.16) was closest
 206 to zero while that for E12 (7.61) was the furthest from zero. Six of the environments (E1, E2, E3
 207 E5, E11 and E12) had IPCA1 scores of more than 5 units away from zero; four environments
 208 (E4, E6, E7 and E9) had IPCA1 scores greater than 1 but less than 5 units away from zero; while
 209 IPCA1 scores for E10 and E8 were fractions of a unit from zero (Figure 4.3a).



210 **Genotype and Environment means**
 211 **IPCA-1**
 212 **IPCA-2**
 213 **IPCA-1**
 214 **IPCA-1**

211 **Figure 4.4: Biplot of Additive Main effects and Multiplicative Interaction (AMMI) analysis for genotypes and**
 212 **environments. (a) AMMI-1 biplot where ordinate is interaction Principal Component Axes 1 (IPCA-1) scores and the**
 213 **abscissa is genotype and environment mean grain yield (g m⁻²). (b) AMMI-2 biplot where the ordinate is IPCA-2 and**
 214 **abscissa is IPCA-1**

215 Figure 4.3b presents an AMMI2 biplot (with IPCA1 scores as abscissa and IPCA2 scores as
 216 ordinate) that showed that among the genotypes, G4 and G1 were the farthest and closest
 217 respectively to the origin, while among the environments. Environments E9, E10, and E7 were
 218 the three closest and E1, E2, and E12 were three farthest from the origin. The remaining six

219 environments (E3, E4, E5, E6, E8, and E11) were positioned at intermediate distances from the
220 origin of the AMMI2 biplot.

221 **4.3.2 Correlation Analysis**

222 **4.3.2.1 Relations between GRY and the other traits at different locations**

223 Correlation coefficients were calculated for data from the different locations to decipher if and
224 how locations influenced relations between grain yield and the other characters. At Farako (LL),
225 correlation coefficients between GRY and each of TLN, LLA, FDD, and TGW ($0.017 \leq r \leq$
226 0.119) were not significant; LAI and LAD had weak but significant ($p \leq 0.05$) correlation
227 coefficients ($0.145 \leq r \leq 0.230$) with GRY; and strong significant ($p \leq 0.01$) correlation
228 coefficients ($0.524 \leq r \leq 0.939$) were found between GRY and the rest of the traits which
229 included PHT, SBM, PWT, HAI, GPP, and TRS (Table 4.4). At Sotuba (ML), weak but
230 significant ($p \leq 0.05$) correlation coefficients ($0.144 \leq r \leq 0.360$) were found between GRY and
231 eight of the traits (TLN, LLA, LAI, LAD, FDD, PHT, HAI and TGW) while the 4 remaining
232 traits (SBM, PWT, GPP and TRS) had highly significant ($p \leq 0.01$) medium to strong correlation
233 coefficients ($0.515 \leq r \leq 0.919$) with GRY (Table 4.4). Data for Cinzana (HL) showed non-
234 significant ($p > 0.05$) correlation coefficients between GRY and two traits (LAD and HAI); weak
235 to medium but significant ($p \leq 0.05$) correlation coefficients ($0.148 \leq r \leq 0.571$) were observed
236 between seven traits (TLN, LLA, LAI, FDD, PHT TGW, and TRS) and GRY; strong and highly
237 significant ($p \leq 0.01$) correlation coefficients ($0.773 \leq r \leq 0.889$) were found between GRY and
238 three of the traits (SBM, PWT, and GPP) (Table 4.4).

239 **4.3.2.2 Relations between GRY and the other traits for sowing dates and** 240 **environments**

241 Data for the first sowing date showed non-significant ($p > 0.05$) correlation coefficients ($r \leq$
242 0.113) between GRY and four traits (TLN, LAD, FDD, and TGW); four of the traits (LLA, LAI,
243 PHT, and HAI) had weak but highly significant ($p \leq 0.01$) correlation coefficients ($0.196 \leq r \leq$
244 0.393) with GRY; four traits (SBM, PWT, GPP, and TRS) had medium to strong and highly
245 significant ($p \leq 0.01$) correlation coefficients ($0.536 \leq r \leq 0.892$) with GRY (Table 4.4). For the
246 second sowing date, correlation coefficients between GRY and each of TLN, LLA, LAI and
247 TGW ($r \leq 0.112$) were non-significant ($p > 0.05$); weak but significant correlation coefficients

248 (0.134 ≤ r ≤ 0.334) were found between GRY and four traits (LAD, FDD, PHT and HAI);
 249 medium to strong and highly significant (p ≤ 0.01) correlation coefficients were found between
 250 GRY and each of SBM, PWT, GPP and TRS (0.652 ≤ r ≤ 0.905) (Table 4.4).
 251 Considering the data for environments, correlation coefficients (r ≤ 0.092) between GRY and
 252 three of the traits (LAD, FDD and TGW) were non-significant (p > 0.05); correlation coefficients
 253 between GRY and each of TLN, LLA, LAI, PHT, and HAI were weak (0.163 ≤ r ≤ 0.339) but
 254 significant (p ≤ 0.05); medium to strong and highly significant (p ≤ 0.01) correlation coefficients
 255 (0.621 ≤ r ≤ 0.899) were observed between GRY and four of the traits including SBM, PWT,
 256 GPP and TRS (Table 4.4).

257 **Table 4.4: Correlation coefficients between grain yield and other plant traits¹ as affected by sowing date, location and**
 258 **genotypic means across environments**

	Farako (LL)	Sotuba (ML)	Cinzana (HL)	First Sowing	Second sowing	Pooled
TLN	0.051 ^{ns}	0.360 ^{**}	0.399 ^{**}	0.113 ^{ns}	-0.071 ^{ns}	0.177 ^{**}
LLA	0.067 ^{ns}	0.152 [*]	0.517 ^{**}	0.224 ^{**}	0.112 ^{ns}	0.262 ^{**}
LAI	0.230 ^{**}	0.266 ^{**}	0.194 ^{**}	0.196 ^{**}	-0.037 ^{ns}	0.208 ^{**}
LAD	0.145 [*]	0.275 ^{**}	0.106 ^{ns}	-0.009 ^{ns}	-0.134 [*]	0.092 ^{ns}
FDD	-0.017 ^{ns}	0.300 ^{**}	0.352 ^{**}	0.001 ^{ns}	-0.232 ^{**}	0.070 ^{ns}
PHT	-0.524 ^{**}	0.174 [*]	0.148 [*]	-0.281 ^{**}	-0.270 ^{**}	-0.163 [*]
SBM	0.848 ^{**}	0.762 ^{**}	0.889 ^{**}	0.771 ^{**}	0.877 ^{**}	0.840 ^{**}
PWT	0.897 ^{**}	0.830 ^{**}	0.773 ^{**}	0.777 ^{**}	0.837 ^{**}	0.816 ^{**}
HAI	0.457 ^{**}	0.277 ^{**}	0.103 ^{ns}	0.393 ^{**}	0.334 ^{**}	0.339 ^{**}
GPP	0.939 ^{**}	0.919 ^{**}	0.791 ^{**}	0.892 ^{**}	0.905 ^{**}	0.899 ^{**}
TGW	-0.119 ^{ns}	0.144 [*]	0.358 ^{**}	0.029 ^{ns}	-0.040 ^{ns}	0.048 ^{ns}
TRS	0.708 ^{**}	0.515 ^{**}	0.571 ^{**}	0.536 ^{**}	0.652 ^{**}	0.621 ^{**}

259 TLN = Total number of leaves; LLA = Area of largest leaf; LAI = Leaf area Index; LAD = Leaf Area Duration; FDD = Number
 260 of days to ligulation of flagleaf; PHT = Plant height; SBM = Shoot biomass; PWT = Panicle weight; HAI = Harvest index; GPP
 261 = number of grains per panicle; TGW = thousand grain weight; TRS = Threshing ability

262 4.3.2.3 Phenotypic Correlation among the traits across environments

263 Table 4.5 presents the phenotypic correlation coefficients among the traits recorded. For
 264 correlations involving leaf characters (TLN, LLA, LAI, and LAD) medium to strong positive

265 relations ($0.502 \leq r \leq 0.836$) were found between TLN and the other leaf characters, between
 266 LAI and LAD, and between FDD and each of TLN, LLA, and LAD. All other relations involve
 267 leaf characters were weak (Table 4.5).

268 For PLHT, correlations with all the other characters were weak, with those involving SBM and
 269 PWT being non-significant, while those involving HAI, GPP and TRS had negative coefficients.
 270 With the exception of PWT and TRS not being related, all other possible pairs of SBM, PWT,
 271 GPP, and TRS, had strong and highly significant correlation coefficients (Table 4.5).

272 HAI was not related to SBM and HAI but had weak significant relations with all other
 273 characters. Its relations with all the other characters were negative, with the exception of PWT.
 274 None of SBM and HAI was related to TGW, while all other characters had weak to average
 275 correlations with TGW (Table 4.5). PWT was not significantly correlated with any of PHT and
 276 TRS but was positively and significantly correlated with the rest of the traits.

277 **Table 4.5: Phenotypic Correlations among the traits for environment data (pooled over genotypes).**

	TLN	LLA	LAI	LAD	FDD	PLHT	SBM	PWT	HI	GPP	TGW
LLA	0.638**										
LAI	0.502**	0.374**									
LAD	0.585**	0.427**	0.836**								
FDD	0.737**	0.529**	0.44**	0.649**							
PHT	0.313**	0.238**	0.363**	0.45**	0.349**						
SBM	0.343**	0.268**	0.341**	0.292**	0.252**	-0.001 ^{ns}					
PWT	0.336**	0.326**	0.309**	0.175*	0.133*	0.001 ^{ns}	0.682**				
HAI	-0.203**	0.038 ^{ns}	-0.176**	-0.289**	-0.264**	-0.278**	-0.183**	0.289**			
GPP	0.033 ^{ns}	0.155*	0.117 ^{ns}	-0.014 ^{ns}	-0.04 ^{ns}	-0.272**	0.73**	0.626**	0.362**		
TGW	0.354**	0.307**	0.192**	0.251**	0.321**	0.232**	0.061 ^{ns}	0.260**	-0.014 ^{ns}	-0.345**	
TRS	-0.163*	0.015 ^{ns}	-0.09 ^{ns}	-0.117 ^{ns}	-0.089 ^{ns}	-0.262**	0.510**	0.107 ^{ns}	0.254**	0.693**	-0.259**

278 TLN = Total number of leaves; LLA = Area of largest leaf; LAI = Leaf area Index; LAD = Leaf Area Duration; FDD = Number
 279 of days to ligulation of flagleaf; PHT = Plant height; SBM = Shoot biomass; PWT = Panicle weight; HAI = Harvest index; GPP
 280 = number of grains per panicle; TGW = thousand grain weight; TRS = Threshing ability

281 HAI was revealed by correlation coefficients to have no significant correlations with both LLA
 282 and TGW; significant positive correlation coefficients were found between HAI and each of
 283 PWT, GPP, and TRS; correlation coefficients between HAI and the remaining six traits were
 284 negative but significant.

285 Four of the traits (TLN, LAI, LAD and FDD) did not correlate significantly ($p < 0.05$) with GPP;
 286 two traits (PHT and TGW) had significant negative correlations with GPP; five traits (PWT,

287 LLA, SBM, HAI, and TRS) had significant positive correlations with GPP. When TGW we
288 related to the other traits, we found that SBM and HAI did not correlate significantly with TGW,
289 that two of the traits (GPP and TRS) had significant negative correlations with TGW, while the
290 remaining seven traits had significant positive correlations with SBM. Significant negative
291 correlations were found between TRS and three traits (TLN, PHT, and TGW). Three other traits
292 (SBM, HAI, and GPP) had significant positive correlations with TRS, while the remaining five
293 traits were not significantly correlated with TRS.

294 **4.3.3 Path Analysis**

295 **4.3.3.1 Path Analysis for Locations**

296 Table 4.6 presents the path coefficients (to GRY) for six yield component traits for the three
297 study locations. The dataset for Farako (LL) included E1 to E4; dataset for Sotuba (ML)
298 involved E5 to E8; dataset for Cinzana (HL) involved E9 to E12. We found that direct path
299 coefficients for FDD to GRY were between -0.004 and -0.014 for the three locations. The
300 indirect path coefficients of FDD through the other traits to GRY were between -0.059 (for TRS
301 at LL) and 0.172 (for PWT at HL). Only indirect path coefficients through PWT and GPP at ML
302 and HL were greater than 0.100 (Table 6). For the path coefficients of PWT to GRY, we found
303 that: direct path coefficients were between 0.312 and 0.476 for all locations; indirect path
304 coefficients through other traits had absolute values between 0.019 and 0.460; only indirect path
305 coefficients through GPP for all locations and TGW for HL had absolute values greater than
306 0.100 (Table 4.6). Direct path coefficients for HAI to GRY were negative for all the locations
307 and had values between -0.039 and -0.077. Indirect path coefficients for HAI were positive for
308 all except that through TGW at ML, but only those through GPP at each of LL and ML as well
309 as those through PWT and TRS at LL were greater than 0.100 (Table 4.6). Path coefficients for
310 GPP were all positive and ranged between 0.429 and 0.677 across locations. For the indirect path
311 coefficients of GPP, those through HAI and TGW were negative, while all those through PWT
312 and TRS were positive for all the locations, however only the indirect path coefficients of GPP
313 through PWT and TRS were above 0.100 (Table 6). Direct path coefficients of TGW were
314 positive for all locations and were between 0.114 and 0.291. Indirect path coefficients for TGW
315 showed that: those through FDD, GPP, and TRS were negative while those through PWT were
316 positive for all locations; those through HAI were negative for LL and HL but positive for ML;

317 those through GPP for all locations, PWT at both ML and HL, as well as TRS at LL had absolute
 318 values greater than 0.100 (Table 4.6). Path coefficients for TRS showed that: direct coefficients
 319 were positive for all locations and ranged between 0.192 and 0.269; indirect path coefficients
 320 through HAI and TGW were negative while those through FDD and GPP were positive for all
 321 locations (Table 4.6).

322 **Table 4.6: Path analysis for 6 traits¹ for sorghum as influenced by 3 dates of sowing in Mali. Data is pooled over 2 years, 3**
 323 **locations, and 6 genotypes. Bold figures indicated direct effects.**

	FDD	PWT	HAI	GPP	TGW	TRS	GRY
Farako (LL)							
FDD	-0.014	0.043	0.005	-0.029	0.037	-0.059	-0.017
PWT	-0.001	0.476	-0.015	0.324	0.017	0.095	0.897
HAI	0.002	0.184	-0.039	0.175	0.018	0.118	0.458
GPP	0.001	0.360	-0.016	0.429	-0.045	0.210	0.938
TGW	-0.005	0.071	-0.006	-0.171	0.114	-0.122	-0.119
TRS	0.003	0.169	-0.017	0.335	-0.052	0.269	0.707
Sotuba (ML)							
FDD	-0.011	0.102	0.019	0.115	0.080	-0.004	0.301
PWT	-0.004	0.312	-0.019	0.460	0.081	-0.001	0.830
HAI	0.003	0.076	-0.077	0.269	-0.034	0.041	0.277
GPP	-0.002	0.212	-0.031	0.677	-0.052	0.114	0.918
TGW	-0.004	0.109	0.011	-0.153	0.232	-0.051	0.144
TRS	0.000	-0.002	-0.016	0.402	-0.062	0.192	0.514
Cinzana (HL)							
FDD	-0.004	0.172	0.011	0.112	0.059	0.001	0.352
PWT	-0.002	0.430	-0.004	0.222	0.135	-0.009	0.773
HAI	0.001	0.038	-0.041	0.066	0.018	0.021	0.102
GPP	-0.001	0.190	-0.005	0.502	-0.070	0.175	0.791
TGW	-0.001	0.200	-0.003	-0.121	0.291	-0.008	0.359
TRS	0.000	-0.015	-0.003	0.341	-0.009	0.257	0.570

324 FDD = Number of days to ligulation of flagleaf; PWT = Panicle weight; HAI = Harvest index; GPP = number of grains per
 325 panicle; TGW = thousand grain weight; TRS = Threshing ability

326 **4.3.3.2 Path Analysis for Sowing date and Environment**

327 Path coefficients for the traits, as influenced by sowing date and environment are presented in
 328 Table 4.7. Direct path coefficients of FDD to GRY for first sowing date and environments were
 329 positive while that for the second sowing date was negative, but were between -0.042 and 0.014.
 330 Path coefficients of FDD through other traits to GRY were between -0.146 and 0.066, with that
 331 through GPP for second sowing date only having a value greater than 0.100 or less than -0.100
 332 (Table 4.7).

333 **Table 4.7: Path analysis for 5 traits¹ for sorghum as influenced by 3 dates of sowing in Mali. Data is pooled over 2 years, 3**
 334 **locations, and 6 genotypes. Bold figures indicated direct effects.**

	FDD	PWT	HAI	GPP	TGW	TRS	GRY
First Sowing							
FDD	-0.042	0.056	0.008	-0.035	0.064	-0.050	0.000
PWT	-0.006	0.406	-0.011	0.335	0.070	-0.018	0.776
HAI	0.008	0.117	-0.040	0.218	0.023	0.068	0.393
GPP	0.002	0.225	-0.014	0.606	-0.090	0.163	0.891
TGW	-0.011	0.120	-0.004	-0.231	0.237	-0.082	0.029
TRS	0.008	-0.028	-0.011	0.391	-0.077	0.253	0.536
Second sowing							
FDD	0.014	-0.092	0.024	-0.146	0.049	-0.082	-0.232
PWT	-0.003	0.468	-0.018	0.313	0.023	0.054	0.837
HAI	-0.006	0.154	-0.055	0.182	-0.020	0.079	0.334
GPP	-0.004	0.315	-0.022	0.464	-0.064	0.215	0.905
TGW	0.004	0.069	0.007	-0.188	0.157	-0.088	-0.039
TRS	-0.004	0.084	-0.014	0.330	-0.046	0.302	0.651
Pooled							
FDD	-0.016	0.053	0.012	-0.022	0.066	-0.023	0.070
PWT	-0.002	0.401	-0.013	0.350	0.054	0.027	0.817
HAI	0.004	0.116	-0.045	0.202	-0.003	0.065	0.339
GPP	0.001	0.251	-0.016	0.559	-0.071	0.176	0.899
TGW	-0.005	0.104	0.001	-0.193	0.206	-0.066	0.047
TRS	0.001	0.043	-0.011	0.387	-0.053	0.254	0.621

335 FDD = Number of days to ligulation of flagleaf; PWT = Panicle weight; HAI = Harvest index; GPP = number of grains per
336 panicle; TGW = thousand grain weight; TRS = Threshing ability

337 Direct path coefficients of PWT to GRY were positive for all dates of sowing and environments,
338 with values between 0.401 and 0.468. The path coefficients of PWT through other traits to GRY
339 had values between -0.018 and 0.350, but only those through GPP were greater than 0.100 or less
340 than -0.100 (Table 4.7).

341 Across dates of sowing and environments, direct path coefficients of HAI to GRY were all
342 negative with values ranging between -0.055 and -0.040. On the other hand, only the path
343 coefficients of HAI through PWT and GPP were greater than 0.100 for all dates of sowing and
344 environments (Table 4.7). Direct path coefficients of GPP to GRY were positive, with 0.606,
345 0.464, and 0.559 for first sowing, second sowing, and environment respectively. Apart from the
346 indirect path coefficients of GPP through PWT and TRS to GRY, none other was greater than
347 0.100 for all dates of sowing and environment datasets (Table 4.7).

348 Path coefficients of TGW and TRS to GRY were all positive. The path coefficients for TGW
349 were between 0.157 and 0.237 while those for TRS were between 0.253 and 0.302 for all the dates
350 of sowing and environment datasets. The following were true for indirect path coefficients of
351 TGW and TRS: Path coefficients of both TGW and TRS through FDD and HAI had absolute
352 values less than 0.100 for all the datasets; the path coefficients of TGW and TRS through GPP
353 had absolute values of between 0.188 and 0.391 for all the datasets; absolute values for path
354 coefficients of TGW through PWT were higher than 0.100 for the first sowing date and
355 environment but lower than 0.100 for the second sowing date (Table 4.7).

356 **4.4. Discussion**

357 The value of genetic resources in the progress of developing new cultivars has been well realized
358 (Upadhyaya, 2005). Over the years, the variability in environmental factors created by climate
359 change has disrupted genotypic adaptation and / or specialization (Wassmann *et al.*, 2009) to the
360 extent that new genotypic and environmental niches are being created. In Mali, sorghum is
361 produced along a latitude gradient, and cultivars have been selected or bred for optimizing yield
362 under local environments, but climate change has necessitated a critical redefinition of genotypic
363 niches or environmental suitability for sorghum. The current study sort to extend the yield and

364 yield stability study of Abdulai *et al.*, 2012 by evaluating six of the genotypes under twelve of
365 the environments they used for potential general or specific genotypic adaptation. It also sought
366 to evaluate relations between grain yield and phenotypic traits, with the view to finding traits that
367 have very stable close relations with grain yield, so that these would be exploited for higher and
368 stable yields in the future. Genotypes had variable performance across environments, with the
369 proportion of treatment sum of squares explained by each of environments and interaction being
370 more twice of that explained by genotypes (Table 4.3). AMMI analysis, which distinguishes the
371 part of interaction sum of squares (SSI) attributable to the effect of genotypes and environments
372 from an unpredictable or un-interpretable residual part (Crossa *et al.*, 1990), showed that the first
373 principal component axis retained the greatest proportion of SSI and values for subsequent axes
374 were always lower (Table 3). The first three principal component axes explained 89.6% of the
375 SSI, and we could have used AMMI4 based on the recommendation of Cornelius *et al.* (1992).
376 Though increasing the number of principal component axes could explain more of SSI, some
377 authors have stated that this option may also increase the influence of noise (Gauch and Zobel,
378 1988; Piepho, 1995). In this study, IPCA4 and IPCA5 non-significantly contributed to
379 accounting for 100% of SSI (Table 4.3). The stability of the genotypes used in this study in
380 addition to four other genotypes was reported by Abdulai *et al.*, 2012 who used two static and
381 five dynamic indices (including IPCA1).

382 The contribution of any component to GEI depends on how far the component is positioned or
383 the length of its vector from the origin of the AMMI2 biplot. Boiguel (G1), an early maturing
384 durra, was shown to contribute the least to GEI while Grinkan (G4), a dwarf, photoperiod-
385 sensitive, medium maturing and improved composite, contributed the most to GEI. IRAT 204
386 (G5), an improved dwarf, photoperiod insensitive and early maturing caudatum and G4 were
387 shown to be most responsive to environments and could be used for optimizing yield in both
388 high and low potential environments while better alternatives are being sought.

389 Two environments (E8 at ML and E10 at HL) were shown to be very small contributors to GEI
390 while six environments (E1, E2, E3 E5, E11, and E12) made large contributions to GEI, with the
391 remaining four environments (E4, E6, E7, and E9) making average contributions to GEI.

392 We noted that E1 and E2 from LL and three environments from HL (E9, E11, and E12) could be
393 classified as favorable environments for obtaining high GRY. The amount and distribution of

394 precipitation and the relatively higher available phosphorus for soils at HL (Table 1) could
395 explain why 75% of its environments were favorable.

396 It is generally difficult to find cultivars with wide environmental adaptation, so it is important to
397 identify cultivars adapted to available environments or create environments to which available
398 cultivars are adapted. It was found in this study that the following could optimize performance:
399 Boiguel (G1) and Lakahieri (G6) be considered for E7, E11, and E12; IRAT 204 (G5) be
400 considered for E2, E4, and E9; Grinkan (G4) should be used for E3 and E1; CSM 63E (G3) and
401 CSM 388 (G2) be considered for E5, E6, and E8 (Figure 3b).

402 Crop cultivars targeted at adaptation to climate change and variability can be developed through
403 direct selection for performance in the target stress environments or indirect selection through
404 specific morphological, phenological or physiological characteristics. However, the use of
405 indirect selection should involve traits that are easy to identify, cheap and fast to measure or
406 those that have a strong genetic correlation with yield performance under the target condition
407 (Falconer 1989). Using a directional model for direct and / or indirect selection for grain yield
408 requires information on the interrelationship of plant characters, which is provided by correlation
409 analysis (Khan *et al.*, 2004). However, Toker and Cagirgan., (2004) stated that indirect selection
410 based on characters with high heritability might prove more effective because direct selection
411 could be misleading. In this study, we found that four characters (SBM, PWT, GPP, and TRS)
412 had consistently strong relations ($0.52 \leq r \leq 0.94$) with GRY across all the sets of data analyzed.
413 Actually, among the four characters, only TRS had correlation coefficients less than 0.761 (Table
414 4). Apparent auto-correlations exist between some of the traits found to be strongly correlated
415 with GRY. The path coefficient analysis showed that neither location nor date of sowing
416 differentially influenced the direct effects of the characters on GRY (Tables 6 and 7). Direct path
417 coefficients of PWT, GPP, TGW and TRS to GRY ranged from 0.114 to 0.677. The path
418 analysis showed that GPP mediated to a larger extent, in the relationships between the other
419 characters and GRY, as indicated by the strong indirect effects on relations between yield and
420 most of the characters. Breeding efforts that target the study environments and /or its analogues
421 should concentrate first on selecting for high GPP. Molecular techniques targeted at GPP could
422 be deployed for rapid results. Traditionally, correlation and path-coefficient analyses are used for
423 determining character interrelationships and yield criteria for indirect selection (Singh *et al.*,
424 1990; Toker and Cagirgan, 2004).

425 **4.5 Conclusion and Recommendations**

426 In this study, we attempted for the first time to look at how newly developed and existing grain
427 sorghum varieties in Mali respond to environments as well as relationships between characters
428 and grain yield under different environments. Grinkan (photoperiod sensitive guinea-caudatum
429 composite) and IRAT 204 (day-neutral caudatum) were found to have high minimum yields and
430 good responsiveness to environments. The majority of the high potential environments were
431 found at Cinzana (the high latitude location) where rainfall the lowest rainfall amounts was
432 received. Strong positive correlations were found between four characters (SBM, PWT, GPP,
433 and TRS) and GRY, suggesting that direct selection for each could improve yield, but path
434 analysis showed selecting for GPP would not improve grain yield only, but the other three
435 characters as well.

436 The number of cultivars used in this study is so limited for generalization, but the findings will
437 serve as an important input for the exploiting genotypic options for adaptation to climate change
438 for the studied target environments and its analogues. The effects of weather elements, especially
439 rainfall, temperature, solar radiation, vapor pressure deficit and evapotranspiration, as it interacts
440 with different phenological phases of the crop were not covered in this study but are very
441 important for proper attribution of causes.

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449

450 **Appendix**451 **Table A.1 - Description of the varieties used in the study**

Name	Improved/Landrace	Botanical type	Adaptation	Maturity type	Height
Boiguel	Malian landrace	Durra	Sahelian zone	early (100 days)	tall
Lakahieri	Malian landrace	Durra	Sahelian Zone	Medium (110 days)	tall
CSM 63E	Improved Malian landrace	Guinea	Sahelian zone	early (90 days)	tall
CSM 388	Malian Landrace	Guinea	Sudano-Sahelian zone	intermediate (120 days)	tall
Grinkan	Improved variety	Composite	Not yet determined	intermediate (110 days)	dwarf
IRAT 204	Improved variety	Caudatum	supplied by CIRAD	early (90 days)	dwarf

452

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5. Discussion

5.1 Environments and performance of the genotypes

The thrust of the study was to expose the grain sorghum genotypes to different environments created by staggering sowing dates at the three locations along a latitude gradient. The first level of variable conditions was found in the different annual mean rainfall figures for the different sites (Figure 5.1).



Figure 5.5: Map of Mali depicting the trial sites and isohyets

The sites have a hot, tropical climate with a mean, annual, maximal (minimal) daily temperature of 36.0°C (21.7°C) at Cinzana, 34.4°C (21.9°C) at Sotuba, and 33.7°C (21.0°C) at Farako (Kouressy et al., 2008). The second level of variation of the climate scenarios used for this study resides in different amounts of rainfall received by the different year-location-sowing date combinations (Figure 5.2). There were also marked differences in the fertility levels of the sites, especially the amounts of nitrogen and phosphorus.

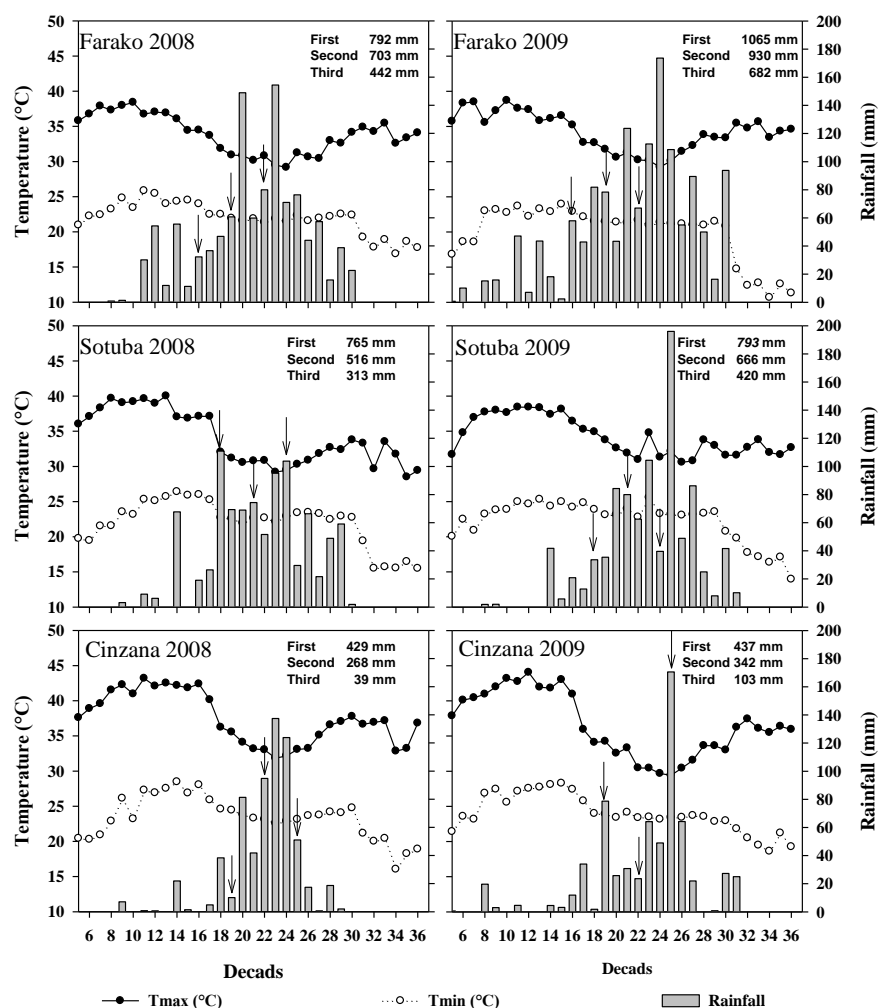


Figure 5.6: 10-day averages for rainfall and temperature for the growing seasons of 2008 and 2009 at Farako, Sotuba, and Cinzana in Mali. Arrows indicate decads when sowing was done. First = first sowing; second = second sowing; third = third sowing. Figures after first, second, and third indicate the total amount of rainfall received for the sowing dates.

5.2 Grain yield, yield stability, and trait relations

Based on genotypic means for grain yield, number of grains per panicle, and harvest index, the Caudatum, and Caudatum-related genotypes proved to be superior genotypes from the other races. Grinkan is a composite of the Caudatum and Guinea races and possess both stay-green and photoperiod sensitivity traits that it drives from its relationship with the Caudatum and Guinea races respectively. Mann *et al.* (1983) described the Caudatum race as high yielding and used it as a source of germplasm for their sorghum breeding programs. In this study, it was found that the genotype that combined photoperiod sensitivity and stay-green produced stably higher yield than the other genotypes. This result concurs with the findings of Kouressy *et al.* (2008) that

genetic dwarfing of tall-traditional cultivars can increase grain yield potential as a result of the reduced competition for assimilates exerted by an otherwise overwhelming sink activity of the elongating internodes. Grinkan was followed closely by IRAT 204, the only wholly-Caudatum genotype in the study. In fact, only one of the six Guinean genotypes used in the study was among the top five yielders. Stay-green characteristics have been found to benefit grain yield (Borrell et al., 2000), straw quality for fodder (Zerbini and Thomas, 2003), and drought tolerance (Borrell et al., 2000).

Exploitation of genetic variability based on phenotypic expression is an important screening and breeding strategy. Phenotypic differences are largely dictated by the environment, and this variability is complicated because no two environments are exactly the same, and genotypes do not react in the same way to changes in the environment (Mutava *et al.*, 2011). Mean yield across environments ceases to be an adequate indicator of genotypic performance in the presence of genotype by environment interaction, and the differential genotypic responses across at different environments complicate breeding, testing, and selection of superior genotypes (Mutava *et al.*, 2011).

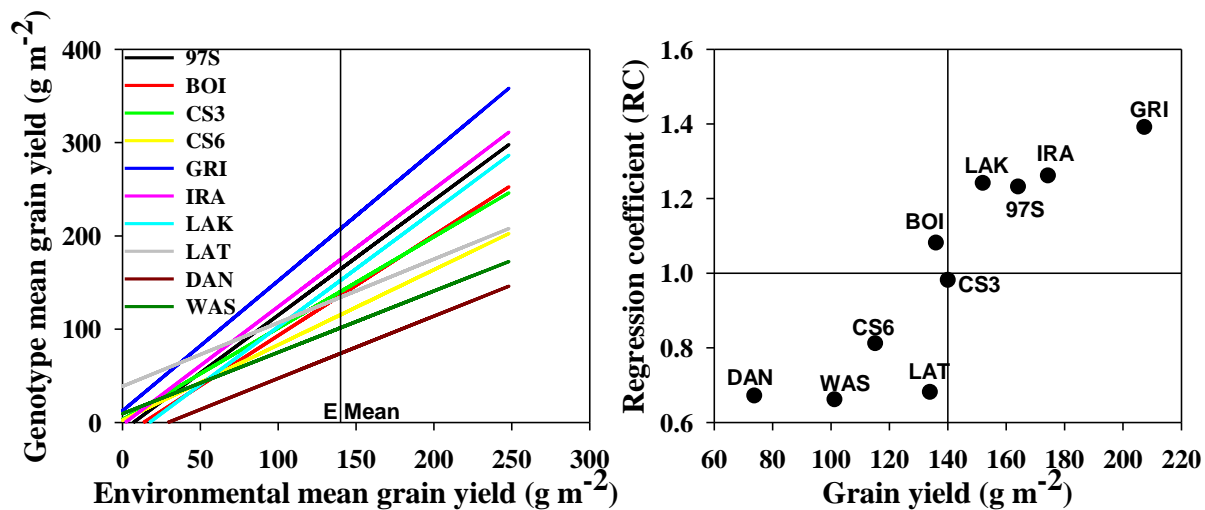


Figure 5.7: Plots of the regression lines for mean grain yields of cultivars on environment mean grain yields (a) and its relationship to cultivar adaptation (regression coefficients) (b) according to Finlay and Wilkinson (1963) (Abdulai *et al.*, 2012).

It is, therefore, important to identify genotypes that are adapted or are stable across environments. In this study, the Caudatum genotypes (Grinkan and IRAT 204) showed higher yield potential than the other genotypes across environments (Figure 5.3). These two cultivars are therefore recommended for use in tactical adaptation to climate change. Grinkan can be used

at all the sites, but IRAT 204 to should be deployed at sites analogous to the northern most site because of its earliness and the short length of growing season at such sites.

Grain yield was positively correlated with panicle weight ($r=0.816$), number of grains per panicle ($r=0.899$) and harvest index ($r=0.339$). The strong correlation observed between grain yield and number of grains per panicle in this study concurs with observations made by Bidinger and Raju (2000) in pearl millet (*Pennisetum glaucum* (L.) R. Br.) and Craufurd and Peacock (1993) in sorghum. Harvest index, the ratio of grain yield to total aboveground plant biomass, is an indication of a plant's efficiency in converting biological yield into economic yield (Kusalkar *et al.*, 2003), and can be used as a criterion in selection for high yielding genotypes. The negative correlation, between harvest index and plant height, found in this study concurs with observations made by Can and Yoshida (1999) and Tariq *et al.* (2007) on sorghum. The significant positive correlation observed between crop duration and plant height in this study is not surprising for tropical germplasm (such as those used in the present study) because this could have resulted from the reported linkage between one of the height loci (*Dw2*) and the major photoperiod sensitivity locus, *Ma1* (Lin *et al.*, 1995). Number of grains per panicle was found to be the most important trait to target for rapid direct improvement in grain yield because it could be improved simultaneously with panicle weight, threshing ability, and harvest index, due to the magnitude of its indirect contribution to grain yield via these traits. This concurs with Veerababirani *et al.* (1994) who earlier reported that grains per panicle had the highest positive effect on grain yield. Similar results were obtained by Mahajan *et al.* (2011) who found that grains per panicle and panicle length had direct positive effects on grain yield. The path analysis showed that grains per panicle mediated, to a larger extent, relationships between grain yield and the other traits, as indicated by its strong indirect effects on grain yield via the other traits. Breeding efforts that target the study environments and /or its analogues should be skewed towards selecting for high grains per panicle. Molecular techniques targeted at grains per panicle could be deployed for rapid results.

5.3 Photo-thermal and latitudinal effects on phenology

Matching the phenology of cultivars to environments in order to evade devastating abiotic and biotic conditions is important for adapting varieties to environments. That is very important under changed climates because an increase in temperature is most likely to modify the duration

cycles of cultivars. Crop duration which is a major determinant of the sizes of sources and sinks is also influenced by both genotype and environment.

Table 5.1: Duration from emergence to panicle initiation (EPI; expressed in days) and total leaf number of seven sorghum varieties evaluated at three sowing dates at three Malian locations with different latitude (Cinzana, Sotuba, and Farako), averaged across two test years and two replications. The \pm symbol precedes the standard error of measurement. Adapted from Abdulai et al., 2012b)

Varieties	Sowing	Days to PI			Total Leaf Number		
		Cinzana	Sotuba	Farako	Cinzana	Sotuba	Farako
Boiguel	Jun. 10th	70 \pm 2.1	65 \pm 1.3	56 \pm 2.1	38.8	36.3	27.8
	Jul. 10th	52 \pm 0.3	53 \pm 2.8	49 \pm 1.3	32.3	27	24.5
	Aug. 10th	36 \pm 1.5	38 \pm 1.3	36 \pm 2.5	21	23.5	18
CSM 388	Jun. 10th	79 \pm 1.9	73 \pm 0.3	60 \pm 0.9	34.3	32.8	24.5
	Jul. 10th	53 \pm 0.9	50 \pm 1.2	40 \pm 0.6	28	23.8	19.8
	Aug. 10th	36 \pm 1.2	33 \pm 2.0	28 \pm 2.4	18.5	18	15
CSM 63E	Jun. 10th	49 \pm 1.3	41 \pm 1.5	28 \pm 0.7	26	23.3	17.5
	Jul. 10th	31 \pm 1.0	30 \pm 2.4	25 \pm 0.5	19.8	17.3	14.5
	Aug. 10th	26 \pm 0.5	24 \pm 1.5	21 \pm 2.2	15.5	15.8	12
Grinkan	Jun. 10th	76 \pm 1.1	73 \pm 0.4	61 \pm 2.4	36.5	34.5	26.5
	Jul. 10th	55 \pm 0.9	54 \pm 1.1	47 \pm 0.3	30.3	25.8	22.3
	Aug. 10th	36 \pm 1.1	39 \pm 3.1	33 \pm 1.6	20	19.3	15.5
IRAT 204	Jun. 10th	31 \pm 0.5	35 \pm 1.8	24 \pm 1.2	19.8	21	17.3
	Jul. 10th	28 \pm 0.9	40 \pm 6.1	26 \pm 0.3	17.8	19.5	15
	Aug. 10th	31 \pm 1.9	35 \pm 3.0	28 \pm 1.7	17.3	17.8	14.3
Keninkeni	Jun. 10th	70 \pm 2.0	66 \pm 1.2	49 \pm 1.0	33	31.8	22
	Jul. 10th	48 \pm 1.1	48 \pm 1.7	35 \pm 1.2	26.8	22.5	18
	Aug. 10th	32 \pm 2.3	29 \pm 2.5	28 \pm 2.6	17.3	16.3	13.3
Dancouma	Jun. 10th	98 \pm 2.1	92 \pm 1.0	85 \pm 1.2	39.5	37	32.5
	Jul. 10th	71 \pm 0.8	71 \pm 1.8	62 \pm 0.8	32	28.8	25
	Aug. 10th	46 \pm 1.7	48 \pm 1.8	39 \pm 0.3	23	22.5	18.3

Crop duration of day-neutral sorghum cultivars is driven mainly by the number of heat units accumulated at the development phases, while development phases of photoperiod sensitive cultivars are driven by temperature initially, and day length after they have passed the basic

vegetative phase (BVP) and started responding to day length for development. This makes the simulation of the time to flowering for photoperiod-sensitive sorghum cultivars complex.

The thrust of this study was, first of all, to determine if and how latitude affects the development of existing sorghum cultivars, and secondly, the precision with which available crop models predict the phenology of photoperiod sensitive sorghum if they are sown at different latitudes. From this study, it was found that the duration of the vegetative phase, and for that matter crop duration as well as the number of leaves, increased with latitude. For example, the highest difference in day-length between the locations was less than 8 minutes, but for the same sowing date, a difference in crop duration of up to 21 days was recorded for some cultivars at different latitudes (Table 5.1).

It was also revealed in this study that for some varieties, sensitivity to day length is a function of location and / or latitude because some cultivars which behaved as day-neutral at one location became photoperiod sensitive at another (Figure 5.4), buttressing the complexity of the photoperiod sensitivity trait. The complexity of photoperiodic responses in sorghum has been acknowledged by a number of researchers (Clerget *et al.*, 2004; Dingkuhn *et al.*, 2008). One other major finding from this study was that existing models underestimate the effect of latitude on the phenology of sorghum, especially the photoperiod sensitive.

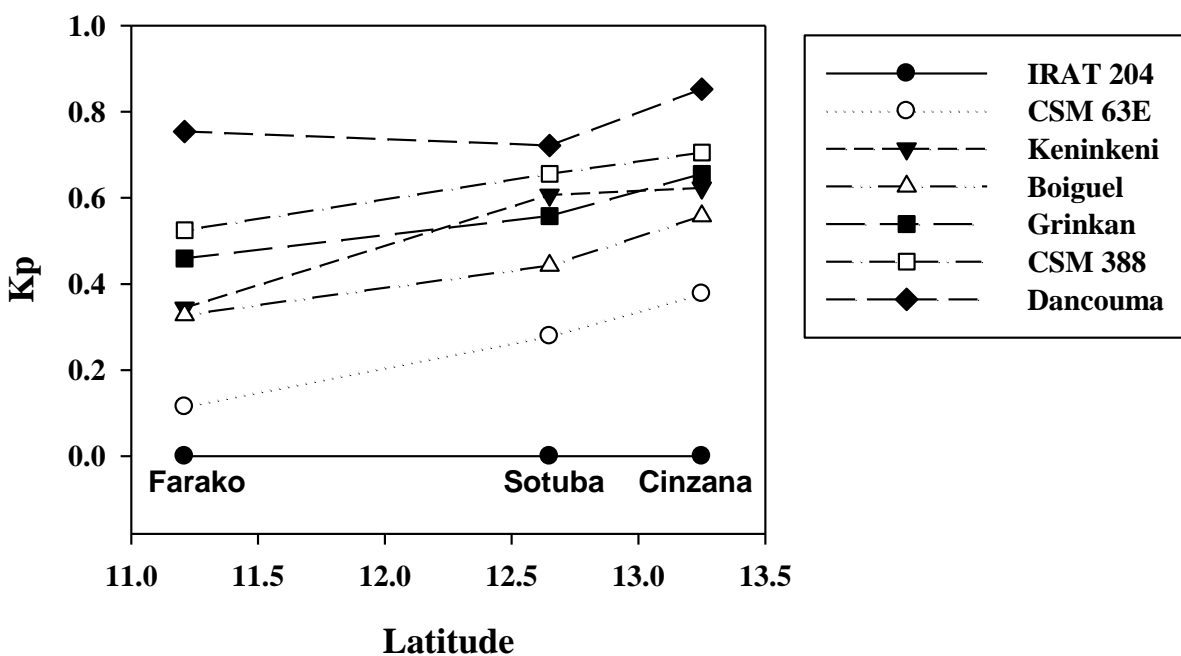


Figure 5.8- Latitude effect on the photoperiodism coefficient (Kp) of seven sorghum cultivars evaluated at three locations (Cinzana, Sotuba, and Farako) along a North-South latitude gradient in Mali.

Another important finding of the study was the necessity to correct simulation coefficients of the current crop models to account for the effect of latitude on the phenology of, especially photoperiod-sensitive sorghum cultivars. This is critical for delineating suitable areas for growing the sorghum cultivars currently found in West Africa, and for forecasting how such cultivars will respond to changing climates. However, it is still necessary to develop new crop models that can accurately simulate the combined effects of sowing date and latitude on the phenology of sorghum. The current study extended knowledge by facilitating the proposal of a very economical phenotyping procedure which requires observed data on just the number of days from seedling emergence to when the ligules on the flagleaf have appeared for three different sowing dates together with daily records of atmospheric temperature. However, the proposed procedure for phenotyping includes some simplifications that could mask the component traits of phenology that are not considered by the model. Thermal time from panicle initiation to the time the ligules of the flagleaf appear is constant (Dingkuhn *et al.*, 2008), so the model estimates the photoperiod-sensitive phase without considering the juvenile phase which cannot be measured in the field. The study, found 22 days to be a more appropriate duration for the time from the initiation of panicles to when the ligules on the flagleaf appear, though this was slightly higher than the 18 days being used in the SARRA-H model (Kouressy *et al.*, 2008) but coherent with the formula presented by Folliard *et al.* (2004). Based on the findings of this study the number of days from seedling emergence to panicle initiation can be estimated by simply deducting 22 days from the number of days from seedling emergence to the appearance of ligules on the flagleaf.

6. Conclusion and outlook

The performance of the genotypes used for this study points to the fact that some of the existing cultivars could be used directly for tactical adaptation to climate change. The superior performance of Grinkan (a composite of Caudatum and Guinea) across environments in this study confirms the need to combine photoperiod sensitivity and stay-green traits in future genotypes. The difference of up to 3 weeks in crop duration observed for the same cultivar sown on the same day at different latitudes that have a maximum of 8-minute difference in their photoperiods shows the importance of latitude on the growth and development of photoperiod

sensitive sorghum cultivars. The current crop model equipped with the "impatience" sub-model for handling photo-thermal the response of the phenology of photoperiod sensitive cultivars does not accurately simulate the effect of latitude when simulating for one location with parameters derived from data collected at another location. It is possible to improve the performance of the "impatience" model if latitude is considered in the adjustment of coefficients of one location to simulate phenology of photoperiod sensitive sorghum cultivars at another location. The results obtained in the study could explain why many of the studies on photoperiodism on trials with various latitudes or with artificial light have not been successful. It is possible to identify niches for different cultivars by integrating photoperiod sensitivity into a crop model and using a Geographic Information System (GIS).

Little is known about how accurately the latitude correction used in this study will work if extrapolated beyond the range of latitude explored by our experiments. It will be first necessary to decipher the physiological basis for the strong effect of latitude observed and also test a larger number of cultivars at a wider range of latitude to confirm and /or improve on the findings of this study.

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Declaration of Originality


I hereby declare that this doctoral thesis is independently written by me. In addition, I confirm that no other sources than those specified in the thesis have been used. I certify that this thesis, either in the current or similar format, has not been submitted to any other institution in order to obtain a Ph.D. or any other academic degree.

Ich erkläre hiermit, dass ich diese Dissertation selbständig angefertigt habe. Es wurden nur die im Literaturverzeichnis aufgeführten Hilfsmittel benutzt und fremdes Gedankengut als solches kenntlich gemacht. Ich versichere, dass ich diese Arbeit in gleicher oder ähnlicher Form noch keiner anderen Institution zur Prüfung vorgelegt habe.



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<p style="text-align: center;">Conference Oral Presentations</p>	<ol style="list-style-type: none"> 2. Abdulai, A.L., Kouressy, M., Vaksmann, M., Asch, F., Giese, M., Brueck, H., 2012. Latitude and date of sowing influence phenology of photoperiod-sensitive sorghums. <i>J. of Agron. and Crop Sci.</i> 198, 340-348. 3. Abdulai, A.L., Parzies, H., Kouressy, M., Vaksmann, M., Asch, F., Brueck, H., 2012. Yield Stability of Photoperiod-Sensitive Sorghum [<i>Sorghum bicolor</i> L. (Moench)] Accessions under Diverse Climatic Environments. <i>Int. J. Agric. Res.</i> 7, 17-32. 4. Owusu, R. K., Clotey, V. A., Abdulai, A.L., 2007. Blanching of hot peppers employing the solarisation method in northern Ghana. <i>Bots. J. Agric. Appl. Sci.</i> 3, 106-111. 1. Abdulai, A.L., Kouressy, M., Vaksmann, M., Tekete, M.L., Kane, M., Asch, F., Giese, M., Brueck, H., 2011. Effect of phenological variation on photoperiod-sensitive sorghum production in the Sahel. Oral presentation at the International Conference on “Crop improvement, Ideotyping, and Modelling for African Cropping Systems under Climate Change (CIMAC)”. February 7-9, 2011. University of Hohenheim, Stuttgart, Germany. 2. Abdulai, A.L., Brueck, H., Kouressy, M., Vaksmann, M., Asch, F., 2011. Morphological traits for sorghum ideotype development to cope with climate variability in Africa. Oral presentation at the International Conference on “Crop improvement, Ideotyping, and Modelling for African Cropping Systems under Climate Change (CIMAC)”. February 7-9, 2011. University of Hohenheim, Stuttgart, Germany. 3. Abdulai, A.L., Kouressy, M., Vaksmann, M., Asch, F., Giese, M., Brueck, H., 2011. Latitude effect on the development of photoperiod sensitive sorghum. Oral presentation at the International Conference on “Crop improvement, Ideotyping, and Modelling for African Cropping Systems under Climate Change (CIMAC)”. February 7-9, 2011. University of Hohenheim, Stuttgart, Germany.
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	<p>4. Abdulai, A.L., Brueck, H., Asch, F., Kouressy, M., Vaksmann, M., 2010. Water-use Efficiency of Sorghum (<i>Sorghum bicolor</i> L. Moench) Genotypes in Mali, West Africa, is Affected by Climate Variability. Oral presentation at the 12th annual Tropentag on “World Food System: A Contribution from Europe”. September 14-16, 2010. Zurich, Switzerland.</p> <p>5. Abdulai, A.L., Kouressy, K., Vaksmann, M., Brueck, H., Asch, F., 2009. Responses of Sorghum Varieties to Climatic Variability — a Case Study Within the RISOCAS Project. Oral presentation at the 11th annual Tropentag on “Biophysical and Socio-economic Frame Conditions for the Sustainable Management of Natural Resources”. October 6-8, 2009. Hamburg, Germany.</p>
<p>Conference Poster Presentations</p>	<p>1. Abdulai, A.L., Kouressy, M., Vaksmann, M., Brueck, H., Asch, F., 2010. Growth Analysis of Biomass Production for Diverse Sorghum Genotypes under different scenarios of climate. Poster presented at the 11th European Society of Agronomy Conference. August 29 – September 03, 2010. Montpellier, France.</p> <p>2. Abdulai, A.L., Asch, F., van de Giesen, N., 2004. Physiological and morphological responses of <i>Sorghum bicolor</i> Moench to static and dynamic drought conditions. Poster presented at the 6th annual “Tropentag” for International Research on Food Security, Natural Resource Management and Rural Development. October 5-7, 2004. Berlin, Germany.</p>
<p>Dissertations</p>	<p>1. Abdulai, A.L., 2005. Morphological and physiological responses of sorghum (<i>Sorghum bicolor</i> Moench.) to static and dynamic drought in a green house. MSc. Thesis. University of Bonn, Germany March 2005.</p> <p>2. Abdulai, A.L., 2001. Studies of the morphology and performance of six (6) local hot pepper (<i>Capsicum annuum</i> L.) cultivars. Dissertation for BSc. Agriculture, Kwame Nkrumah University of Science and Technology, Kumasi-Ghana.</p>

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