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Quantifying potential benefits of drought and heat tolerance in rainy season sorghum for adapting to climate change

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ABSTRACT

Maintaining high levels of productivity under climate change will require developing cultivars that are able to perform under varying drought and heat stresses and with maturities that match water availability. The CSM-CERES-Sorghum model was used to quantify the potential benefits of altering crop life cycle, enhancing yield potential traits, and incorporating drought and heat tolerance in the commonly grown cultivar types at two sites each in India (cv. CSV 15 at both Akola and Indore) and Mali (cv. CSM 335 at Samanko and cv. CSM 63E at Cinzana), West Africa. Under current climate CSV 15 on average matured in 108 days and produced 3790 kg ha^{-1} grain yield at Akola; whereas at Indore it matured in 115 days and produced 3540 kg ha^{-1} grain yield. Similarly under current climate, CSM 335 matured in 120 days and produced 2700 kg ha^{-1} grain yield at Samanko; whereas CSM 63E matured in 85 days at Cinzana and produced 2210 kg ha^{-1} grain yield. Decreasing crop life cycle duration of cultivars by 10% decreased yields at all the sites under both current and future climates. In contrast, increasing crop life cycle by 10% increased yields up to 12% at Akola, 9% at Indore, 8% at Samanko and 33% at Cinzana. Enhancing yield potential traits (radiation use efficiency, relative leaf size and partitioning of assimilates to the panicle each increased by 10%) in the longer cycle cultivars increased the yields by 11–18% at Akola, 17–19% at Indore, 10–12% at Samanko and 14–25% at Cinzana under current and future climates of the sites. Except for the Samanko site, yield gains were larger by incorporating drought tolerance than heat tolerance under the current climate. However, under future climates yield gains were higher by incorporating heat tolerance at Akola, Samanko and Cinzana, but not at Indore. Net benefits of incorporating both drought and heat tolerance increased yield up to 17% at Akola, 9% at Indore, 7% at Samanko and 16% at Cinzana under climate change. It is concluded that different combinations of traits will be needed to increase and sustain productivity of sorghum in current and future climates at these target sites and that the CSM-CERES-Sorghum model can be used to quantify benefits of incorporating certain traits.

1. Introduction

Sorghum (*Sorghum bicolor* L.) is an important staple food for many poor people and a source of feed and fodder for livestock production in India and sub-Saharan Africa. In India, it is grown on 8.02 M ha with an average productivity of 920 kg ha^{-1}. In West Africa, Nigeria is the largest producer of sorghum followed by Burkina Faso and Mali. In Mali, it is grown on 1.06 M ha with an average productivity of 1020 kg ha^{-1} (mean of 2006–2010 production data, FAO, 2012). Climate change, in terms of higher temperatures, changing precipitation patterns and increased frequency of extreme weather events (IPCC, 2007), will alter the current crop growing conditions across the globe with crop yields affected either negatively or positively. However, in the most arid and semiarid tropical regions, the projected climate change effect will be mostly negative thus threatening food security in these regions (Fischer et al., 2005; Howden et al., 2007). In the semi-arid tropical regions the changes in rainfall coupled with a rise in temperature may reduce the length of the growing period (LGP) as determined by the duration of soil water availability (Cooper et al., 2009). Therefore, it will be important that the maturities of crops match the periods of water availability to achieve higher and stable yields. The optimum air temperature range for vegetative and reproductive growth of sorghum is 26–34 °C (Hammer et al., 1993; Alagarswamy and Ritchie, 1991) and 25–28 °C (Prasad et al.,

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2006, 2008), respectively. In the semi-arid tropics where sorghum is currently grown during the rainy season, the mean crop-season temperatures are already close to or above these optimum temperatures. However, increased CO_2 concentration in the atmosphere could have beneficial effects on crop growth, and could partially negate the detrimental effects of rising temperatures depending on the degree of the temperature rise, and the extent of crop transpiration reductions under elevated CO_2. Srivastava et al. (2010), using the InfoCrop-Sorghum simulation model and the HadCM3 output for the A2a scenario, projected that climate change in different regions of India will reduce the rainy season sorghum yield by 3–16% by 2020 and 17–76% by 2050–2080; whereas for the post-rainy season sorghum, climate change would likely reduce yields up to 7% by 2020, 11% by 2050 and 32% by 2080. Blane (2012) used a panel data approach to relate crop yields to standard weather variables and estimated 7–47% reduction in yield of sorghum for sub-Saharan Africa by 2100. Using the EPIC crop model and the HadCM climate model output, Butt et al. (2005) predicted an 11–17% reduction in sorghum yield for Mali by 2030. Other simulation studies for Africa (Tingem et al., 2008, 2009; Chipanshi et al., 2003) also reported substantial reductions in sorghum yield under future climates.

When climate changes are relatively small, the current agronomic adaptation measures can help farmers adapt. However, more extensive changes may require genetic improvement of crops for greater tolerance to elevated temperatures and drought, improved responsiveness to rising CO_2 and the development of new agronomic technologies (Boote et al., 2011). Because agriculture will not experience the same climate change in all regions, site-specific improved crop varieties, cropping systems and management practices will be needed to adapt to the characteristics of the future climates and other natural endowments of each region. Plant breeders are already targeting specific plant traits to breed new crop varieties that will perform better in future climates (Reddy et al., 2011; Nguyen et al., 2013). Therefore, an early assessment of the potential benefits of such traits in the target environments is needed before significant investments are made to pursue these goals. Plant growth simulation models can be used to assess crop growth and yield advantages due to new technologies in different environments by using environment-specific weather, soil and agronomic management data (Boote et al., 2001). Since these crop models incorporate parameters representing genetic traits, they can be used to predict the potential benefit single or multiple combinations of traits would have on crop performance in a target environment (Boote et al., 2001; Singh et al., 2012). Using crop models, many researchers in the past have proposed plant ideotypes or genetic improvement of crops for higher yields (Landivar et al., 1983; Boote and Tollenaar, 1994; Yin et al., 1999; Hammer et al., 1996, 2002, 2005, 2010; Tardieu, 2003; White and Hoogenboom, 2003; Messina et al., 2006; Suriharn et al., 2011). Hammer et al. (2005, 2010) used the ASPIM modeling framework to hypothesize genetic improvement in sorghum, although they did not focus on issues of adaptation to climate change. Under climate change new constraints and opportunities for crop production are emerging, thus these studies need to be further extended to determine new plant types for improved adaptation to future climates of the target regions. With improved knowledge, understanding and modeling of crop response to climate change factors (high temperatures, increased rainfall variability, increased atmospheric CO_2 concentration and their interactions); crop models have excellent potential to assess benefits of genetic improvement for higher yields and adaptation to current and future target environments. The objective of this study was to quantify the potential benefits of genetic improvement, particularly crop life cycle, yield potential, drought and heat tolerance traits and their combinations, on sorghum yields under current and future climates of selected sites in the sorghum growing areas of India and West Africa.

2. Materials and methods

Simulations of sorghum were carried out for two sites each in India (Akola and Indore) and Mali (Samanko and Cinzana), West Africa. The geographical, soil and climatic characteristics of the sites are given in Table 1.

2.1. The sorghum model and input data

We used the CSM-CERES-Sorghum model, which is a part of the DSSAT v4.5 (Decision Support System for Agro-technology Transfer, version 4.5) (Hoogenboom et al., 2010), to study the impact of climate change factors and genetic modifications on the productivity of sorghum. The major components of the sorghum model are vegetative and reproductive development, carbon, water and nitrogen balance and these processes have been described in detail by Ritchie et al. (1998) and Ritchie (1998). The model simulates sorghum growth and development using a daily time step from sowing to maturity and ultimately predicts yield. The model is sensitive to various climate change factors such as high temperature, variability in rainfall and increased CO_2 concentrations in the atmosphere. In the model, high temperature influences growth and development by shortening the crop life cycle and reducing allocation of biomass to the reproductive organs through decreased seed set and seed growth rate. Increased CO_2 concentration in the atmosphere increases crop growth and biomass production through increased radiation use efficiency (RUE). Increased CO_2 also reduces transpiration from the crop canopy via an empirical relationship between canopy conductance and CO_2 concentration. These two processes of CO_2 effects are described in detail in Sections A.1 and A.2 of Appendix A. Changes in rainfall characteristics influence soil water balance and thus the pattern of water availability to the crop during its life cycle. Thus the model has the potential to simulate the impact of climate change on growth and development of sorghum.

The minimum data set required to simulate a crop is described by Jones et al. (2003). Briefly, it includes site characteristics (latitude and elevation), daily weather data (solar radiation, maximum and minimum air temperatures and precipitation), basic soil profile characteristics by layer (soil saturation limit, drained upper limit and lower limit of water availability, bulk density, organic carbon, pH, root distribution factor, runoff and drainage coefficients) and management data (cultivar, sowing date, plant population, row spacing, sowing depth, dates and amounts of irrigation and fertilizers applied). The cultivar data include the genetic coefficients (quantified traits) that distinguish one cultivar from another in terms of phenological development, photoperiod sensitivity, growth and partitioning to vegetative and reproductive organs. Crop-specific parameters, which describe the basic processes of crop growth, development and yield formation of sorghum, are also inputs to the model.

For India, the soil profile data for the sites were obtained from the soil survey bulletins published by the National Bureau of Soil Survey and Land Use Planning, Nagpur, India (Lal et al., 1994). Long-term weather data (daily records of rainfall, maximum and minimum temperatures) for the sites were obtained from the India Meteorology Department, Pune, India. Solar radiation for the sites was estimated from the temperature data following the method of Bristow and Campbell (1984). For the Samanko and Cinzana sites, the soils data were taken from the records of the ICRISAT Research Station at Bamako, Mali. The weather data for the Samanko and Cinzana sites were downloaded from the NASA site