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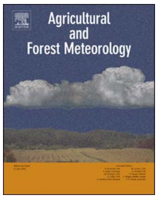

Research Paper

Characterising production environments for maize in eastern and southern Africa using the APSIM Model

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ABSTRACT

Maize is a staple food crop in eastern and southern Africa with significant contribution for food security of this vast region. Efforts to breed superior maize cultivars for the region are challenged by high genotype x environment interactions arising mainly due to variable soil moisture supply caused by high temporal and spatial variability in rainfall. Information on major drought patterns and their frequencies, which can assist in dealing with such interactions in the region, however, is not available. The objectives of this study were therefore to (i) identify major drought patterns and their frequencies, (ii) identify iso-environments based on the similarity of drought patterns and (iii) explore scope for yield improvement through optimising genotype and management in various drought patterns. We used the well validated APSIM model to characterise major drought patterns and their frequencies experienced by maize cropping systems in the target population of environments spread across six countries of the region including Ethiopia, Kenya, Tanzania, Malawi, Mozambique and Zimbabwe. The database used for the model simulations consisted of 35 locations, 17–86 years of daily climate records and three cultivars. The dynamic changes in water supply-demand ratio in each season was simulated against the thermal time for each cultivar across the 35 locations and clustering analysis was used to cluster the major drought patterns. The analysis identified four major drought patterns characterised by low-stress, mid-season drought, late terminal drought and early-terminal drought patterns, occurring at 46%, 11%, 22% and 21% of the years, respectively. The frequencies of these patterns varied in relation to locations, genotypes and management. Yield reduction of up to 80% was observed for early terminal drought compared with low-stress drought pattern. There was significant scope for yield improvement through manipulating genotype and management. These results have important implications for germplasm enhancement and deployment over similar environments in the region.

1. Introduction

Maize (*Zea mays* L.) is a staple food in Africa. The crop is particularly important in eastern and southern Africa where it accounts for 32% of consumed calories and 29% of the total area under cereal production (FAOSTAT, 2015). In eastern and southern Africa, maize is grown by the vast majority of rural households under rainfed conditions and plays a major role in food security in the region (Bänziger et al., 2006; Heisey and Edmeades, 1999). In spite of its importance, maize yield in sub-Saharan Africa has stagnated at $< 2\ \mathrm{t\ ha^{-1}}$ compared to the world average of more than $5\ \mathrm{t\ ha^{-1}}$ (FAOSTAT, 2015). This is partly due to inability to mitigate the effect of biotic and abiotic stresses that limit maize production and productivity across countries in sub-Saharan Africa (Badu-Apraku et al., 2003; Badu-Apraku et al., 2011; Vivek et al., 2010). Drought, high temperature and low soil fertility are the most important abiotic stresses that affect maize production in Africa (Bänzinger and Diallo, 2004; Lobell et al., 2011; Weber et al., 2012; Worku et al., 2007). Further, it is predicted that climate change will have a negative impact on maize production in Africa (Fisher et al., 2015; Lobell et al., 2011).

Increasing and stabilising the productivity of maize for climatically variable environments is an important breeding goal in the region (Badu-Apraku et al., 2003; Bänziger et al., 2006). Efforts to overcome these abiotic stresses through the development of better adapted cultivars have been occurring in several breeding programs in Africa (Cairns et al., 2013; Weber et al., 2012; Windhausen et al., 2012).

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However, breeding for these abiotic stresses is complicated by substantial interactions between the stresses and the developmental stages of the crop, which poses challenges to the efficiency of selection. Further, spatial and temporal variations in rainfall coupled with the different soil types can give rise to different seasonal drought frequencies as has been noted for Malawi, Mozambique, Zambia and Zimbabwe in southern Africa (Tesfaye et al., 2016).

Breeders have traditionally used multi-location trials to classify crop growing environments (Atlin et al., 2000; Windhausen et al., 2012) or used probe and/or reference genotypes (Brancourt-Hulmel et al., 1999; Mathews et al., 2011) in their quest to minimize genotype × environment interactions arising due to climatic variability. This type of classification can lead to site groupings that can vary from year to year (Yang et al., 2005). Mega-environment classification based on environmental factors such as day length, average precipitation and temperature has also been used to sub-divide maize testing environments in Africa (Hartkamp et al., 2000; Setimela et al., 2005). However, this classification of maize testing sites into mega-environments has been refined and modified at different times due to subjectivity of defining mega-environments (Bänziger et al., 2006; Hartkamp et al., 2000). There is thus a need to characterise environments to identify main drought patterns and enable research and breeding to focus on environments of interest (Chapman et al., 2000; Windhausen et al., 2012).

The use of a crop model with historic weather data presents an alternative approach to describe the types and frequency of major abiotic stresses in the target population of environments (TPE) which is defined as sets of environments to which improved crop varieties developed by a breeding program need to be adapted (Chapman et al., 2003; Muchow et al., 1996). It also helps to estimate the phenotypic performance of traits in specific managements and environments that are difficult to predict through use of multi-environment trials (Hammer et al., 2010; Messina et al., 2009). This approach has been used for different crops in different parts of the world to characterise the water-deficit patterns experienced by a crop (Chapman et al., 2000; Chauhan et al., 2013; Chenu et al., 2013; Harrison et al., 2014) and its relevance in terms of improving breeding efficiency has been demonstrated (Chenu et al., 2011; Hammer et al., 2005).

Characterization and identification of stress patterns for maize production in eastern and southern Africa is of paramount importance to improve breeding efficiency by identifying breeding priorities and allocation of resources. This is particularly useful in light of recurring droughts (Bänzinger and Diallo, 2004) and changing climatic conditions in the region (Lobell et al., 2011; Schlenker and Lobell, 2010). Therefore, the objectives of this study were to (i) identify types and frequencies of drought patterns for maize grown in eastern and southern Africa, (ii) identify *iso*-environments based on the similarity of drought patterns and (iii) explore scope for maize yield improvement through optimising genotype and management in various drought patterns.

2. Materials and methods

2.1. Focus regions

The study was focussed on six eastern and southern African countries including Ethiopia, Kenya, Tanzania, Malawi, Mozambique and Zimbabwe where maize is the predominant crop produced in the country (Fig. 1). Sites in each country were selected to represent major maize production areas as well as their use by regional and national research programs. A total of 35 probe locations (26 sites, nine of which had bimodal rainfall pattern and hence two seasons) were targeted for this study (Table 1).

2.2. Model simulations

The simulations were run using the APSIM-Maize module (Keating et al., 2003), version 7.8 (www.apsim.info). The APSIM-Maize module simulates several key underpinning physiological processes and operates on a daily time step in response to daily input of weather data, soil characteristics and crop management actions. Information on soil characteristics was collected from published papers, national and regional research reports, and personal communications with on-site agronomists. Parameterized generic soils (Dimes et al., 2015; Tesfaye et al., 2016) that match the soil types of each location based on secondary information were used in these simulations. Weather parameters such as daily maximum and minimum temperature, rainfall and solar radiation were accessed from the International Maize and Wheat Improvement Center (CIMMYT), International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) and national agricultural research organizations in Ethiopia, Malawi and Kenya. The period for which these data were available varied from 17 years to 86 years (Table 1). Weather data for each selected site were subjected to quality control measures to fill in missing data in weather data acquisition (Bai et al., 2010; Van Wart et al., 2013). The gaps were filled using the National Aeronautics and Space Administration (NASA) data (http://power.larc.nasa.gov) (Bai et al., 2010; Arndt et al., 2012; Folberth et al., 2013; Van Wart et al., 2013; Van Wart et al., 2015) following the method used by Bai et al. (2010) and Van Wart et al. (2013).

APSIM parameterized maize cultivars of different maturity groups, early (SC401, 990 °Cd), medium (SC625, 1060 °Cd) and late (SC709, 1090 °Cd) (Keating et al., 2003) were used in the simulations.

Planting windows, hybrids, planting density and nitrogen fertiliser rates were the key management input that varied for different locations. Each year the simulated crop was planted at the first planting opportunity within a planting window of the location which was determined on the basis of secondary information collected from published papers, national and regional research reports, and personal communications with on-site agronomists. Maize planting windows for southern African countries including, Malawi, Mozambique and Zimbabwe is between November 1 and January 15 (Table 1). In some parts of Kenya and Tanzania, which are characterized by bimodal rainfall, maize is grown in two seasons. The planting window for short rainy season in Kenya and Tanzania is between 1 and 30 October and in the long rainy season maize is planted between February 20 and April 30. In Ethiopia, however, maize is grown only once per year (Table 1). The planting date was determined based on a sowing criteria which was accumulation of 20 mm of rainfall over 3 days, and at least 30 mm plant available soil water in the top 60 cm soil profile to initiate germination (Kassie et al., 2013; Smith et al., 2016). If this requirement was not met, sowing was still done on the last day of the window which became effective if there was rainfall within 10 days after sowing.

Two different sets of simulations were run for this study. The first set of simulations were run using one level of research recommended site-specific nitrogen (N), plant density, and the most commonly grown cultivar at each of the 35 probe locations to identify drought patterns. Plant density used in different sub-regions varied from 3.7 to 5.3 plants m^{-2} (Table 2). Research recommended nitrogen fertilizer rates also varied for different sites (Table 2). These research recommended rates were generally derived in experiments to optimise yield, and are not related to the farmers' ability to apply them or government policies towards supporting fertiliser use. Although the recommended N rates were expected to meet N demand of the crop, the possibility that the crop may still experience N-stress cannot be ruled out as other factors such as drought during determination of N rates may have favoured lower N rates.

The second set of simulations were run to analyse drought frequencies in the region as influenced by sets of three cultivars representing early, medium and late maturity and three planting densities including 4, 5 and 6 plants m^{-2} for each of the 35 probe locations, to