Characterization of maize growing environments in eastern and southern Africa using the APSIM model

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Abstract
Maize grown in eastern and southern Africa experiences random occurrences of drought. This uncertainty creates difficulty in developing superior varieties and their agronomy. Characterisation of drought types and their frequencies could help in better defining selection environments for improving resistance to drought. We used the well tested APSIM maize model to characterise major drought stress patterns and their frequencies across six countries of the region including Ethiopia, Kenya, Tanzania, Malawi, Mozambique and Zimbabwe. The database thus generated covered 35 sites, 17 to 86 years of daily climate records, 3 varieties and 3 planting densities from a total of 11,174 simulations. The analysis identified four major drought environment types including those characterised by low-stress which occurred in 42% of the years, mid-season drought occurring in 15% of the years, late-terminal stress which occurred in 22% of the years and early-terminal drought occurring in 21% of the years. These frequencies varied in relation to sites, genotypes and management. The simulations showed that early terminal stress could result in a yield reduction of 70% compared with low-stress environmental types. The study presents the importance of environmental characterization in contributing to maize improvement in eastern and southern Africa.

Key words
Drought stress, environmental types, GxE interactions and Zea mays L.

Introduction

In eastern and southern Africa maize (*Zea mays* L.) is predominantly grown in small-holder farming systems under rain-fed conditions with limited inputs. This generates high genotype x environment interactions which complicates the efforts to develop superior varieties and their agronomy. Breeders have been classifying environments based on results from multi-environment trials conducted over locations and seasons. Due to time and cost constraints, mapping of the entire maize growing region cannot be performed using this approach. Better understanding of temporal dynamics of water stress patterns experienced by the crop and the frequency with which each pattern occurs in the maize growing areas can be achieved using crop models (Chapman et al., 2003). It can also help to estimate the phenotypic performance of traits in specific managements and environments that are difficult through use of multi-environment trials (Hammer et al., 2013). Studies on several field crops have used this approach in different parts of the world to characterise the water-deficit patterns experienced by a crop (Chauhan et al., 2013; Chenu et al., 2013; Hammer et al., 2014; Harrison et al., 2013). Characterisation of maize growing environments in eastern and southern Africa using long-term climate data based on crop simulations has, however, not been attempted. Therefore, this study was initiated to identify types and frequency of stresses, and identify iso-environments based on the similarity of stress patterns.

Materials and methods

The study was carried out for six eastern and southern African countries including Ethiopia, Kenya, Tanzania, Malawi, Mozambique and Zimbabwe (Figure 1). Thirty five probe sites from these countries were selected to represent major maize production areas in these countries. The efficacy of APSIM maize model was tested using yield data recorded from 16 eastern and southern Africa maize testing sites for five hybrids ($r^2 = 0.84$) and the result can be obtained upon request from the authors. The specific planting window for each site and relevant soil types were determined based on expert knowledge and from

secondary information. The planting window for southern Africa countries including, Malawi, Mozambique and Zimbabwe varied between November 1 and January 15. In eastern African countries of Kenya and Tanzania, which are characterized by bimodal rainfall, the planting window for the long rainy season varies between February 20 and April 30 whereas for the short rainy season varies between 1 and 30 October. APSIM parameterized maize varieties of different maturity groups including early, medium and late with three different planting densities (4, 5 and 6 plants/m2) were used to identify the potential stress levels in the region. To avoid the confounding effects of nitrogen with water stress, nitrogen fertilizer was considered as non-limiting and set to the maximum, 300 kg/ha. Daily weather data including maximum and minimum temperature, rainfall and solar radiation were accessed from different sources. The period for which these data were available varied from 17 years to 86 years. Plant available soil water at planting was set to 30 mm within the planting window to initiate germination. The temporal pattern of daily crop water stress (water supply/demand (SDR)) for each simulation was centred at anthesis and averaged at every 100oCd from 400 ^{o}Cd before anthesis and 700 ºCd after anthesis. SDRs were clustered using the R program (R Core Team (2014)), and major drought patterns determined. Further, sites were clustered into four yield clusters, cluster 1 to 4, based on simulated yield.

Figure 1. Map of the study countries and sites in eastern and southern Africa.

Results

Drought patterns and their yield distribution in the region

Maize growing sites in eastern and southern Africa were clustered into four distinct major maize environmental types (Figure 2a). The sites that were dominated by low-stress environmental types (LS) comprising situations where plants were not limited by drought, with SDR being close to unity. Mid-season stress environmental types (MS) were characterized by stress that started early at the vegetative stage, exposed the crop to drought at anthesis and relieved by rainfall events during the late grain filling stage. The late terminal (LT) and early terminal (ET) environmental types differed on severity and time of the onset of drought. The late terminal drought environmental types (LT) commenced after flowering and the crop experienced drought late at the grain filling stage while early terminal drought environmental types (ET) started early at the vegetative stage, stressed the crop with increasing severity from anthesis to maturity. These drought types in the region were related with yield performance. The highest median yield (6.69 t/ha) was observed for LS while the lowest median yield (2.33 t/ha) was observed for ET (Figure 2b).

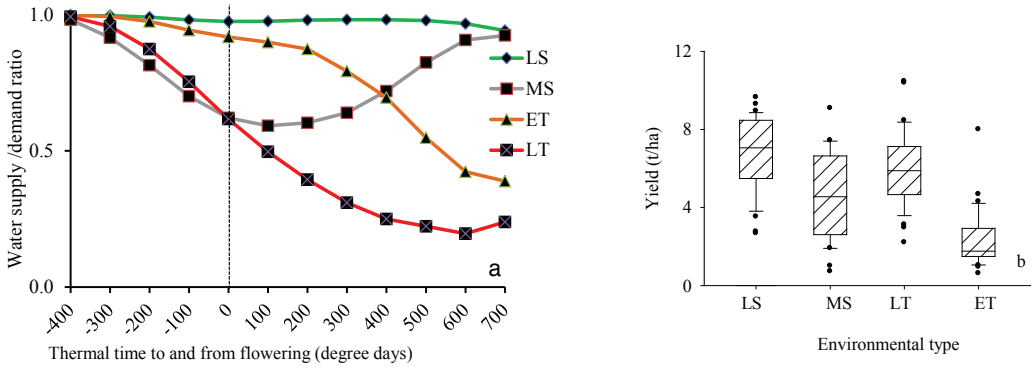

Figure 2. Water supply and demand ratio as a function of thermal time around flowering for the environmental types identified in maize growing sites in the region (a) and their yield distribution (b). Vertical bars and points outside the box plots indicate the standard errors and the outliers in each environmental type respectively.

Frequency of drought patterns in the region

The frequency of occurrence of LS, MS, LT and ET environmental types was 42, 15, 22 and 21% of the seasons, respectively (Figure 3a). The frequency of occurrence of these environmental types, however, was highly variable across sites and yield clusters (data not shown). The range of frequency of occurrence of different environmental types at each maize growing site was different. For instance, the frequency of MS, LT and ET ranged from 0 to 61, 4 to 37 and 0 to 77 respectively across different sites. ET was more frequent accounting for 43% of the seasons at sites in yield cluster 1 (Figure 3b). However, in sites of yield cluster 4 LS environmental types accounted for 68% of the seasons. The frequencies of occurrence of terminal drought environmental types increased from early maturity variety Katumani to late maturity variety H614 as the planting density increased from 4 to 6 plants/m^2 (Figure 3b). However, changes in stress frequency due to changes in maturity and density were higher for the sites in yield cluster 2 and 3.

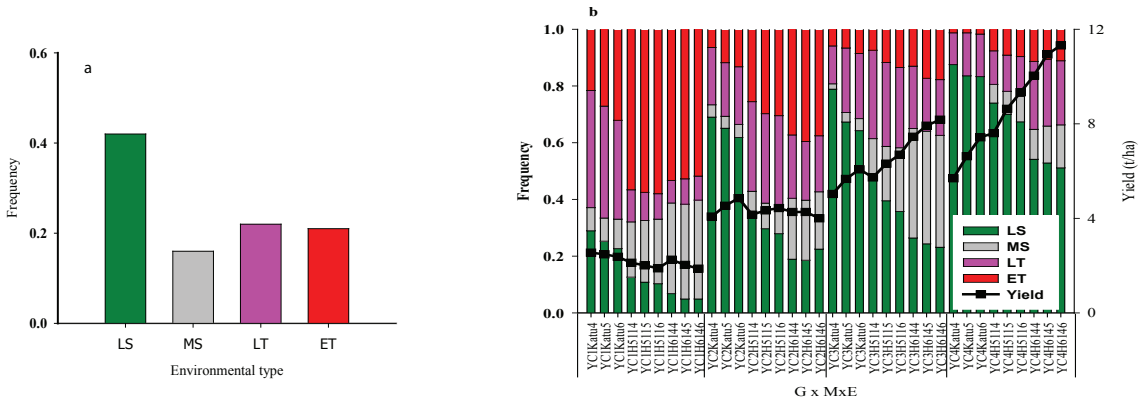

Figure 3. Frequency of occurrence of environmental types in the region (a) and for each combinations of variety x density x environment (GxMxE) in each yield cluster. The numbers 4 – 6 are the densities 4 to 6 and genotypes Katu, H511 and H614 are early maturity variety Katumani, medium maturity variety H511 and late maturity variety H614 respectively. YC1 to YC4 are yield cluster 1 to 4.

Discussion

Drought frequencies varied across sites, maturity and management in the region

Broad ranges of drought patterns occurring in the region were classified into four major environmental types (Figure 2a). The stress free environmental type (LS) was more frequent in the region (42 % of the seasons) (Figure 3a). This was higher than non-stress environmental type frequency reported for different crops in Australia (Chauhan et al., 2013; Chenu et al., 2013; Hammer et al., 2014) and closer to that reported for maize in Europe (Harrison et al., 2013). The frequency of environmental types varied in relation to maturity and planting density in the region. MS and ET environmental types were least frequent for early maturity variety while the late maturing type experienced frequent terminal stress particularly in environments with low growing season rainfall (Figure 3b). This is because earlier flowering mostly increases LS conditions and could be recommended to escape water stress in the absence of other limiting factors around flowering

(Chenu et al., 2013). Earliness *per se* will reduce yield potential (e.g., in yield cluster 3 and 4). This emphasizes the relative merits of different traits for various target population of environments (Harrison et al., 2013; Hammer et al., 2014).

Yield variability in the region

The range of yield difference in the region was very high, 1.3 to 9.7 t/ha. Across the region a close relationship between rainfall and maize yield was observed (Figure 3b). As expected, the highest grain yield was observed for the LS environmental types (Figure 2b). However, yield was significantly reduced for MS and ET environmental types. This was attributed to the stresses coinciding with flowering and grain filling stages of the crop. High yield reduction, 70 %, in our study for ET stress environmental types was consistent with the previous reports 55 - 75 % reduction in yield from drought stress created by withholding irrigation before flowering to maturity (Cairns et al., 2013). Smaller (8 to 10 %) yield reduction, observed for LT suggested that the crop experienced the stress at the late grain filling stage, after good synchronization and seed set were secured.

Conclusion

The eastern and southern Africa maize growing environments can be classified into four environmental types based on timing, intensity and frequency of drought, i.e. water non-limiting, mid-season stress, late terminal and early terminal stresses environmental types. When other abiotic stresses are alleviated, targeting breeding objectives based on environmental types could provide a better framework for breeding and agronomy research. For instance, it could enhance germplasm deployment over similar environmental types across the region and optimize resources that are scarce and usually constraining breeding and agronomic research in eastern and southern African countries.

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