Field Crops Research 217 (2018) 113–124

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Application of the APSIM model to exploit G × E × M interactions for maize improvement in Ethiopia

Solomon Seyoum[a,*], Rao Rachaputi[a], Yash Chauhan[a,b], Boddupalli Prasanna[c], Solomon Fekybelu[d]

[a] *Queensland Alliance for Agriculture and Food Innovation, The University of Queensland, Gatton, QLD 4343, Australia*
[b] *Department of Agriculture and Fisheries, Kingaroy, QLD 4610, Australia*
[c] *International Maize and Wheat Improvement Centre (CIMMYT), Nairobi, United Nations Avenu, Gigiri, Kenya*
[d] *Advanta Seeds Pty Ltd., Toowoomba, QLD 4350, Australia*

ARTICLE INFO

Keywords:
APSIM
G × E × M interaction
Plant density
Drought patterns
Zea mays L.

ABSTRACT

High inter-seasonal rainfall variability presents the biggest risk for farmers to invest in best management practices in maize grown in much of Ethiopia. Optimising genotype (G) and management (M) of maize for different growing environments (E) could alleviate risks associated with seasonal rainfall variability and enhance reliability of production of this crop. In this study, we explored this possibility with the help of the APSIM maize model. The model was first calibrated and then tested on different sets of data for its ability to simulate phenology, dry matter and yield of six genotypes of differing maturity grown under rainfed conditions at four plant densities at four sites including Bako, Hawassa, Melkassa and Adamitulu in Ethiopia in 2013 and 2014. The model accurately predicted plant available soil water (NRMSE = 6%), days-to-flowering (NRMSE = 4%), days to maturity (NRMSE = 4%), leaf area index (NRMSE = 6%), biomass (NRMSE = 13%) and yield (NRMSE = 5%). The simulations revealed that increasing plant density increased water use efficiency of genotypes at all sites. The model in conjunction with site-specific soil properties and 33 years of daily weather data was then used to simulate changes in the water supply demand ratio to determine dominant drought patterns at each site which could be clustered into four major drought patterns. These drought patterns included low stress occurring in 55% of the seasons, mid-season occurring in 11% of the seasons, early terminal drought in 17% of the seasons, and late terminal drought 17% of the seasons. The frequencies of these drought patterns varied at different sites. These could also be manipulated by genotypes of different maturity and plant density resulting in different yield outcomes at each site. The study revealed significant scope for yield improvement by manipulating G and M, with larger effects in favourable seasons.

1. Introduction

Maize (*Zea mays* L.) in Ethiopia is currently grown over 2.1 million ha and has the largest smallholder coverage with 8.7 million land holders (FAOSTAT, 2015). It accounts 27% of Ethiopia's total cereal production and is critical for food security for smallholder subsistence farmers. In the 2014 cropping season, a total of 7.2 million tons of maize was produced and there is a trend for increase in area and productivity in the last 10 years (FAOSTAT, 2015). Between 2003 and 2013, maize productivity increased from 1.5 to 3.2 t ha^{-1}, mainly due to adoption of improved varieties and fertilizers (Abate et al., 2015). However, the average maize yield at farm level remains low compared to the yields (5–10 t ha^{-1}) recorded on research stations and in on-farm trials (Howard et al., 2003; Bogale et al., 2011; Legesse et al., 2011). This yield gap is further complicated by extreme variability in rainfall distribution (Kassie et al., 2013; Deressa and Hassan, 2009).

Rainfall variability and associated risks influence farmers' decisions to adopt best management practices, such as the choice of hybrids, plant density and sowing date adjustments (Shiferaw et al., 2014; Kassie et al., 2013). The plant densities of 4.4 plants m^{-2} for the sub-humid and 5.3 plants m^{-2} for the semi-arid environments that are currently being used by farmers in Ethiopia were recommended in the 1980s using old hybrids and open pollinated varieties (Workayehu et al., 2002; Workayehu et al., 1993). However, several new hybrids with different attributes have been developed for these environments (Legesse et al., 2011; Bogale et al., 2011). Adoption of improved hybrids and the use of fertilizer by farmers have substantially increased in Ethiopia (Abate et al., 2015). The recent rapid germplasm development and deployment in maize breeding leading to new hybrids, requires a reassessment of current varietal and agronomic options for maize

---

[*] Corresponding author.
E-mail address: solomon.seyoum@uq.net.au (S. Seyoum).

https://doi.org/10.1016/j.fcr.2017.12.012
Received 9 October 2017; Received in revised form 10 December 2017; Accepted 12 December 2017

production in Ethiopia.

An understanding of the timing, duration and intensity of drought stress relative to crop phenology is critical to manage the potential impact of stress levels on maize (Cooper et al., 2014; Harrison et al., 2014). However, this largely depends on the understanding of the key processes driving crop growth under a range of biophysical and socio-economic conditions (Webber et al., 2014). Traditional plant breeding and/or agronomic studies lack an understanding of the underpinning factors driving genotype × environment × management interactions (Chenu et al., 2011). This can, however, be explored through the use of a process-based crop simulation models (Chenu et al., 2013; Hammer et al., 2010). Crop models can be applied to understand the interactions amongst the environment, genotype and management processes governing crop growth, and thus assist in explaining yield variation between genotypes and environments (Hammer et al., 2006; Hammer et al., 2014; Chenu et al., 2013; Messina et al., 2009).

Several crop models, including the Agricultural Production System sIMulator (APSIM), have been successfully used to simulate crop growth over a wide range of conditions (Holzworth et al., 2014; Hammer et al., 2010; Keating et al., 2003; Asseng et al., 2000). The APSIM maize model has the potential for wide applicability in exploring various management options under African conditions (Roxburgh and Rodriguez, 2016; Probert et al., 2005; Mkoga et al., 2010). However, there has been limited use of APSIM in exploring G × E × M interactions and it has not been used to characterize maize growing environments in Ethiopia.

The objectives of this study were to a) calibrate and test the APSIM maize model using G × E × M data collected from field experiments conducted in the target production environments in Ethiopia, b) to test local practices against the best-bet genotype and management combinations identified in the field study, and c) to characterize drought patterns and to assess the potential risks and opportunities for increasing maize productivity in target environments.

2. Materials and methods

2.1. Site description

The study was conducted at four sites in Ethiopia including Bako, Hawassa, Melkassa and Adamitulu where maize is grown as a staple food crop. Bako and Hawassa are classified as tepid to cool sub-humid agro-ecology (Abera et al., 2009). Bako is characterized by a unimodal rainfall pattern with rainy season occuring from April to December while Hawassa is characterized by bimodal rainfall received between March and September (Abera et al., 2009; Workayehu, 2014). Melkassa and Adamitulu are situated in the Central Rift Valley (CRV) of Ethiopia. The CRV is characterized as a semi-arid where agricultural production adversely affected by rainfall variability (Biazin et al., 2011; Kassie et al., 2013). All the field sites were located in the sub-humid mid-altitude and semi-arid areas which account for 80% of the total maize growing areas in Ethiopia (Nigussie et al., 2001).

2.2. Field experiments for model calibration and testing

Field experiments were conducted in the 2013 and 2014 seasons. Physical, weather and crop management details of the experimental sites is given in Table 1. Ten and six genotypes were tested in the 2013 and 2014 cropping seasons, respectively. Six genotypes were common across the two seasons. A plant density of 5, 6 and 7 plants m^{-2} were used in 2013, whereas 2, 5, 7 and 9 plants m^{-2} were used in 2014. Plant densities were common across all the sites within a season.

2.2.1. Experimental design and crop husbandry

At all sites field trials were laid out in split-plot designs, with plant density as main-plots and genotypes as sub-plots. All genotypes were planted in six rows of 5.1 m length with 75 cm inter-row spacing, i.e., 22.95 m^2 area. Plant to plant spacing varied depending on the plant density. The research-recommended nitrogen (N) rates in Ethiopia vary from 41 kg ha^{-1} to 119 kg N ha^{-1}, depending on the soil type. To avoid the confounding effects of N with soil moisture, the APSIM maize model, in conjunction with site specific soil properties and 33 years of daily weather data, was used to simulate maize yield responses to N and to determine the N level when the yield reaches a plateau at each site. Based on the model outputs, soil N content was brought up to a level of 100 kg N ha^{-1}. The N was applied in the form of urea (46%) ($(NH_2)_2CO$) with a third applied as basal dose at planting while the remaining two-thirds side-dressed at about 35 days after emergence.

Table 1
Site coordinates, soil, weather and field operation for experiments conducted at four sites during the period 2013 and 2014 cropping seasons in Ethiopia.

Station	Hawassa	Bako	Melkassa	Adamitulu
Latitude (°N)	7°03′	9°12′	8°24′	7°90′
Longitude (°E)	38°31′	37°08′	39°21′	38°43′
Altitude (m)	1689	1650	1550	1650
Soil (0–30 cm)				
Type	Clay loam	Clay	Clay loam	Sandy loam
Organic carbon (%)	1.85	2.88	1.34	0.95
Total N (%)	0.15	0.23	0.14	0.09
pH	6.47	5.18	7.29	8.08
Weather (1982–2014)				
Annual mean MaxT (°C)	27.28	27.98	28.62	27.42
Annual mean MinT (°C)	12.76	13.80	13.83	12.89
Annual total rainfall (mm)	1006	1303	825	810
Crop management				
Planting 2013	10 May	5 Jun	4 Jul	29 May
Planting 2014	21 May	6 Jun	9 Jul	
Harvesting 2013	23 Oct	5 Dec	7 Dec	10 Nov
Harvesting 2014	24 Oct	25 Nov	27 Nov	

Where MinT and MaxT were minimum and maximum temperatures, respectively.

The seeds were hand-planted at the onset of rainfall at each site, resulting in some variation in dates of planting, as indicated in Table 1. Two seeds per hill were planted, and later thinned to one seedling per hill to maintain the desired plant population in each plot. The crop was adequately protected from pests and diseases.

2.2.2. Measurements

Days to flowering was counted when 50% of plants in a plot had extruded silk visible (Betrán et al., 2003) and physiological maturity was recorded when a black layer had formed at the kernel base (Ritchie et al., 1993). For leaf area measurement, plants were sampled from a unit land area at the vegetative (V5) and flowering (VT) stages at each site. All leaves were dissected and individual leaf area was computed as lamina length × maximum width × 0.75 (Birch et al., 1998). Leaf area per plant was calculated as the sum of the area of all leaves (Muchow and Carberry, 1989). Leaf area index (LAI) was computed as the ratio of total leaf area per unit ground area (D'Andrea et al., 2006). The shoot biomass was measured at the vegetative (V5), flowering (VT) and physiological maturity (R6) stages of the crop. The plant samples were dried in a fan-circulated oven set at 65 °C to a constant weight and expressed on dry weight basis. Plants in the middle two rows, from an area of 7.65 m^2 were hand-harvested at physiological maturity for yield measurement. The harvested ears were shelled, kernel weight and kernel moisture content recorded, and kernel yield was adjusted to 0% grain moisture content.

2.3. Weather data

The daily weather data during the experimental period including maximum and minimum temperatures and rainfall were obtained from the weather stations located within a radius of 500 m from the experimental site. Data on daily incoming solar radiation were lacking and were estimated using the modified Hargreaves-Samani equation