Agricultural Water Management 180 (2017) 88–98

Contents lists available at ScienceDirect

Agricultural Water Management

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

Research paper

Modeling yield and biomass responses of maize cultivars to climate change under full and deficit irrigation

L. Ma[a,*], L.R. Ahuja[a], A. Islam[b], T.J. Trout[c], S.A. Saseendran[d], R.W. Malone[e]

[a] USDA-ARS, Agricultural Systems Research Unit, Fort Collins, CO 80526, United States
[b] Division of Natural Resources Management (NRM), Indian Council of Agricultural Research (ICAR), New Delhi, 110012, India
[c] USDA-ARS, Water Management and Systems Research Unit, Fort Collins, CO 80526, United States
[d] USDA-ARS, Crop Production Systems Research Unit, Stoneville, MS 38776, United States
[e] USDA-ARS, The National Lab for Agricultural and The Environment, Ames, IA 50011, United States

ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form 20 October 2016
Accepted 6 November 2016

Keywords:
Systems modeling
RZWQM
DSSAT
Cultivar traits
Climate adaptation
Crop simulation
Irrigation management
Colorado

ABSTRACT

With as much as 4.8 °C increase in air temperature by end of 21st century, new crop cultivars are needed for adapting to the new climate. The objective of this study was to identify maize (*Zea mays* L.) cultivar parameters that maintain yield under projected climate for late in the 21st century under full and deficit irrigation in a semi-arid region. The Root Zone Water Quality Model (RZWQM2) was calibrated with four years of maize data from northeastern Colorado, USA, under various irrigation conditions and was then used to simulate climate change effects on maize production with current management practices. Results showed that projected climate change decreased yield by 21% and biomass by 7% late in the 21st century (2070–2091) under full irrigation, compared to yield in the current climate (1992–2013). Under deficit irrigation, the corresponding reductions were 14% and 3%, respectively. Using the cultivar parameters calibrated with RZWQM2 for southern Colorado condition did not show yield decrease under future climate, but it simulated much lower yield under current climate in northeastern Colorado. A cultivar from the DSSAT (Decision Support Systems for Agrotechnology Transfer) crop database (GL 482) produced similar yield to experimental data under current climate and increased yield by 4% at full irrigation under future climate in northeastern Colorado. Using Latin Hypercube Sampling (LHS), we also identified 70 cultivars with longer maturity duration (between silking and physiological maturity) and higher grain filling rate for mitigating climate change effects on maize production. These two identified traits can guide plant breeders in developing cultivars for the future.

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1. Introduction

The 5th Assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014) presents the evidence that the planet has already warmed up and that the climate warming will continue during the 21st century. The increase of global mean surface temperature by the end of the 21 st century (2081–2100) relative to 1986–2005 is likely to be 0.3 °C–1.7 °C under the most stringent mitigation of greenhouse gas emissions scenario (Representative Concentration Pathway RCP2.6), 1.1 °C–2.6 °C under intermediate scenario RCP4.5, 1.4 °C–3.1 °C under RCP6.0, and 2.6 °C–4.8 °C under very high emissions scenario RCP8.5. Assessment of many studies covering a wide range of regions and crops shows that negative impacts of climate change on crop yields have been more common than positive impacts. The positive impacts occurred at higher latitudes due to prolonged growing season (Lobell et al., 2011). Adaptive responses to a changing climate require actions that range from incremental changes to more fundamental, transformational changes. Incremental changes include the improvement of soil and water conservation practices, tillage and fertility management, changing planting dates, and the selection of alternate cultivars and crops at the farm scale. The transformational changes include the development of new systems and technologies, and the related infrastructures on the regional scale.

To find adaption strategies for the upcoming climate change, the Consultative Group on International Agricultural Research (CGIAR)

Abbreviations: AET, actual evapotranspiration; DSSAT, decision support systems for agrotechnology transfer; ET, Evapotranspiration; ETc, Crop evapotranspiration; ETr, Alfalfa reference evapotranspiration; GLEAMS, Groundwater Loading Effects of Agricultural Management Systems; IPCC, Intergovernmental Panel on Climate Change; LHS, Latin Hypercube Sampling; RCP, Representative Concentration Pathway; RZWQM, Root Zone Water Quality Model; SHAW, simultaneous heat and water; TDR, time domain reflectometry; WUE, Water use efficiency.

* Corresponding author.
E-mail address: Liwang.Ma@ars.usda.gov (L. Ma).

http://dx.doi.org/10.1016/j.agwat.2016.11.007
0378-3774/Published by Elsevier B.V.

centers, whose research is focused on plant genetic resources, are reorganizing their conservation and improvement activities for developing cultivars adapted to climate change for different regions (Lopez-Norliega et al., 2012). They have a new program on Climate Change, Agriculture, and Food Security (CCAFS), and are using climate change analogues to guide the adaptation strategies for selected high-priority regions. Using one or more General Circulation Model (GCM) models, the analogues tool (available online at: analogues.ciat.cgiar.org/climate) takes climate and rainfall predictions for a particular site and searches for places with similar conditions at present. Armed with the knowledge of what they may face in future, farmers, researchers and policy makers can determine their adaptation options based on real – as opposed to crystal ball-gazing – models. Other scientists are using transgenic hybrid crops for cultivation in warmer climates (Lavaria et al., 2015).

System models are also used to project climate change effects on crop adaptation. The most commonly simulated incremental adaptation strategies are the planting date (Bhuvaneswari et al., 2014; Singh et al., 2014a; Dharmarathna et al., 2014), plant population (Brisson et al., 2011), irrigation (Singh et al., 2014a; Moradi et al., 2013), fertilization (Rezaei et al., 2014; Nendel et al., 2014), double cropping (Meza et al., 2008; Monzon et al., 2007), crop rotation (Nendel et al., 2014), and new crop cultivars resistant to heat and drought and longer growing season (Singh et al., 2014b,c; Liu et al., 2013). In Ethiopia, the farmers have already changed their farming practices to adapt to perceived climate change and variability through crop and variety choice, adjustment of cropping calendar, and in-situ soil moisture conservation (Kassie et al., 2013). In northeast China, the farmers' adapted longer-season alternate varieties of maize and rice (*Oryza sativa* L) led to a significant yield increase in both crops (Yu et al., 2014).

One of the models used for simulating climate change effect on crop production is the DSSAT (Decision Support Systems for Agrotechnology Transfer) cropping system model (Jones et al., 2003). Since this model has a simple water balance module, it was coupled with the Root Zone Water Quality Model (RZWQM) that has more detailed soil water and soil nutrient simulations (Ma et al., 2006). This hybrid model was released as RZWQM2 and used for a wide range of management effects on crop production and environmental quality (Ma et al., 2007). Recently the hybrid model has been used to study climate change effects in the Central Great Plains of the U. S. (Islam et al., 2012a; Ko et al., 2012). Islam et al. (2012a) showed that maize yield under full irrigation decreased in future years of 2050 s and 2080s, because the negative effects of higher temperatures dominated over the negligible positive effects of increasing CO_2 levels. They further showed that the yield decrease was linearly related to the shortening of the growing period caused by increased temperature. They suggested that cultivars with longer growth duration and tolerant to higher temperatures might be one of the possible adaptation strategies. Ko et al. (2012) also simulated decrease in winter wheat (*Triticum aestivum* L.), maize and proso millet (*Panicum miliaceum* L.) yields in dryland cropping systems under climate change conditions using RZWQM2. The yield decrease was significant for both maize and proso millet in year 2075, but not for wheat. They also found that changes in planting dates did not mitigate the yield reduction of the crops significantly in dryland cropping systems. However, few studies have focused on testing different crop cultivars and their responses to climate change under deficit irrigation conditions. Recently, Ding et al. (2016) found that climate change effects on yield and water use efficiency (WUE) could be offset by adapting later maturity cultivars for winter wheat. In addition, later maturity cultivars better adapted to variation and distribution of precipitation.

However, few studies have focused on finding the appropriate cultivars or cultivar traits that maintain similar yield under projected future climate, especially under different irrigation conditions. As a continuation of our previous study (Islam et al., 2012a), the objective of this paper was to identify maize (*Z mays* L) cultivar traits that are adaptable to maintaining maize production under projected climate for late in the 21st century (2080s) under both full and deficit irrigation conditions in northeast Colorado. Different from previous studies (Islam et al., 2012a,b; Ko et al., 2012), we used the Fifth Assessment Report (AR5) climate change projections based on new emission scenarios called Representative Concentration Pathways (RCP), as opposed to those used by Islam et al. (2012a). RZWQM2 coupled with the DSSAT-Maize (version 4.0) was first calibrated for an irrigation study in Colorado from 2008 to 2011, and then used to simulate maize yield and biomass with 22 years of projected climate between 2070 and 2091 in comparison with baseline (historical) weather from 1992 to 2013. Maize cultivars evaluated are a local cultivar, a cultivar south of the experimental location, several cultivars with long growing seasons from the DSSAT crop database, and hypothetical cultivars created using the Latin Hypercube Sampling (LHS) method.

2. Materials and methods

2.1. Experimental data for model calibration

The four year field experiment was initiated in 2008 near Greeley, Colorado (40.45° N, 104.64° W, and 1428 m above the sea level) in the semi-arid High Plains of the USA to study crop water use efficiency under deficit irrigation. The site has mean air temperature of 9.5 °C and annual mean precipitation of 24.8 cm from 1992 to 2013. The soil is a sandy loam with average sand, silt, and clay contents of 71, 11, and 18%. Surface soil pH and organic matter content varied between 7.5–8.2 and 0.9–1.1%. The site contains three major soil types: Nunn (Fine, smectitic, mesic Aridic Argiustolls), Olney (Fine-loamy, mixed, superactive, mesic Ustic Haplargids), and Otero (Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents). Soil physical properties with depth are shown in Table 1. Weather data were recorded on site with a standard meteorological station (GLY04) (http://ccc.atmos.colostate.edu/~coagmet/), including hourly solar radiation ($W\,m^{-2}$), precipitation (mm), air temperature (°C), wind speed ($m\,s^{-1}$), and relative humidity (%). Missing data were obtained from a station 800 m to the east of the field site (GLY03).

Maize ('Dekalb 52–59′) was planted in early May at an average rate of 81,000 seeds per hectare with 0.76 m row spacing. Six irrigation treatments (micro-irrigation with surface drip tubing adjacent to each row) with four replicates each were designed (Randomized Block Design on 24 9 × 40 m plots) to meet a certain percentage of potential crop evapotranspiration (ETc) requirements as estimated from Food and Agriculture Organization reference ET standard (FAO 56, Allen et al., 1998) during the growing seasons: 100% (T1), 85% (T2), 75% (T3), 70% (T4), 55% (T5), and 40% (T6) of ETc. These treatments were selected to cover a wide range of crop water stress, yet producing viable yields. ETc requirement was estimated on a daily basis from the product of reference evapotranspiration ETr (alfalfa) and a crop coefficient. Actual average percentage of full ET requirements met across the four years was 100% ETc, 88% ETc, 80% ETc, 75% ETc, 60% ETc, and 52% ETc. In this study, 100% ETc (full irrigation) and 60% ETc (deficit irrigation) were used to evaluate irrigation effects under climate change conditions, because 60% ETc treatment had sustainable higher yield than the 52% ETc treatment. In addition, both 100% ETc and 60% ETc treatments had similar average water use efficiency. Detailed information about the experiment is available in Ma et al. (2016) and Fang et al. (2014)

All the experimental data (four years and six treatments) were used to calibrate the DSSAT-Maize crop module in RZWQM2 and