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Research paper

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

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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.

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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

Table 1
Soil bulk density, saturated soil water content, and field capacity calibrated in RZWQM2 (Fang et al., 2014).

Soil Depth (cm)	Bulk Density ρ_b (g cm^{-3})	Saturated soil water content (θ_s) (cm^3 cm^{-3})	Measured ranges for field capacity ($\theta_{1/3}$) (cm^3 cm^{-3})	Final calibrated values for $\theta_{1/3}$ (cm^3 cm^{-3})
0–15	1.492	0.437	0.180–0.320	0.231
15–30	1.492	0.437	0.140–0.320	0.242
30–60	1.492	0.437	0.130–0.380	0.230
60–90	1.568	0.408	0.130–0.370	0.206
90–120	1.568	0.408	0.130–0.320	0.205
120–150	1.617	0.390	0.130–0.310	0.263
150–200	1.617	0.390	0.130–0.310	0.310

Table 2
Cultivar parameters used to identify the traits that sustain maize yield under climate change conditions.

Acronyms used and definitions of traits.	Units	Range of values given in the DSSAT database	Calibrated values for the Greeley site (Fang et al., 2014)	Calibrated values for the Rocky Ford site (Saseendran et al., 2015)	A Cultivar from DSSAT database (GL 482)	70 LHS sampled cultivars, mean and ranges
P1 – Degree days (base temperature of 8 °C) from seedling emergence to end of juvenile phase.	ptd[a]	100–450	245.6	330	240	312(250–365)
P2 – Day length sensitivity coefficient [the extent (days) that development is delayed for each hour increase in photoperiod above the longest photoperiod (12.5 h) at which development proceeds at maximum rate].		0–2	0.156	0.3	0.7	0.85(0.14–1.0)
P5 – Degree days (base temperature of 8 °C) from silking to physiological maturity	ptd	600–1000	704	920	990	921(862–989)
G2 – Potential kernel number	kernel number per plant	440–1000	994	740	907	762(606–957)
G3 – Potential kernel growth rate	mg per kernel per day)	5–16	6.24	6.0	8.8	11.9(8.6–15.0)
PHINT – Degree days required for a leaf tip to emerge (phyllochron interval)	ptd	38–55	52.89	40.0	38.9	46.2(41–52)

[a] Photothermal days.

the calibrated results were published in Fang et al. (2014) and Ma et al. (2012, 2016). The six cultivar parameters were calibrated along with field capacity (Tables 1 and 2) by minimizing simulation errors for yield, biomass, leaf area index, and soil water content using the PEST software (Ma et al., 2016). Fig. 1 shows the simulated yield and biomass in comparison with measured values with root mean squared errors of 354 kg ha^{-1} for yield and 1202 kg ha^{-1} for biomass. Tables 1 and 2 list the calibrated soil and plant parameters.

2.2. RZWQM2 model

The Root Zone Water Quality Model (RZWQM2, version 2.0) with the DSSAT 4.0 crop modules was used in this study. The RZWQM2 is a process-oriented agricultural system model that integrates various physical, chemical and biological processes and simulates the impacts of soil-crop-nutrient management practices on soil water, crop production, and water quality under different climates (Ahuja et al., 2000). The model simulates potential crop evapotranspiration, soil water retention and uptake, and plant growth. The crop simulation modules (CSM) from the DSSAT 4.0 package facilitate detailed growth and development simulations of 16 different crops (Jones et al., 2003). The DSSAT4.0-CERES plant growth module for corn in RZWQM2 simulates phenological stage, vegetative and reproductive growth, and crop yield and yield components. The soil and water routines of RZWQM are linked with the CSM-DSSAT 4.0 crop modules in the current version of RZWQM2 (Ma et al., 2006). It has the advantages of combining the detailed soil water, nitrogen, and management modules of RZWQM2 with the detailed crop modules of DSSAT 4.0. RZWQM2 uses the Green-Ampt equation for infiltration and the Richards' equation for redistribution of water among different soil layers (Ahuja et al., 2000). Potential evapotranspiration is calculated using the extended Shuttleworth–Wallace equation modified to include the surface crop residue dynamics on aerodynamics and energy fluxes. RZWQM2 also includes algorithm to reduce potential transpiration due to CO_2 effect with the Shuttleworth-Wallace equation. The decrease in potential transpiration demand, in turn, decreases root water uptake and actual transpiration, and reduces plant water stress (Islam et al., 2012a,b). Management practices simulated in the model include: tillage, applications of irrigation, manure and fertilizer at different rates and times by different methods, planting and harvesting operations, and surface crop residue dynamics.

The CSM-DSSAT 4.0 crop model uses a base temperature of 8.0 °C. Maximum air temperature for maize development is 34 °C. The base temperatures for plant growth and grain filling are 6.2 °C and 5.5 °C, respectively. Optimum air temperature ranges for growth and grain filling are 16.5–33.0 °C and 16.0–39.0 °C, respectively. Plant growth and grain filling stop at 44.0 °C and 48.5 °C, respectively. CO_2 effect on photosynthesis follows the Michaelis-Menten equation (Islam et al., 2012a).

2.3. Climate change scenario projections

In this study, bias corrected and spatially disaggregated (BCSD) projections from the World Climate Research Program's (WRCP) CMIP5 climate projections archive (ftp://gdo-dcp.ucllnl.org/pub/dcp/archive/cmip5/bcsd/BCSD/) were used to generate multi-model ensemble climate change scenarios using 37 available GCM

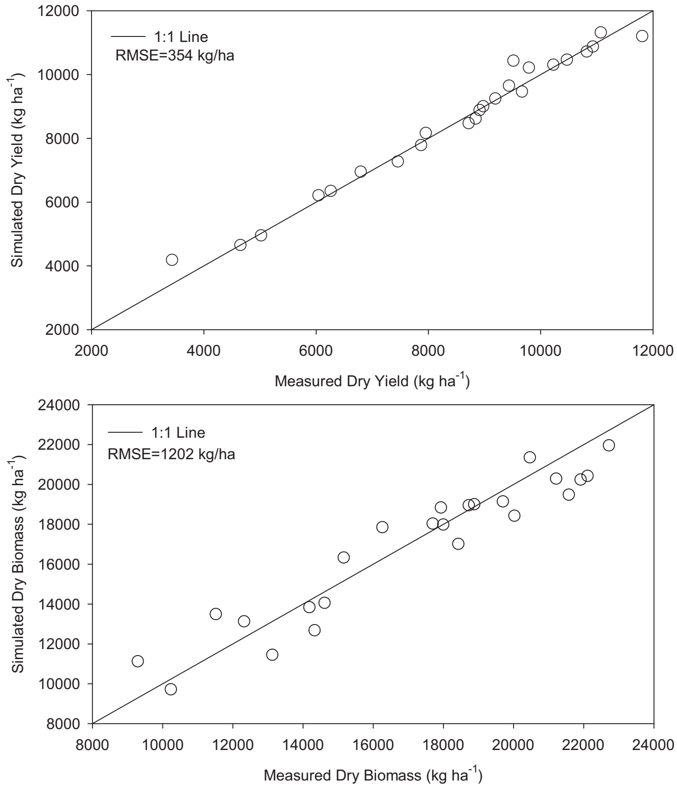

Fig. 1. Calibrated maize yield and biomass for the Greeley experiments from 2008 to 2011 for all the irrigation treatments by Ma et al. (2016) and Fang et al. (2014).

projections from 24 modeling centers/groups for assessing the impact of climate change (Hamlet et al., 2010; Islam et al., 2012a,b). Since our goal was to find suitable cultivars for late in the 21st century, we did not present the simulation results for climate change conditions in the 2020s and 2050s as did by Islam et al. (2012a). The worst climate change scenario was generated with RCP8.5 for assessing climate change effect on cultivar adaptation. As some GCMs have multiple projections, we used all the available 71 projections from 37 GCMs for RCP8.5 for generating climate change scenarios. The RCP8.5 represents high greenhouse gas emission pathways and also the upper bound of RCPs, in which the rising radiative forcing pathway leads to 8.5 W m^{-2} (1370 ppm CO_2 eq.) by 2100. The CO_2 concentration projected for RCP8.5 by 2080 was 757 ppm (Meinshausen et al., 2011; IPCC, 2013).

For generating climate change scenarios, we used hybrid-Delta (HD) ensemble method (Hamlet et al., 2010; Islam et al., 2012a,b). This method considers inter-annual variability for each month as opposed to the delta change method which does not account for variability or change in time series behavior in the future (Hamlet et al., 2010; Islam et al., 2012a,b). In the Hybrid-Delta (HD) ensemble method, BCSD monthly data for the selected location (GLY04 in this study) were disaggregated into individual calendar months and cumulative distribution functions (CDF) for each of the months were developed for historical (1980–2009) and future time periods of 2070–2099 (2080s) using the BCSD monthly GCM data. These CDFs are referred as historical and future CDFs, respectively, hereinafter. Similarly, the CDF for each month was developed from the observed time series data (1980–2009) of the weather station GLY04, and referred to as the observed CDF. Quantile mapping (Wood et al., 2002) was done to re-map the observations onto the bias corrected GCM data to produce a set of transformed observations reflecting the future scenario. For quantile mapping, non-exceedance probability for a given observed value (temperature/precipitation) of a given month (say Jan) is first

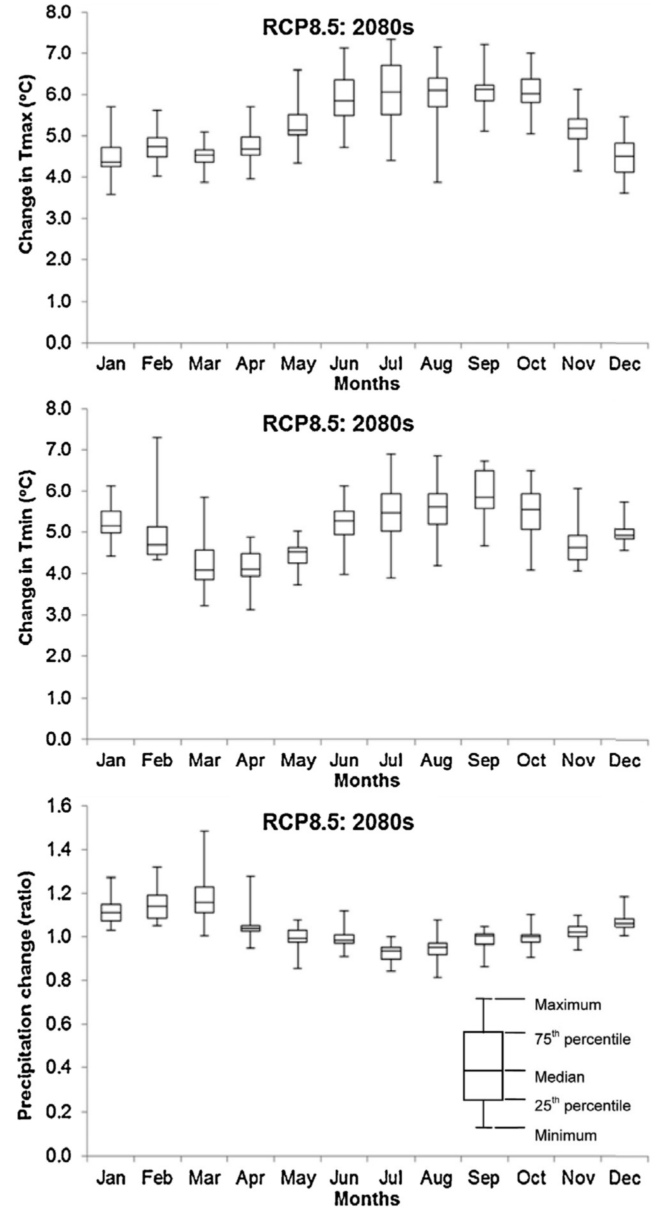

Fig. 2. Box plots showing distributions of General Circulation Model (GCM) generated minimum air temperature (Tmin,°C), maximum air temperature (Tmax,°C), and precipitation (mm) for the 2080s'.

computed from the observed CDF of. Then, corresponding to this non-exceedance probability level, the historical and future temperature/precipitation value for the given month (say Jan) from the historical and future CDFs was computed. The difference/ratio (ratio in case of precipitation) between the future and historical temperature/precipitation values is the resultant change factor. This process is repeated for all the 12 months and for all the years (1980–2009) to generate change factors. Compared to historical weather (1980–2009), average minimum and maximum air temperature was projected to increase by 3–7 °C, depending on the month of the year in the 2080 s (2070–2099). Precipitation also was projected to increase in the winter months, but decreased somewhat for the summer months (Fig. 2). On an annual basis, average rainfall increased by 9% from current 24.8 cm–27.1 cm in the 2080 s and average temperature increased from 9.5 to 14.8 °C. There were 22 days when average daily air temperature exceeded 33 °C in the 2080s, with the highest average daily temperature of 35.5 °C compared to the highest value of 29 °C for the historical weather data,

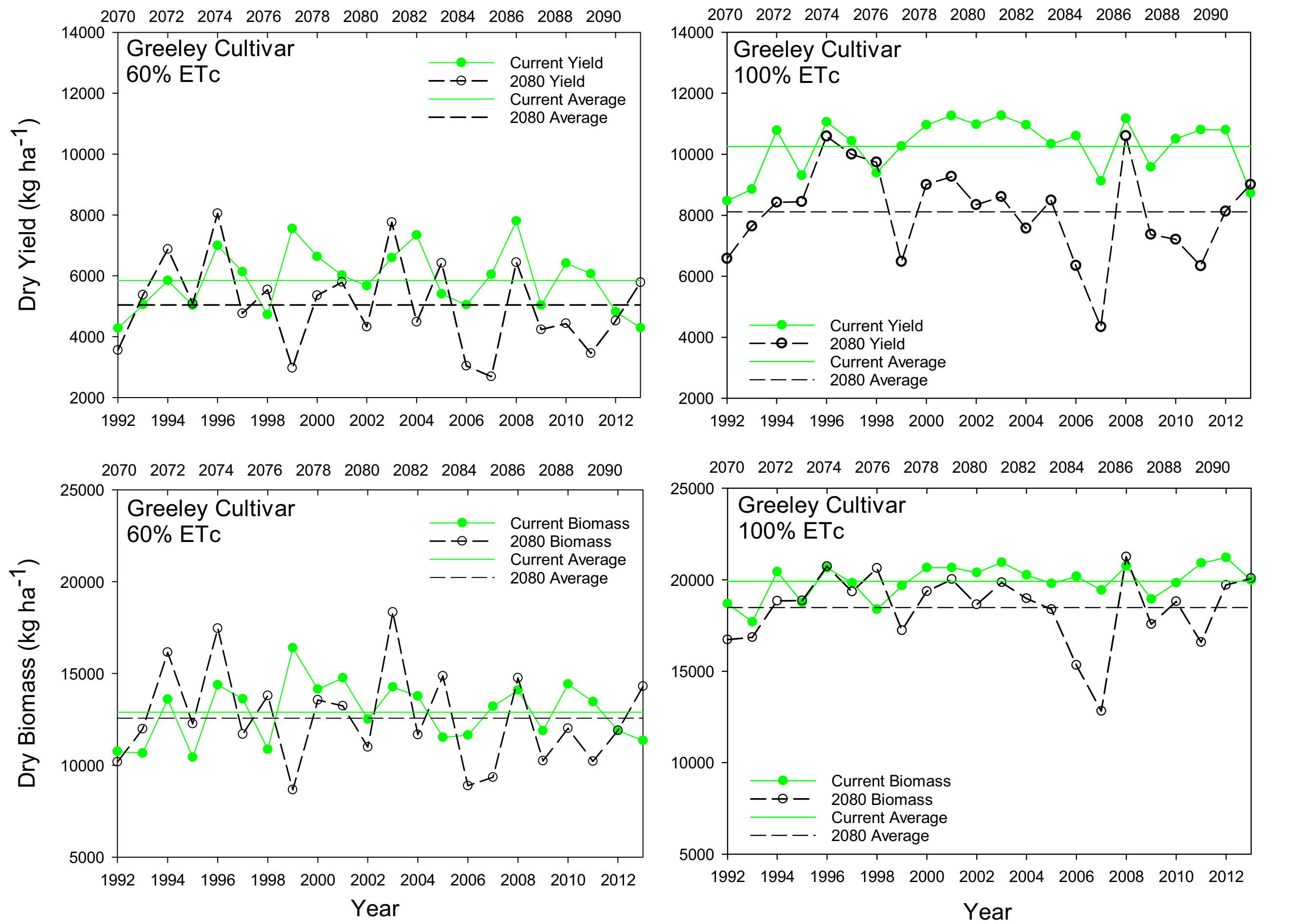

Fig. 3. Simulated yield and biomass with current and 2080s weather conditions under 100% ETc (left) and 60% ETc (right) irrigation treatments. ETc: Crop Evapotranspiration.

which are lower than the maximum temperatures of 44.0 °C and 48.5 °C for plant growth and grain filling. Therefore, the CSM-DSSAT 4.0 model should be valid in the temperature ranges of the simulations. For simulating the impact of projected climate change, the projected changes in precipitation and temperature were superimposed on the observed baseline data series for the period of 1992–2013. Thus, the baseline scenarios were run from 1992 to 2013 (22 years, instead of 30 years used in the BCSD projection) and the future scenarios were from 2070 to 2091. The reason for this modification was that reliable data on solar radiation, relative humidity, and wind speed were available for the site from 1992 onward.

2.4. Evaluation of maize cultivars under climate change

For the long-term simulations under both current and future climate conditions, fertilizer as UAN was applied at planting at 150 kg ha^{-1}, which was the average N application rate during the four years of experiment (Ma et al., 2012). Irrigation was scheduled every three days to meet either 100% or 60% of potential crop ET as calculated by the Shuttleworth-Wallace equations (Ma et al., 2012). Maize was planted on May 11 each year and harvested at physiological maturity, although planting date may be another adaptation strategy (Ko et al., 2012). Keeping the calibrated soil parameters and other management practices the same, we evaluated maize production under both current and future climate conditions for the current cultivar at Greeley, CO (referred as 'Greeley'), a cultivar from Rocky Ford, southern Colorado (Rocky Ford') (Saseendran et al., 2015), and 10 longer season cultivars ('Cargill 1115′, PIO X 304C', 'PB 8′, 'H610(UH)', 'LONG SEASON', 'PIO 3165′, 'PIO 3324′, 'EV 8449-SR', 'EV 8449-SRx', 'GL 482′) (with >1200 °C degree days) in the DSSAT database to see their performance under current and projected climate conditions. In addition, based on the range of cultivar parameters in the DSSAT database (Table 2), we randomly sampled 500 maize cultivars (Latin Hypercube Sampling-'LHS', Ma et al., 2000) with long growing seasons (>1200 °C days) to find out the characteristics of those parameters that maintain maize yield under the projected climate conditions at both 100% and 60% ETc irrigation treatments. These cultivars are defined by the six parameters in the cultivar file of CERES-Maize model (Table 2). Other crop parameters in the species and ecotype files related to photosynthesis, crop temperature responses, and root growth were kept unchanged in the simulation.

3. Results and discussion

3.1. Responses of current (Greeley) cultivar to climate change

For both irrigation levels (100% ETc and 60% ETc), yield and biomass were reduced under future climate conditions, compared to current conditions (Fig. 3). However, the reduction was relatively greater at 100% ETc (21% for yield and 7% for biomass) than at 60% ETc (14% for yield and 3% for biomass). Compared to current conditions, there was much higher variability (standard deviation around the mean) in simulated yield and biomass under future climate condition at both irrigation levels: 10256 ± 900 kg ha^{-1} vs 8115 ± 1535 kg ha^{-1} for yield and

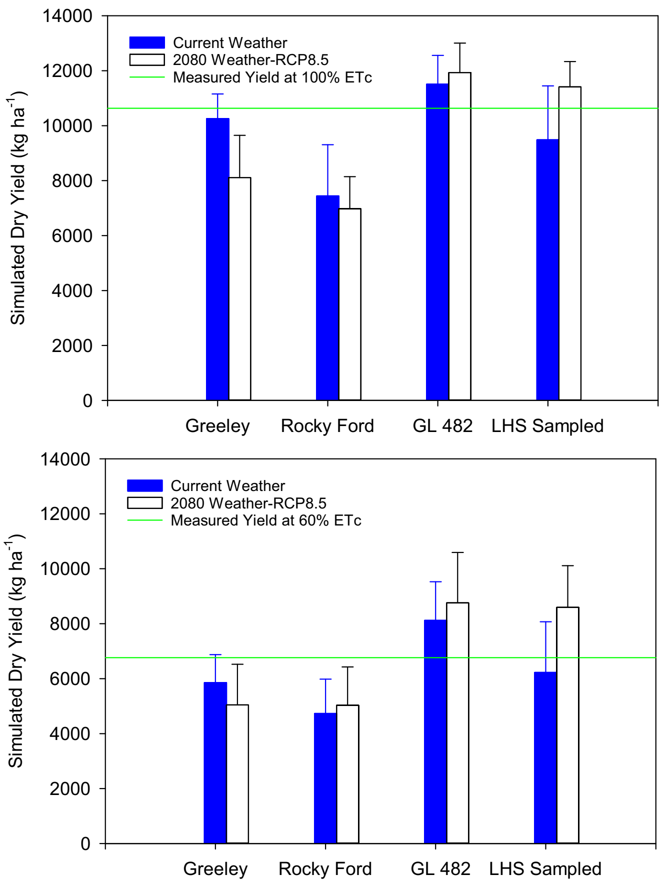

Fig. 4. Simulated yield with current and proposed cultivars, averaged over 22 years. For Latin Hypercube Sampling (LHS) generated cultivars, the results were averaged over 70 cultivars. Top: 100% ETc. Bottom: 60% ETc. Average measured yield for the 4-yr experimental data at 100% and 60% ETc was plotted as reference. ETc: Crop Evapotranspiration.

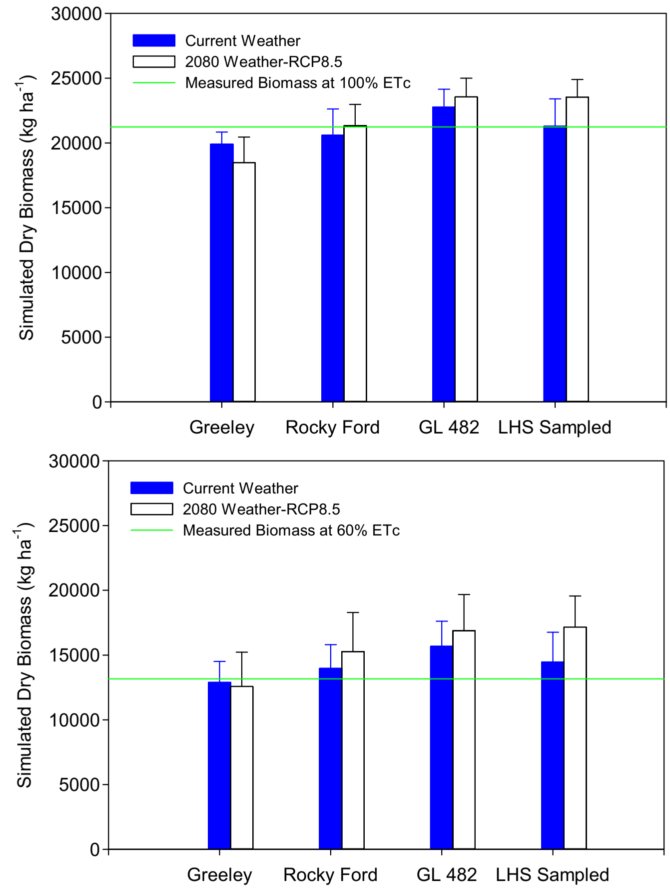

Fig. 5. Simulated biomass with current and proposed cultivars, averaged over 22 years. For Latin Hypercube Sampling (LHS) sampled cultivars, the results were averaged over 70 cultivars. Top: 100% ETc. Bottom: 60% ETc. Average measured biomass for the 4-yr experimental data at 100% and 60% ETc was plotted as reference. ETc: crop evapotranspiration.

19908 ± 930 kg ha^{-1} vs 18482 ± 1971 kg ha^{-1} for biomass under 100% ETc; and 5854 ± 1023 kg ha^{-1} vs 5044 ± 1480 kg ha^{-1} for yield and 12888 ± 1620 kg ha^{-1} vs 12568 ± 2647 kg ha^{-1} for biomass under 60% ETc (Figs. 4 and 5). In addition, the simulated yield and biomass were more variable from year to year under deficit irrigation than under full irrigation. Simulated yield was more vulnerable to climate change (21% and 14% decrease for full and deficit irrigation, respectively) than biomass (7% and 3% decrease for full and deficit irrigation, respectively). The main reason for yield decrease under future warmer climate was the accelerated maturity with the average simulated growing season (planting to physiological maturity) shorten from143 days to 102 days, which is in agreement with decreases reported in the literature (Moradi et al., 2013, 2014; Islam et al., 2012a). Coefficient of variation (CV) of simulated yield across years increased from 0.087 under current climate to 0.19 under 2080s climate conditions for the 100% ETc and from 0.17 to 0.19 for the 60% ETc. Similarly, CV of simulated biomass increased from 0.047 to 0.11 for the 100% ETc treatment and from 0.13 to 0.21 for the 60% ETc.

With the 100% ETc treatment, seasonal actual evapotranspiration (AET) decreased considerably under future climate conditions, due to shorter growing seasons and to a lesser extent due to lower stomatal conductance at the higher CO_2 concentration (Fig. 6, Guo et al., 2010; Islam et al., 2012a). As a result, irrigation requirement was slightly lower under future climate conditions (Fig. 7) and water use efficiency, defined as yield per cm AET (WUE), remained largely unchanged (Fig. 8). CV for simulated AET and irrigation requirements were similar between current and future climate conditions (Figs. 6 & 7). However, CV for WUE increased from 0.076 under current climate to 0.22 under future climate for 100% ETc, and from 0.14 to 0.26 for 60% ETc due to variability in simulated yield (Fig. 8).

3.2. Responses of the Rocky Ford cultivar to climate change

To find a cultivar that would maintain or increase yield under future climate conditions, we evaluated a cultivar ('Rocky Ford') from southern Colorado, which was calibrated previously with RZWQM2 for southern Colorado (Saseendran et al., 2015). This cultivar has a long growing season of 1250 photothermal days (P1 + P5). As shown in Fig. 4, this cultivar simulated lower yield than the Greeley cultivar under both the current and future climates in northeastern Colorado, especially under full irrigation, although it did not simulate the yield decrease from current to future climate as the Greeley cultivar did. However, the simulated biomass was closer to that of the Greeley cultivar (Fig. 5). Since simulated actual evapotranspiration (AET) and irrigation requirement were the same or slightly higher than that with the Greeley cultivar (Figs. 6 and 7), WUE was much lower under both full and deficit irrigation treatments compared to the Greeley cultivar (Fig. 8). Growing season was shortened by 42 days from 164 under current climate to 122 days under future climate conditions.

Coefficient of variation of simulated yield across the years decreased from 0.25 under current weather to 0.17 under future weather for the 100% ETc treatment, but remained constant around 0.27 for the 60% ETc. For simulated biomass, CV decreased slightly

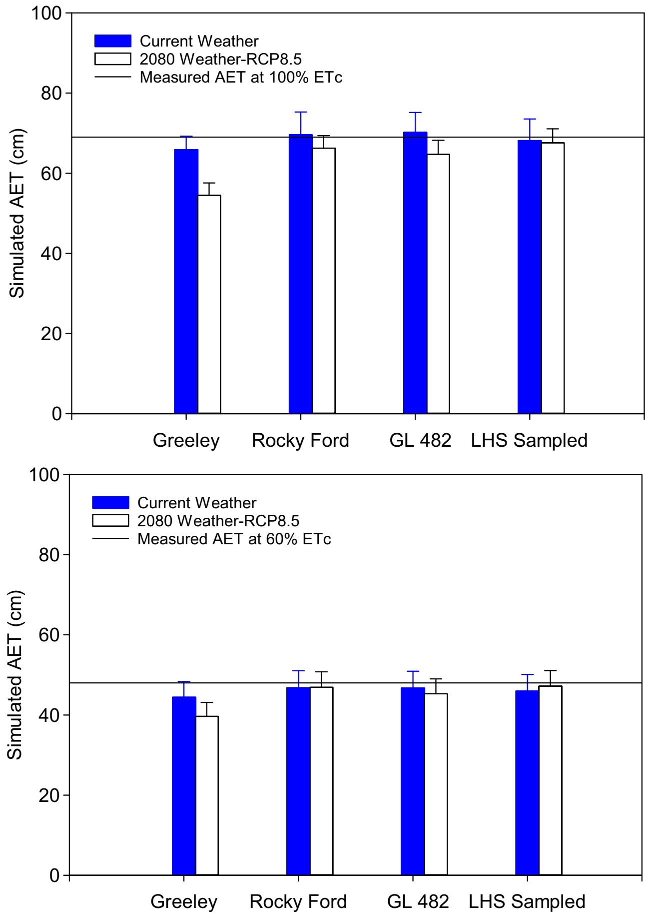

Fig. 6. Simulated actual evapotranspiration, AET, with current and proposed cultivars, averaged over 22 years. For LHS sampled cultivars, the results were averaged over 70 cultivars. Top: 100% ETc. Bottom: 60% ETc. Average simulated AET for the four year experimental data (2008–2011) at 100% and 60% ETc was plotted as reference. ETc: Crop Evapotranspiration. AET: Actual Evapotranspiration. LHS: Latin Hypercube Sampling.

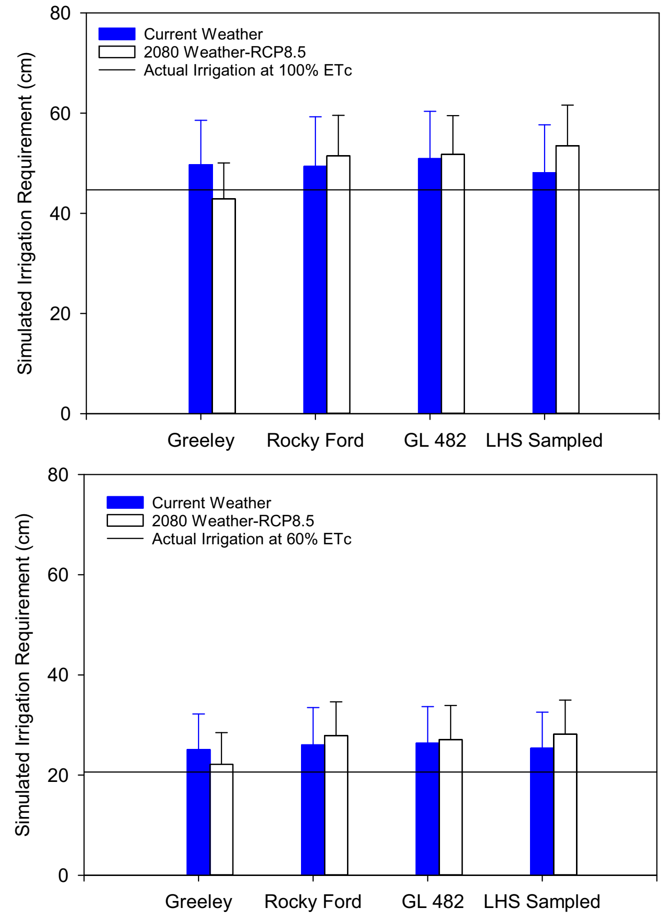

Fig. 7. Simulated irrigation water demand with current and proposed cultivars, averaged over 22 years. For LHS sampled cultivars, the results were averaged over 70 cultivars. Top: 100% ETc. Bottom: 60% ETc. Average irrigation amounts for the four year experimental data (2008–2011) at 100% and 60% ETc was plotted as reference. ETc: Crop Evapotranspiration.

from 0.098 to 0.077 for the 100% ETc and increased slightly from 0.13 to 0.20 for the 60% ETc. CV for simulated AET was less than 0.1 under all conditions and treatments, with slightly decreasing under future climate conditions. Variability of simulated irrigation water requirements decreased slightly under the future climate from 0.20 to 0.16 for the 100% treatment and from 0.29 to 0.24 for the 60% ETc treatment. CV of WUE decreased somewhat under the future climate condition from 0.22 to 0.19 for the 100% ETc but increased from 0.24 to 0.26 for the 60% ETc.

3.3. Evaluation of DSSAT cultivars for climate change

We also evaluated ten of the cultivars documented in the DSSAT database ('Cargill 1115′, PIO X 304C', 'PB 8′, 'H610(UH)', 'LONG SEASON', 'PIO 3165′, 'PIO 3324′, 'EV 8449-SR', 'EV 8449-SRx', 'GL 482′) with P1 + P2 > = 1230 photothermal days to find out if any of these cultivars maintained the yield under future climate conditions. Only one cultivar with G3 = 8.8 mg/kernel/day, GL 482, simulated increased yield (Fig. 4) and biomass (Fig. 5) in the 2080 s and had yields under current climate conditions comparable to the Greeley cultivar (Table 3). Since simulated yield decreased from 100% ETc to 60% ETc (30% yield decrease) was less than the experimentally observed response (43% decrease), WUE was higher than the experimental measured values at 60% ETc (Fig. 8). Similar to the Rocky Ford cultivar, this cultivar shortened growing days by 47 days from 164 to 117 days under future climate conditions. These results are in agreement with those reported by Wang et al. (2016) who also found that GL 482 was best adapted to climate change than other DSSAT cultivars tested under the Iowa, USA condition.

Different from the Greeley cultivar, GL 482 simulated higher WUE under future climate than under current climate (Fig. 8), although the increase might not be significant because of overlapping in standard derivation. Higher WUE under future climate condition was due to simulated higher yield (Fig. 4) and lower evapotranspiration (Fig. 6) (Guo et al., 2010; Estes et al., 2013). WUE increased in 2080s by 12.8% at 100% ETc and 12.1% at 60% ETc, which was within the 0.8–17.7% increase reported by Guo et al. (2010) in the North China Plain. However, less variability was simulated for the 100% ETc than for the 60% ETc treatments. Our results showed lower average AET under future climate than that under current climate, which is similar to that simulated by Guo et al. (2010) using the DSSAT-Maize model under similar climate conditions.

Coefficient of variation of simulated yield remained constant at 0.09 between current and future climates for the 100% ETc but increased somewhat from 0.17 to 0.21 for the 60% ETc. Similarly, for simulated biomass, CV was 0.06 for both current and future climates for the 100% ETc, but increased from 0.12 to 0.16 for the 60% ETc. Variation of simulated AET among years was under 0.1 for all treatments and climate conditions. CV for simulation irrigation water requirement decreased slightly to 0.15 under future climate from 0.19 under current climate condition for the 100% ETc, and to 0.25 from 0.28 for the 60% ETc. CV for simulated WUE increased

Table 3
Crop parameters of the ten maize cultivars selected from DSSAT database along with simulated average yield using historical weather and projected climate conditions.

Cultivar ID	Cultivar Name	P1[a]	P2	P5	G2	G3	PHINT	Simulated Average Yield ($kg\ ha^{-1}$)			
								100%ETc		60%ETc	
								Historical	Projected	Historical	Projected
IB0070	CARGILL 111S	340	0.00	1000	780.0	5.3	38.9	11518	11932	8117	8760
IB0063	PIO X 304C	385	0.52	940	687.5	6.0	38.9	6690	9573	3692	7029
IB0061	PB 8	300	0.52	990	440.0	7.0	38.9	6816	6263	4498	4331
IB0060	H610(UH)	345	0.52	920	638.0	6.4	38.9	6849	6291	4526	4356
990001	LONG SEASON	320	0.52	940	620.0	6.0	38.9	6849	6291	4526	4356
IB0066	PIO 3165	320	0.52	940	625.0	6.0	38.9	6606	6455	4365	4736
IB0067	PIO 3324	320	0.52	940	625.0	6.0	38.9	6526	6010	4385	4208
IF0006	EV 8449-SR	385	0.60	860	700.0	8.0	50.0	5395	6492	3553	5088
IF0007	EV 8449-SRx	385	0.60	860	945.4	7.2	50.0	7429	7136	4986	5059
IB0090	GL 482	240	0.70	990	907.0	8.8	38.9	5981	8336	3372	6175

P2 – Day length sensitivity coefficient [the extent (days) that development is delayed for each hour increase in photoperiod above the longest photoperiod (12.5 h) at which development proceeds at maximum rate]. P5 – Degree days (base temperature of 8 °C) from silking to physiological maturity (photothermal days). G2 – Potential kernel number per plant. G3 – Potential kernel growth rate (mg per kernel per day). PHINT – Degree days required for a leaf tip to emerge (phyllochron interval) (photothermal days).

[a] P1 – Degree days (base temperature of 8 °C) from seedling emergence to end of juvenile phase (photothermal days).

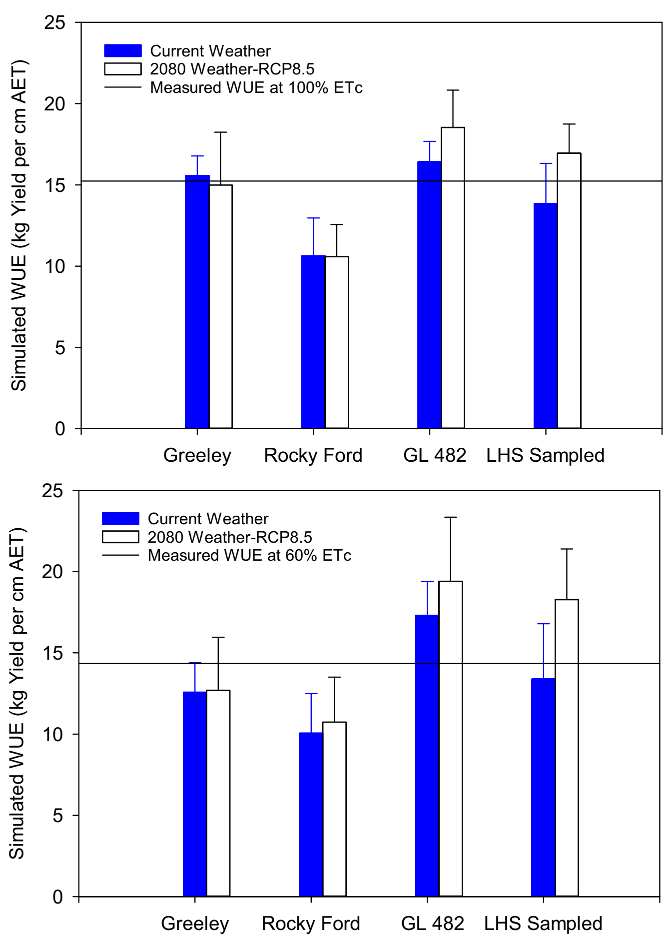

Fig. 8. Simulated water use efficiency, WUE (kg yield percm AET) with current and proposed cultivars, averaged over 22 years. For LHS sampled cultivars, the results were averaged over 70 cultivars. Top: 100% ETc. Bottom: 60% ETc. Average simulated WUE for the four year experimental data (2008–2011) at 100% and 60% ETc was plotted as reference. ETc: Crop Evapotranspiration. AET: Actual Evapotranspiration. WUE: Water Use Efficiency. LHS: Latin Hypercube Sampling.

from 0.076 to 0.12 for the 100% ETc, and from 0.12 to 0.20 for the 60% ETc.

To further investigate the correlation between yield maintained in 2080s and cultivar parameters, we ran all 121 cultivars in the DSSAT database. Using the criteria that average yield of current and future weather conditions had to be greater than 10,000 $kg\ ha^{-1}$ and yield in 2080s should not be decreasing, we identified eight cultivars from the database (GL 482, McCurdy 84aa, McCurdy 6714, B73xMO17, FM 6, Garst 8555, Pioneer 3475 Orig, and Pioneer 3489). The common parameter values among the cultivars were G3 >8.5 mg/kernel/day with P1 varying from 215 to 275 photothermal days, P2 from 0.3 to 0.7, P5 from 825 to 990, G2 from 677 to 990, and PHINT from 39 to 49. Total growing season length ranged from 1070 to 1230 photothermal days. Therefore, a viable cultivar for adapting climate change should have both longer growing season and higher grain filling rate.

3.4. Search of new cultivars using statistical sampling

Finally, we used the LHS technique to sample all the cultivar parameters within the ranges given in Table 2, within the constraint of P1 + P2 > 1200 photothermal days. Of the 500 sets of parameters sampled, seventy simulated yield within 10% of the current experimental results under both current and future climate conditions. The ensembles of the 70 cultivars showed increases in yield and biomass under future climate compared to current climate. The model also simulated only 34% yield reduction from full to deficit irrigation, compared to the measured 43% reduction. Simulated AET and irrigation requirements were on par with the Greeley and GL 482 cultivars (Figs. 6 and 7). Simulated WUE was close (within standard derivation) to experimentally measured values at both 100% and 60% ETc treatments under current climate, but higher under future climate conditions (Fig. 8).

The CV of simulated yield across years and cultivars decreased under future climate to 0.081 from 0.21 under current climate for the 100% ETc and to 0.17 from 0.29 for the 60% ETc treatment. CV of simulated biomass also decreased slightly under future climate to 0.057 from 0.098 for the 100% ETc and to 0.14 from 0.16 for the 60% ETc. CV for simulated AET was all under 0.1 without a slightly decrease under future climate conditions. CV for simulated irrigation water requirements was slightly lower under future climate conditions than under current climate conditions for both 100% ETc (0.20 vs 0.15) and 60% ETc (0.28 vs 0.24), CV for simulated WUE decreased from 0.17 under current climate to 0.11 under future climate for the 100% ETc, and from 0.25 to 0.17 for the 60% ETc treatment.

Since the parameters of the selected 70 cultivars were scattered widely (Table 2, Fig. 9), it was not a single parameter but the combination of these parameters that contributed to yield increase under the future climate conditions (Singh et al., 2014a,b). However, we

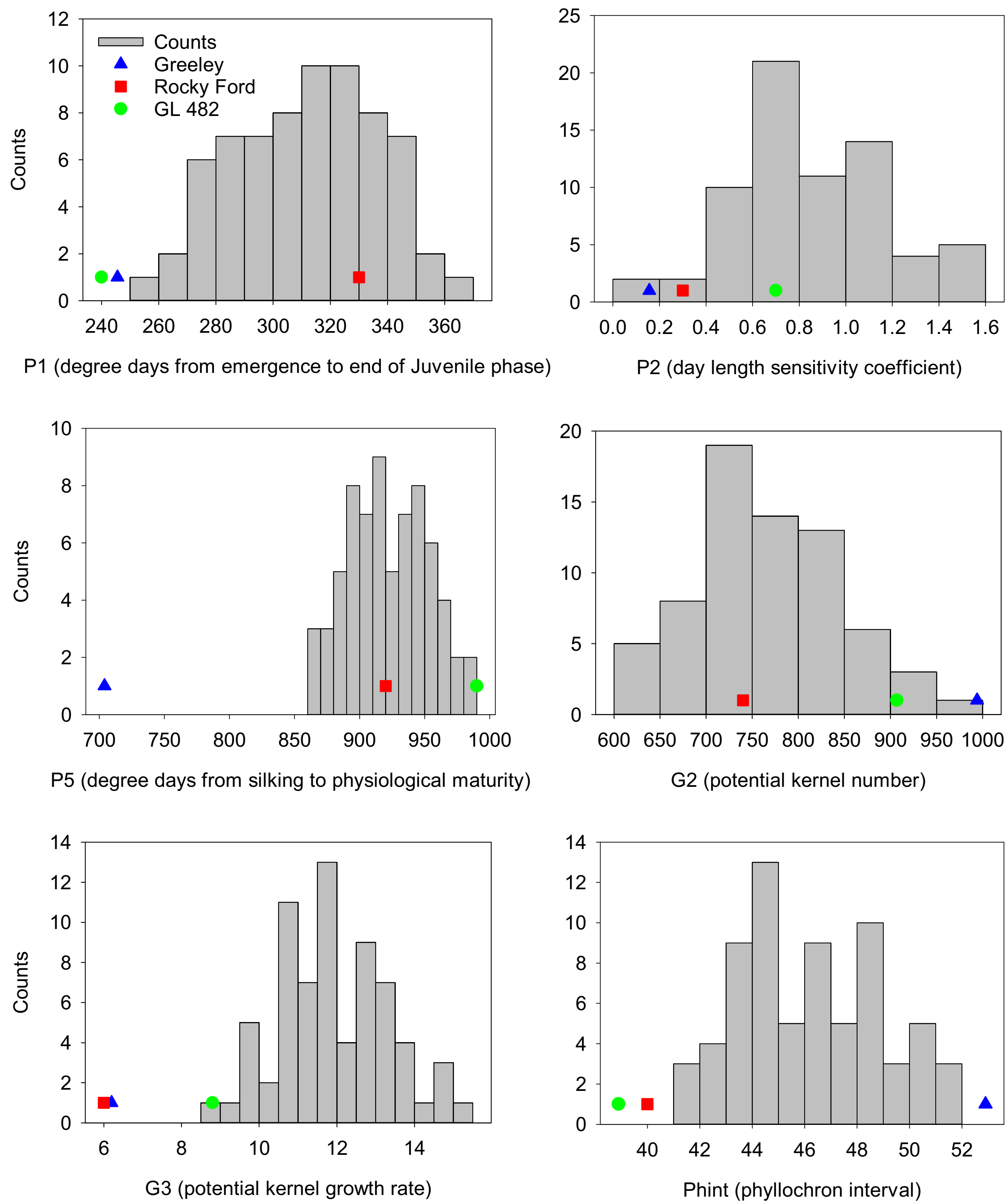

Fig. 9. LHS sampled 70 cultivars that provided good simulation of maize production under current and future climate change conditions, along with the Greeley, Rocky Ford, and GL 482 cultivars. These cultivars simulated average yield and biomass within 10% of measured average values at both 100% and 60% ETc. ETc: Crop Evapotranspiration. *P1 – Degree days (base temperature of 8 °C) from seedling emergence to end of juvenile phase (photothermal days). P2 – Day length sensitivity coefficient [the extent (days) that development is delayed for each hour increase in photoperiod above the longest photoperiod (12.5 h) at which development proceeds at maximum rate]. P5 – Degree days (base temperature of 8 °C) from silking to physiological maturity (photothermal days). G2 – Potential kernel number per plant. G3 – Potential kernel growth rate (mg per kernel per day). PHINT – Degree days required for a leaf tip to emerge (phyllochron interval) (photothermal days).

did notice that the grain filling rate G3 greater than 8.5 mg per kernel per day was necessary (Fig. 9). Both Greeley and Rocky Ford cultivars had G3 around 6 mg per kernel per day. With short growing season under future climate conditions, fast grain filling rate assured better yield development. On average, growing season was shortened by 36 days from 164 under current climate to 128 days under future climate among the 70 cultivars. Similar to Moradi et al. (2013) and Tachie-Obeng et al. (2013), the potothermal days from silking to physiological maturity P5 should be greater than 860. The importance of G3 in climate adaptation could also be inferred from the study of Moradi et al. (2014) who found that their shorter season cultivar had the least yield reduction between current and

2080 s climate. By examining their parameters for the short growing season cultivars, we found that G3 was 11.6 mg per kernel per day compared to average of 7.8 for the long season cultivars and 9.3 for the medium season cultivars. Thus, grain filling rate (G3) could be more important than growing season length in adaptation to future climate.

4. Conclusion

We examined maize response to climate change under full (100% ETc) and deficit (60% ETc) irrigation treatments under central High Plains, USA, climate conditions. These conditions are representative of a substantial portion of the temperate irrigated maize production area in the world. Climate change had bigger effect on maize production at 100% ETc treatment than at 60% ETc treatment. Maize yield decreased by 21% and biomass by 7% with full irrigation, whereas the corresponding reduction under 60% ETc was 14% and 3%. Water use efficiency (WUE) decreased by 4% at 100% ETc but remained constant at 60% ETc. Irrigation requirement increased slightly under future climate conditions for the cultivars that was able to maintain current yield. In general, higher variabilities of simulated yield, biomass, irrigation water requirement and WUE were obtained for the 60% ETc treatments than for the 100% ETc treatment. However, these variabilities may increase or decrease under future climate conditions depending on the crop parameters. Variability of simulated actual crop evapotranspiration among years was much less than that of simulated yield and biomass.

Based on the cultivars evaluated in the study, to maintain high maize yield at end of 21st Century at RCP8.5, new cultivars with longer growing season (especially between silking and physiological maturity) and higher grain filling rate should be introduced, especially under fully irrigated conditions. Since irrigation water had a much more effects on maize yield, proper water management needed to be implemented along with new cultivars.

These results should be taken with precaution, however, because only one soil type was used in the simulations. In addition, crop parameters related to extreme temperature, photosynthesis, and root growth were not investigated in this study. New cultivars from crop breeding will most likely change those parameters besides the cultivar parameters explored in this report. Further studies are needed to find the best combinations of all crop parameters including those common to the species Nonetheless, the current results should be applicable to other maize growing regions because the general conclusions are in agreement with research results in the literature, and the temperature and water response functions in the model are mechanistic and site independent.

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