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Simulating future climate change impacts on seed cotton yield in the Texas High Plains using the CSM-CROPGRO-Cotton model

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ABSTRACT

The Texas High Plains (THP) region contributes to about 25% of the US cotton production. Dwindling groundwater resources in the underlying Ogallala aquifer, future climate variability and frequent occurrences of droughts are major concerns for cotton production in this region. Assessing the impacts of climate change on cotton production enables development and evaluation of irrigation strategies for efficient utilization of groundwater resources in this region. In this study, the CROPGRO-Cotton module within the Cropping System Model (CSM) that is distributed with the Decision Support System for Agrotechnology Transfer (DSSAT) was evaluated for the THP region using measured data from cotton water use efficiency experiments at Halfway over a period of four years (2010–2013). Simulated seed cotton yield matched closely with observed yield during model calibration (average percent error of 0.1) and validation (average percent error of 6.5). The evaluated model was able to accurately simulate seed cotton yield under various irrigation strategies over the four growing seasons. The evaluated CROPGRO-Cotton model was later used to simulate the seed cotton yield under historic (1971–2000) and future (2041–2070) climate scenarios projected by three climate models. On an average, when compared to historic seed cotton yield, simulated future seed cotton yield across the THP decreased within a range of 4–17% when carbon dioxide (CO_2) concentration was assumed to be constant at the current level (380 ppm) under three climatic model scenarios. In contrast, when the CO_2 concentration was assumed to increase from 493 ppm (in year 2041) to 635 ppm (in year 2070) according to the Intergovernmental Panel on Climate Change (IPCC) A2 emission scenario, the simulated future average seed cotton yield in the THP region increased within a range of 14–29% as compared to historic average yield. When the irrigation amount was reduced by 40% (from 100% to 60%), the average (2041–2070) seed cotton yield decreased by 37% and 39% under the constant and increasing CO_2 concentration scenarios, respectively. These results imply that cotton is sensitive to atmospheric CO_2 concentrations, and cotton production in the THP could potentially withstand the effects of future climate variability under moderate increases in CO_2 levels if irrigation water availability remains at current levels.

1. Introduction

Cotton (*Gossypium hirsutum* L.) is a major fiber crop cultivated in the Texas High Plains (THP) region in west Texas. The THP region contributes to about 25% and 64% of the US and Texas cotton production, respectively (USDA, 2012). The Ogallala aquifer underlying the THP is the primary source of irrigation water in this region and over 95% of the groundwater pumped from this aquifer is used for irrigation (HDR, 2001). Cotton production in the THP region faces severe challenges due to a rapid decline of groundwater levels in the Ogallala aquifer (Musick et al., 1988; Colaizzi et al., 2009; Chaudhuri and Ale, 2014) and increases in groundwater pumping costs (Nieswiadomy, 1985; Musick et al., 1988; Colaizzi et al., 2009; Adusumilli et al., 2011). In addition, climate change studies

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for this region predict warmer summers and reductions in annual precipitation in the future (Nielsen-Gammon, 2011; Modala, 2014), and such trends necessitate larger groundwater withdrawals to meet higher evapotranspiration needs of cotton. Furthermore, an increase in the number of dairies in this region is motivating farmers to grow more water demanding crops such as corn, a high water use crop that further increases demand for depleted groundwater resources.

The Underground Water Conservation Districts (UWCDs) in the THP region have recently enacted restrictions on groundwater pumping to prolong the usable lifetime of the Ogallala aquifer. For example, the High Plains UWCD set the annual allowable groundwater pumping rate for the year 2015 at 46 cm (HPWD, 2015). The UWCDs have proposed these rules to insure that at least 50% of the water currently available in the aquifer will still be available after 50 years (popularly known as 50/50 water policy). The proposed restrictions on groundwater use and projected impacts of climate change make it imperative that producers in the Ogallala aquifer region adopt effective irrigation management plans to efficiently use groundwater resources.

Climate change affects agriculture both positively and negatively. Increases in carbon dioxide (CO_2) concentration due to climate change is a positive for plant growth, and several researchers (Kimball, 1983; Cure and Acock, 1986; Allen et al., 1987; Adams et al., 1990; Morison, 1993) reported that the elevated CO_2 levels could enhance crop growth and yield by increasing photosynthesis, decreasing stomatal conductance and thereby reducing transpiration per unit leaf area, and enhancing overall water use efficiency. In contrast, some other studies (Adams et al., 1990, 1998; Sage, 1995; Hatfield et al., 2011) reported that the projected increase in temperature and variability in precipitation in the future could potentially offset the positive effect of increased CO_2 on crop yield. Therefore, a critical understanding of the interactions of climate variables on cotton growth and yield in the THP region is highly important for developing efficient irrigation strategies and sustainable production systems for climate change adaptation. Crop simulation models are very useful for assessing the climate change impacts on cotton growth and yield, and developing efficient irrigation strategies.

The Cropping System Model (CSM) that is distributed with the Decision Support System for Agrotechnology Transfer (DSSAT) can simulate crop growth, development and yield in response to variability in weather conditions, soil properties and management practices. The CSM can expand the knowledge gleaned from field experiments by using modern computational resources to rapidly and inexpensively simulate crop responses under a broad set of experimental conditions. The DSSAT CSM has been extensively used by researchers worldwide for various applications (Jones et al., 2003; Pathak et al., 2007; Thorp et al., 2014, 2010). Garcia y Garcia et al. (2010) used CSM-CROPGRO-Cotton to study the impacts of El Niño Southern Oscillation (ENSO) based climate variability on water use efficiency across rainfed cotton in Alabama, Florida and Georgia. They suggested that more attention should be given to planting dates of rainfed cotton during El Niño years during which early planting had a negative impact on crop yield. Similarly, the CSM-CROPGRO-Cotton model was used to predict the effect of climate change on cotton production in the northern Cameroon from 2005 to 2050 (Gérardeaux et al., 2013). They reported that cotton yield would increase by 1.3 kg ha^{-1} $year^{-1}$ during 2005–2050 due to shorter crop cycles and fertilizing effect of CO_2 enrichment.

The CSM-CROPGRO-Cotton model combined with kriging was used by Guerra et al. (2007) to estimate the spatial distribution of monthly irrigation water use for cotton. Wajid et al. (2014) used the CSM-CROPGRO-Cotton model to simulate development, growth, and seed cotton yield of four cotton cultivars under varying nitrogen fertilization and planting dates in Pakistan. They reported that the simulated values of crop phenology, seed cotton yield, and total dry matter were reasonable when compared with the observed data. Similarly, the CSM-CROPGRO-Cotton model was used to simulate cotton production under different light levels in a pecan alleycropping system in Jay, Florida (Zamora et al., 2009), to study the impact of root-knot nematodes on cotton biomass and yield in Tifton, Georgia (Ortiz et al., 2009), and to evaluate the economics of cotton irrigation strategies in Australia (Cammarano et al., 2012). Recently, Modala et al. (2015a) evaluated the CSM-CROPGRO-Cotton model for the Texas Rolling Plains and used the calibrated model to suggest optimum deficit irrigation strategies for the region.

A majority of the previous studies evaluated the CSM-CROPGRO-Cotton model using experimental data from only one or two growing seasons. Evaluating the model using measured data from more than two growing seasons will enhance confidence in model predictions over a wide range of climatic conditions. Also, data from field experiments that test deficit irrigation strategies during each growing season are useful for testing simulated crop growth and water use responses to water-limited conditions. Furthermore, studies evaluating the CSM-CROPGRO-Cotton model for cotton in the THP region are rare. The objectives of this study were therefore to (i) evaluate the CSM-CROPGRO-Cotton model using 4 seasons and 27 treatments of measured data from field experiments that tested cotton water use efficiency at the Texas A&M AgriLife Research Center at Halfway, Texas in Hale County, and (ii) assess the impacts of future climate variability and change on cotton yield at Halfway and four other locations (Bushland, Lockney, Lubbock and Lamesa) in the THP region.

2. Materials and methods

2.1. Study area

The THP region consists of 41 counties in northwest Texas, and it borders with Oklahoma to the north and New Mexico to the west (Fig. 1). The semi-arid, windy, flat THP region is one of the most intensive irrigated agricultural areas in the USA. Major crops grown in the THP region include cotton, sorghum (*Sorghum bicolor* L.), corn (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.). The Ogallala aquifer, which underlies all THP counties, is the major source of irrigation water for this region. About 95% of the groundwater pumped from the Ogallala aquifer in the THP region is used for irrigation (HDR, 2001). The most common method of irrigation in the THP is center pivot irrigation.

The annual precipitation in the THP region ranges from about 36 cm in the west to 61 cm in the east. Most of the precipitation in the THP occurs during the months of May and September (Allen et al., 2008). Months from October to February are generally dry whereas the months of March, April and May are the windiest. The soils in the THP region are characterized as deep well-developed soils, with increasing clay content and accumulation of calcium carbonates in subsoil horizons (USDA, 2008). Common soil series found in the THP region are Sherm (Fine, mixed, superactive, mesic Torrertic Paleustolls), Darrouzett (Fine, mixed, superactive, thermic Pachic Paleustolls), Pullman (Fine, mixed, superactive, thermic Torrertic Paleustolls), Amarillo (Fine-loamy, mixed, superactive, thermic Aridic Paleustalfs), and Fine, Lofton (mixed, superactive, thermic Vertic Argiustolls).

2.2. The DSSAT CROPGRO-Cotton Cropping System Model

The CSM-CROPGRO-Cotton model distributed with the DSSAT was used to assess the impacts of climate change on seed cotton yield. The DSSAT integrates a database management system

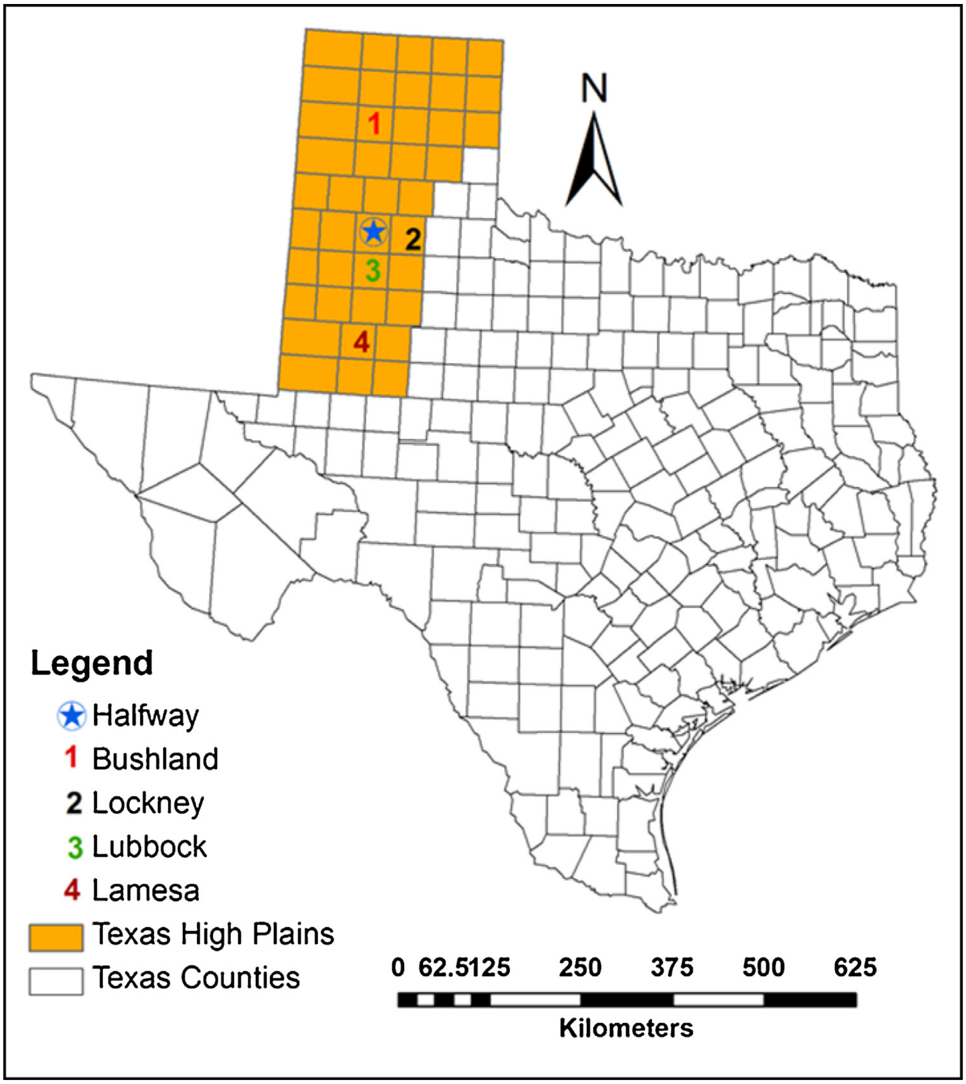

Fig. 1. Locations of study sites in the Texas High Plains region.

(soil, climate, and management practices) and crop models with various application programs (Hoogenboom et al., 2012). It brings together 28 individually developed crop models to a single platform. The latest DSSAT 4.6.0.038 version was used in the current study. The CSM-CROPGRO-Cotton model predicts cotton growth and yield as well as soil, water, carbon and nitrogen processes over time based on weather, soils, crop management, and crop cultivar information. The model also estimates the dates of various crop development stages from planting to harvest, such as emergence, first leaf, first flower, first seed, first crack boll and 90% open boll, based on photothermal unit accumulation, and calculates flower and fruit numbers.

The CSM-CROPGRO-Cotton model requires various soil parameters such as soil texture, slope, albedo, color, drainage, drained upper limit (DUL), lower limit (LL), saturated water content (SAT), hydraulic conductivity, organic carbon content, bulk density and total soil nitrogen. The model also requires crop management, environment and cultivar related information as inputs (Hunt et al., 2001). Required crop management parameters include planting date and method, seedling depth, plant population, row spacing, cultivar characteristics, tillage type, tillage depth and dates, method of irrigation, irrigation dates and amounts, fertilizer application method, fertilizer amount and application dates, and harvesting method and date. Environmental variables such as daily maximum and minimum temperature, incoming solar radiation and precipitation are also required as inputs while dew point temperature and wind speed are optional.

2.3. Model inputs

2.3.1. Climate data

The climate data required for model simulations were obtained from the following sources:

2.3.1.1. Measured data. The daily weather parameters such as maximum and minimum temperature, incoming solar radiation, precipitation, wind speed and dew point temperature at the Halfway Research Station during the period from 2010 to 2013 were obtained from the Texas High Plains Evapotranspiration Network (TXHPET) (Porter et al., 2005). This network provides hourly as well as daily weather parameters since 1998 for 18 metrological stations located in 15 west Texas counties. For all of these stations, the TXHPET network also provides daily reference ET data, which is calculated by using a new standardized ET equation that uses temperature, solar radiation, wind speed and relative humidity data (Marek and Porter, 2009). Monthly average weather parameters at Halfway during the 2010–2013 cotton growing seasons are presented in Table 1.

Table 1
Monthly summary of weather parameters at Halfway, TX during 2010–2013 growing seasons.

Month	RAIN (mm)[a]	TMAX (°C)	TMIN (°C)	SARD (MJ/m²)	DEW (°C)	WIND (kmph)
2010						
May	60.7	25.8	12.0	740.2	9.3	13.9
June	29.7	32.6	18.9	784.0	21.1	12.3
July	55.4	29.3	18.9	721.4	26.9	8.1
August	45.0	32.1	18.3	751.0	22.3	7.6
September	13.2	30.1	15.5	586.1	18.6	8.6
October	32.3	24.6	7.8	526.7	4.6	7.7
Sum	236.2	–	–	4109.5	–	–
Average		29.1	15.2	–	17.2	9.7
2011						
May	3.6	28.6	11.2	860.6	−4.9	15.0
June	0.3	36.3	19.7	856.0	5.4	15.1
July	7.9	35.9	21.5	820.1	16.9	10.4
August	3.8	36.4	21.6	765.3	15.1	9.8
September	4.3	29.2	13.1	629.5	10.2	11.3
October	34.3	24.1	7.2	553.6	3.9	14.2
Sum	54.1	–	–	4485.1	–	–
Average		31.8	15.7	–	7.8	12.6
2012						
May	11.7	29.2	12.9	804.2	3.9	17.2
June	70.4	33.4	18.0	805.1	15.0	17.8
July	11.2	33.2	18.8	829.6	19.8	11.9
August	10.7	33.0	17.9	746.3	17.6	11.1
September	7.6	28.2	13.4	553.3	13.8	10.5
October	0.3	22.7	5.9	530.5	3.2	12.7
Sum	111.8	–	–	4269.1	–	–
Average		29.9	14.5	–	12.2	13.5
2013						
May	1.8	28.5	10.5	845.0	1.3	17.7
June	81.3	32.9	17.7	833.9	16.6	18.3
July	76.7	30.7	17.6	795.9	20.5	12.1
August	24.4	32.0	17.2	799.8	21.2	10.3
September	47.5	29.8	14.6	622.4	16.3	10.8
October	9.1	23.5	6.5	529.9	2.7	13.4
Sum	240.8	–	–	4426.9	–	–
Average		29.6	14.0	–	13.1	13.8

[a] RAIN = precipitation, TMAX = maximum daily air temperature, TMIN = minimum daily air temperature, DEW = dew point temperature, WIND = wind speed.

Observed historic (1971–2000) daily precipitation, and minimum and maximum temperature data for five locations in the THP, including Halfway, Bushland, Lockney, Lubbock and Lamesa, was obtained from the Integrated Agricultural Information and Management System (iAIMS) Climatic Data Center (Wilson et al., 2007; Yang et al., 2010). The center gathers weather information from different sources including the National Climatic Data Center (NCDC), Cooperative Observer Network (COOP) stations and Meteorological Aviation Report (METER). These observed historic weather data obtained from the iAIMS were used for bias correcting the climate model projected historic weather data.

2.3.1.2. Climate model projected historic and future climate data. The historic (1971–2000) and future (2041–2070) climate data (precipitation, maximum and minimum temperature, and solar radiation) for five climate grids, which contain Halfway, Bushland, Lockney, Lubbock and Lamesa locations, were obtained from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2007; Modala, 2014). The weather data projected by three different Regional Climate Models (RCMs) namely, RCM3-GFDL (Regional Climate Model Version3-Geophysical Fluid Dynamics Laboratory), RCM3-CGCM3 (Regional Climate Model Version3- Third Generation Coupled Global Climate Model), and CRCM-CCSM (Canadian Regional Climate Model-Community Climate System Model) were used for the five study sites including Bushland, Halfway Lockney, Lubbock and Lamesa. The projected weather data pertaining to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 scenario was used in this study. These data were based on the Coupled Model Intercomparison Project 3 (CMIP3) simulations and they were available at a spatial grid resolution of 50 km^2 and on a daily time step. Additional details about these RCMs and their major characteristics are available at https://www.narccap.ucar.edu/data/model-info.html. Although newer future climate datasets such as CMIP5 were available, we preferred to use NARCCAP CMIP3 data because of its availability on a daily temporal resolution, which is the resolution required for the DSSAT-CSM-CROPGRO weather inputs.

Many climate models either overestimate or underestimate weather variables, while some of them can't reproduce the seasonal cycle. Therefore, after obtaining the downscaled meteorological variables, it is important to remove the possible bias to bring the projected distributions close to the observed patterns. The quantile mapping method, which uses the empirical probability distributions for observed and simulated weather variables, was used in this study to remove biases (Modala, 2014; Modala et al. 2015b). The Gaussian and Gamma distribution mapping techniques were used for removing bias from the projected historic temperature and precipitation data, respectively. The solar radiation data was not bias-corrected, however. More details about the processing and bias correction of projected climate data are available in Modala (2014) and Modala et al. (2015b).

A comparison of RCM3-GFDL model-projected historic (1971–2000) and future (2041–2070) monthly means of precipitation and temperature (before- and after bias correction) for a climate grid in which Halfway is located, is shown in Fig. 2. Similarly, bias-corrected monthly means of precipitation and temperature data projected by RCM3-CGCM3 and CRCM-CCSM

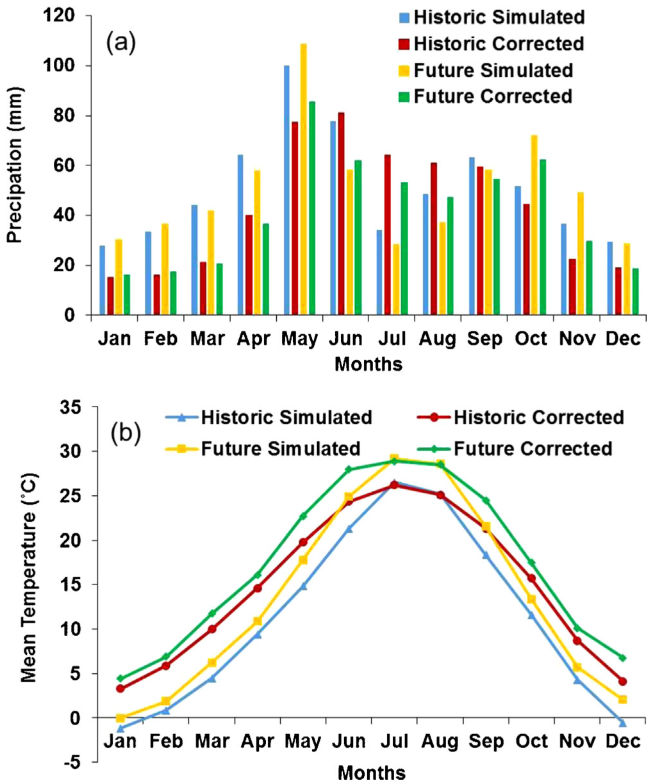

Fig. 2. Comparison of average monthly historic (1971–2000) and RCM3-GFDL model projected future (2041–2070) (a) precipitation and(b) temperature for Halfway in the Texas High Plains.

climate models for historic (1971–2000) and future (2041–2070) time periods were compared in Fig. 3. These RCMs, in general, predicted a decrease in mean annual precipitation [with in a range of 3.5% (GFDL) to 11.5% (CCSM)] and increases in average annual maximum air temperature (within a range of 2.0–2.6 °C) and minimum air temperature (about 1.91–2.4 °C) in the THP region in the future (2041–2070) when compared to historic (1971–2000) period (Modala, 2014). A wide variability in projected monthly mean future precipitation was noticed among the three RCMs (Figs. 2a and 3a and b), but the projected monthly mean future temperature was similar among the RCMs, except in July and August (Figs. 2b, 3c and d).

2.3.2. Crop management parameters

The crop management related parameters that were input to the CSM-CROPGRO-Cotton model, were based on actual management during field experiments that tested cotton water use efficiency over four growing seasons from 2010 to 2013 at the Texas A&M AgriLife Research Center at Halfway (34.18°N, 101.95°W) in the Hale County (Fig. 1) (Bordovsky and Mustian, 2013). The experiments contained 27 treatments composed of combinations of three levels of maximum irrigation capacity (high (H), medium (M) and low (L)) during three cotton growth periods that were representative of vegetative, reproductive and maturation cotton growth periods irrigated by a Low Energy Precision Application (LEPA) center pivot. The details of tillage, planting, fertilizer application, harvesting and irrigation management practices adopted during these years are outlined in Table 2. Cotton plots of size 30 × 8 m with a row spacing of 1 m were prepared with tillage practices that included shredding stalks, reshaping beds with a rolling cultivator, and furrow diking between late March and mid-May of each year. The Fibermax 9680B2RF cotton seed variety was planted in all the plots using a John Deere Maxemerge Planter at 3.8-cm depth at

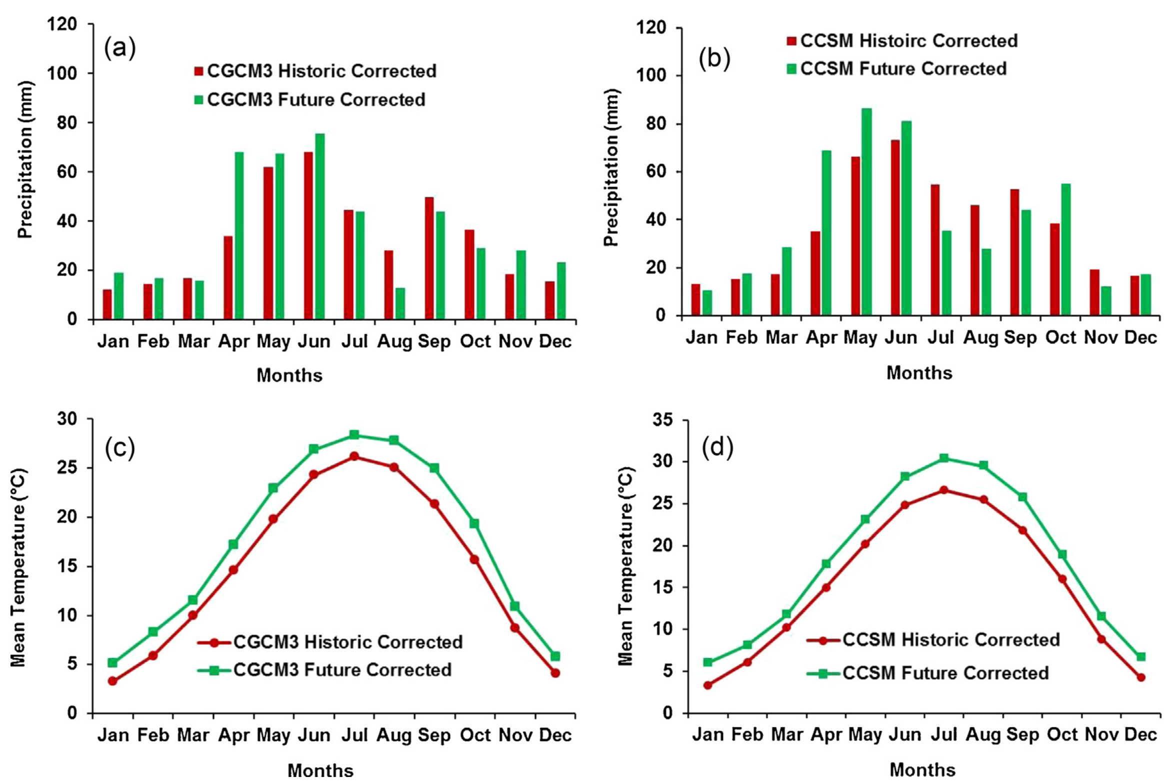

Fig. 3. Comparison of bias-corrected historic (1970–2000) and future (2041–2070) average monthly (a and b) precipitation and (c and d) mean temperature at Halfway in the Texas High Plains as projected by RCM3-CGCM3 (Third Generation Coupled Global Climate Model) and CRCM-CCSM (Canadian Regional Climate Model-Community Climate System Model) models.

Table 2
Management practices adopted at Halfway Research Station during 2010–2013 cotton growing seasons.

Management practices	2010	2011	2012	2013
Planting date	11 May	11 May	9 May	13 May
Harvest date	1 November	11 November	7 November	5 November
Seed rate (seed ha^{-1})	58240	52209	55205	62637
Irrigation start date[a]	24 June	6 April	28 April	24 April
Irrigation end date[b]	8 September	31 August	5 September	14 September
Annual irrigation amount (mm)[c]	0–232	138–584	92–463	100–490
(i) Vegetative[d]	0–51 (24 June–18 July)	0–165 (14 June–10 July)	0–114 (19 June–13 July)	0–152 (13 June–20 July)
(ii) Reproductive	0–102 (19 July–7 August)	0–152 (11 July–3 August)	0–133 (14 July–4 August)	0–134 (21 July–6 August)
(iii) Maturation	0–146 (8 August–8 September)	0–160 (4 August–1 September)	0–171 (5 August–5 September)	0–195 (7 August–14 September)
Number of irrigations	0–24	17–55	8–62	12–60
Type of fertilizer	Urea, phosphorous pentoxide (P_2O_5)	Urea, phosphorous pentoxide (P_2O_5)	Urea, phosphorous pentoxide (P_2O_5)	Urea, phosphorous pentoxide (P_2O_5)
Amount of fertilizer as elemental N and P ($kg\,ha^{-1}$)	N = 44, P = 14	N = 58, P = 20,	N = 25, P = 20,	N = 34, P = 20
Tillage	Conventional	Conventional	Conventional	Conventional
Cultivar	Fibermax 9680B2RF	Fibermax 9680B2RF	Fibermax 9680B2RF	Fibermax 9680B2RF

[a] Irrigation start date was the same for all treatments in respective years.
[b] Irrigation end dates varied among various irrigation treatments. The dates shown were for the HHH treatment.
[c] Irrigation amounts shown were for LLL (lowest amount) and HHH (highest amount) treatments. The irrigation amounts for the remaining treatments were within the specified range. During 2010, LLL treatment plots were not irrigated and the next lowest irrigation amount applied was 76.2 mm for the LLM treatment.
[d] Irrigation was also applied before the vegetative growth period except during 2010.

approximate rates of 5.8, 5.2, 5.6 and 6.2 seeds m^{-2} in 2010, 2011, 2012 and 2013, respectively. Chemical fertilizers were applied by banding on wet sides of the LEPA irrigated cotton beds at depths of 10–20 cm. Additional details about these field experiments can be found in Bordovsky et al. (2015).

2.3.3. Soil sampling

A majority of the soil parameters input to the CROPGRO-Cotton model were based on the results of soil sample analysis. Composite bulk soil samples were collected at depths of 0–15, 15–30, 30–45, 45–60 and 60–75 cm at the Halfway, Bushland, Lockney, Lubbock and Lamesa study sites during 2014 using a 6.6 cm bucket auger. Soil samples were air dried, ground, and sieved with a 2 mm sieve at the Geospatial Hydrology lab at Vernon and then sent to the Ward Laboratory at Kearney, Nebraska for analysis of soil texture, organic matter (OM), $pH_{1:1}$, electrical conductivity ($EC_{1:1}$), and nitrate, following the standard procedure. The results of the soil analysis are presented in Table 3.

2.4. Model calibration and validation

The measured data from four irrigation treatments (HHH, HHM, MHH, MHM), which experienced little or no water stress, in four growing seasons from 2010 to 2013 (a total of 16 treatment-years) was used to calibrate the CSM-CROPGRO-Cotton model. Measurements from the remaining 92 treatment-years during the 2010–2013 growing seasons were used for model validation. Since the DSSAT cultivar database did not include the Fibermax 9680B2RF variety, it was added as a new cultivar in the DSSAT cultivar database and its parameters were populated based on the literature values for the THP region (Robertson et al., 2007). Some of the cultivar parameters were later adjusted during model calibration. Several other input parameters that govern the crop growth, development, and yield were adjusted manually to improve the model simulation results. The model evaluation was carried out in two steps. Initially, the simulated dates of various cotton phenological stages were compared with generally observed dates in the study area. Later, simulated seed cotton yields were compared with measured yields.

Table 3
Soil physical and chemical properties at different locations of the Texas High Plains (THP) region at 0–15, 15–30, 30k45, 45–60 and 60–75 cm depths.

Study	Sand	Clay	OM[a]	$pH_{1:1}$	$EC_{1:1}$[b]	Nitrate
Sites	%				$dS\,m^{-1}$	$mg\,kg^{-1}$
0–15 cm						
Bushland	21	33	2.5	7.7	0.5	25.5
Halfway	64	17	1.6	8.3	0.35	16.2
Lockney	47	25	2.1	8.5	0.59	26.2
Lubbock	59	15	1	8.3	0.31	1.5
Lamesa	75	7	0.5	7.9	0.18	1
15–30 cm						
Bushland	21	39	2.5	7.7	0.62	14.9
Halfway	48	25	1.5	8.1	0.61	48.3
Lockney	47	27	1.7	8.4	0.72	28.5
Lubbock	53	21	1.2	8	0.46	2.5
Lamesa	77	9	0.5	8.2	0.19	1.4
30–45 cm						
Bushland	19	35	2.4	8.1	0.79	18.5
Halfway	42	31	2	7.9	1.22	95.8
Lockney	39	35	2.3	8.2	0.71	21.6
Lubbock	47	31	1.4	8	1.12	27.5
Lamesa	75	11	0.7	8.1	0.26	1.5
45–60 cm						
Bushland	21	37	2.1	8.2	0.65	15.2
Halfway	40	36	2	7.8	1.27	131
Lockney	34	37	1.9	8.4	0.57	15.5
Lubbock	39	31	1.3	7.8	1.41	52.3
Lamesa	75	11	0.7	8.4	0.39	1
60–75 cm						
Bushland	23	37	2.2	8.1	0.79	12.7
Halfway	42	34	1.7	7.9	1.47	157
Lockney	38	36	1.7	8.3	0.73	9.6
Lubbock	39	29	1.2	7.9	1.42	58.3
Lamesa	75	11	0.6	8.2	0.54	1.8

[a] OM = organic matter.
[b] EC = electrical conductivity.

Table 4
Parameters adjusted during the CSM-CROPGRO-Cotton model calibration.

Parameter	Description	Testing range	Calibrated value
Cultivar parameters			
EM-FL	Time between plant emergence and flower appearance (photothermal days)	34–44	42
FL-SH	Time between first flower and first pod (photothermal days)	6–12	6
FL-SD	Time between first flower and first seed (photothermal days)	12–18	12
SD-PM	Time between first seed and physiological maturity (photothermal days)	42–50	42
FL-LF	Time between first flower and end of leaf expansion (photothermal days)	55–75	55
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 ppm CO_2, and high light (mg CO_2 m^{-2} s^{-1})	0.7–1.4	1.1
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	170–175	170
SIZLF	Maximum size of full leaf (three leaflets) (cm^2)	250–320	300
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.7–0.9	0.8
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	22–35	35
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	8–14	12
THRSH	Threshing percentage. The maximum ratio of (seed/(seed + shell)) at maturity.	68–72	70
Ecotype parameters			
PL-EM	Time between planting and emergence (thermal days)	3–5	4
EM-V1	Time required from emergence to first true leaf, thermal days	3–5	4
RWDTH	Relative width of the ecotype in comparison to the standard width per node	0.8–1.0	1
RHGHT	Relative height of the ecotype in comparison to the standard height per node	0.8–0.95	0.9
FL-VS	Time from first flower to last leaf on main stem (photothermal days)	40–75	40
Initial conditions (calibrated values)			
Year	2010	2011	2012
Nitrate (μg g^{-1})	40	40	40
Soil water content (cm^3 cm^{-3})	0.18	0.10	0.11

The effect of each adjusted parameter on the modeled processes (or growth stages) was studied by graphically comparing simulated and measured seed cotton yield (scatter plots). In addition, model performance statistics such as coefficient of determination (r^2) (Legates and McCabe, 1999), root mean square error (RMSE), index of agreement (d) (Willmott et al., 1985), and percent error (PE) were determined using equations 1, 2, 3, and 4. The r^2 ranges between 0 and 1, where 0 indicates no fit and 1 indicates perfect fit between simulated and observed values; the closer the *RMSE* to 0, the better the agreement between the simulated and observed values; d ranges between 0 and 1, where 0 indicates no agreement and 1 indicates perfect fit between the simulated and observed values; and PE varies between −100 and∞, with smaller absolute values closer to 0 indicating better agreement.

$$r^2 = \frac{\left(\sum_{i=1}^{N}(Yi-\overline{Y})(\hat{Y}i-\overline{Y}i)\right)^2}{\sum_{i=1}^{N}(Yi-\overline{Y})^2\sum_{i=1}^{N}\left(\hat{Y}i-\overline{Y}i\right)^2} \quad (1)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(\hat{Y}-Yi)^2}{N}} \quad (2)$$

$$d = 1-\left[\frac{\sum_{i=1}^{N}\left(\hat{Y}_i-\overline{Y}_i\right)^2}{\sum_{i=1}^{N}\left(|\hat{Y}_i-\overline{Y}_i|+|Y_i-\overline{Y}|\right)^2}\right], 0 \le d \ge 1 \quad (3)$$

$$\mathrm{PE} = \left(\Sigma_{r=1}^{N}\frac{\hat{Y}-Yi}{Yi}\right)\times 100 \quad (4)$$

where Yi, observed value, $\hat{Y}$, simulated value, $\overline{Yi}$, average of simulated value, $\overline{Y}$, average of observed value, N, number of observations.

The model calibration effort was carried out until the resultant RMSE was low (<0.5), and r^2 and d were higher than 0.85. Twelve cultivar parameters, five ecotype parameters, and initial soil nitrate and volumetric soil moisture content were adjusted until the simulated crop development stages, and seed cotton yield matched reasonably well with measured data (Table 4). Although the model developers generally recommend not to change parameters in the species (CROPGRO046.SPE) file, the EORATIO was adjusted from a default value of 1.0 to 1.1 based on the suggested crop coefficients for cotton in the THP region by Swanson and Fipps (2015).

Accurate simulation of reference ET is the first step toward accurate simulation of crop ET (Thorp et al., 2014). Options available for ET calculation in the CSM-CROPGRO-Cotton model include the FAO-56 Penman–Monteith and the Priestley–Taylor methods. Recently, Thorp et al. (2014) modified the ET routines in the CROPGRO-Cotton model to obtain more realistic ET simulations in the arid conditions of central Arizona because default approaches in the model underestimated seasonal ET by about 15%. Their approach combined the ASCE Standardized Reference Evapotranspiration Equation (Walter et al., 2005) with the approach of DeJonge et al. (2012) for calculation of a crop coefficient (K_c) as a function of LAI. In this study, both FAO-56 Penman–Monteith and Thorp et al. (2014) methods were tested, and the results from the later method, which gave better results for our study site, were reported. Additional modifications to the CSM-CROPGRO-Cotton model code made by Thorp et al. (2014) to output reference ET, were also used in this study. The simulated daily reference ET was then compared with the reference ET calculated by REF-ET, a reference ET calculation software, version 3.1.15 (Allen, 2015). The REF-ET program provides standardized calculations of reference ET that can be compared with other ET computer programs.

2.5. Assessing climate change impacts on cotton production

Several DSSAT CSM-CROPGRO-Cotton projects were created using the projected weather data from RCM3-CGCM3, RCM3-GFDL and CRCM-CCSM climate models to predict historic (1971–2000) and the future (2041–2070) seed cotton yield at Halfway and other four study sites: Bushland, Lockney, Lubbock and Lamesa. The calibrated cultivar parameters (including ecotype and species parameters) from CROPGRO-Cotton model evaluated for Halfway were used in the DSSAT projects for the remaining THP study sites. A common planting date of May 11th and conventional tillage practices were assumed for all historic (1971–2000) and the future (2041–2070) simulations. Fertilizer application amount and date were specified based on actual management practices at Halfway during the 2010–2013 growing seasons. The automatic irrigation method was implemented by triggering irrigation when the simulated soil moisture was depleted to 50% of available soil water

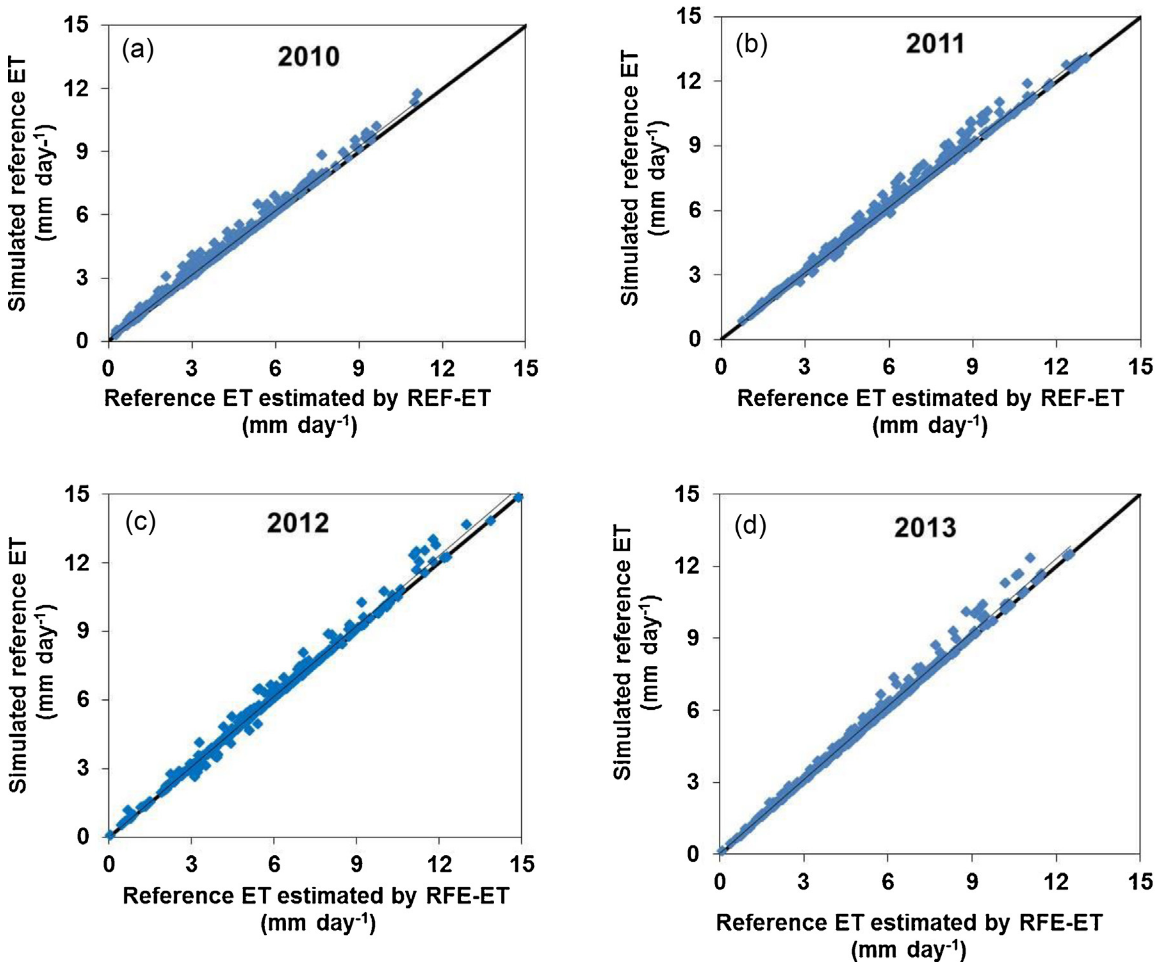

Fig. 4. Comparison of simulated reference ET with the reference ET calculated using the REF-ET software during 2010–2013 for Halfway, TX.

capacity (difference of field capacity and permanent wilting point volumetric soil moisture contents), and irrigation was applied until the profile was filled to 85% of available soil water capacity.

The CSM- CROPGRO-Cotton model interface provides three options for simulating CO_2 concentrations: (i) actual CO_2 concentration at Mauna Loa, Hawaii (Keeling Curve), (ii) default CO_2 concentration of 380 ppm, and (iii) annual CO_2 concentration from the weather file. In this study, the second option was used for the model calibration and validation, and historic (1971–2000) simulations. For the future (2041–2070) simulations, the projected future increases in CO_2 concentration were manually entered into the weather file for each year. According to various IPCC emission scenarios, the projected CO_2 concentration in the year 2100 is expected to vary between 450 ppm (standardization scenario) and 970 ppm (A1F1 scenario) (USGCRP, 2009). In this study, the CO_2 concentration increases as projected under A2 emission scenario were adopted, and the CO_2 concentration was gradually increased from 493 ppm (in year 2041) to 635 ppm (in year 2070) (USGCRP, 2009).

The impacts of climate change on (auto) irrigated seed cotton yield at five THP study sites were then assessed by running CSM-CROPGRO-Cotton simulations for both historic (1971–2000) and future (2041–2070) time periods using the climate data projected by three climate models. In view of the projected declines in groundwater availability for irrigation in the THP in the future, an additional analysis was carried out to study the effects of various deficit irrigation levels on seed cotton yield at Halfway using the climate data projected by the RCM3-GFDL climate model only. For

Table 5
Comparison of simulated and generally measured dates of onset of cotton phenological stages.

Crop phenological stage	Measured(days after planting)[a]	Simulated (days after planting)			
		2010	2011	2012	2013
Calibration					
Emergence	4–9	9	8	10	7
Anthesis	60–70	66	62	67	66
Physiological maturity	130–160	152–153	133–136	155–158	147–163
Validation					
Emergence	4–9	9	7–8	10	7
Anthesis	60–70	66	61–63	67	66
Physiological maturity	130–160	141–152	126–138	142–158	144–165

[a] Robertson et al. (2007).

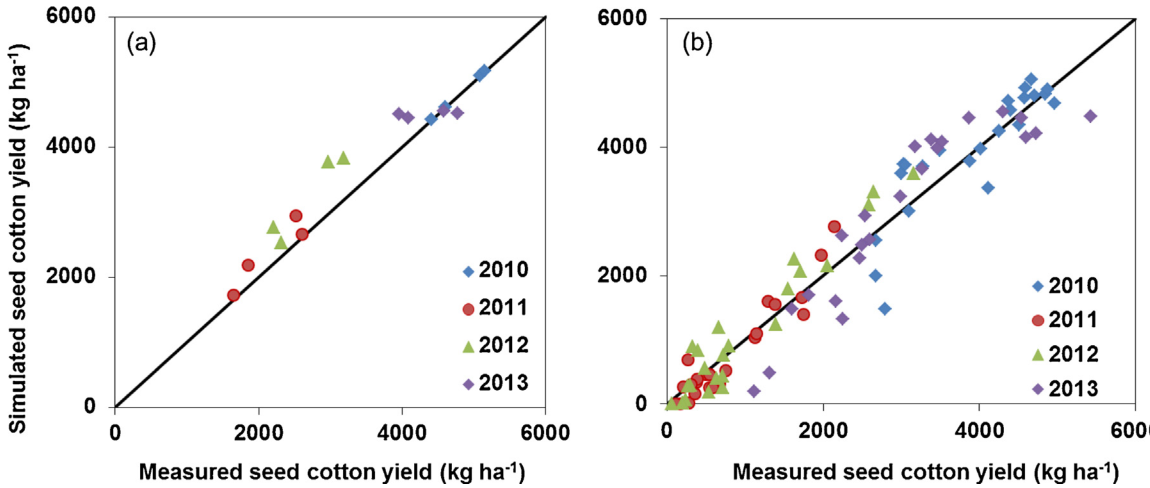

Fig. 5. Comparison of CSM-CROPGRO-Cotton model simulated and measured seed cotton yield for (a) model calibration (HHH, HHM, MHH and MHM treatments during each growing season from 2010 to 2013) and (b) model validation (23 treatments during each growing season from 2010 to 2013) at Halfway.

Table 6
Model performance statistics for the simulation of reference ET and seed cotton yield at Halfway, TX.

Reference ET	Coefficient of determination (r^2)	Root mean square error (RMSE) mm/day	Index of agreement (d)	Percent error (PE) (%)
2010	0.99	0.023	1.0	4.7
2011	0.99	0.014	1.0	2.6
2012	0.99	0.016	1.0	2.8
2013	0.99	0.017	1.0	3.0
Seedcotton yield kg/ha				
Calibration	0.94	292	0.90	0.1
Validation	0.94	481	0.83	6.5

Where r^2 coefficient of determination, RMSE is root mean square error, d is index of agreement and PE is percent error.

this analysis, the thirty-year future (2041–2070) time period was divided into dry, normal and wet years according to the growing season precipitation. The CROPGRO-Cotton simulated future "auto" irrigation amounts for the period from 2041 to 2070 were considered as the 100% irrigation level and then four different simulations with 90%, 80%, 70% and 60% irrigation levels were run to represent various "reduced irrigation water availability" scenarios in the future. The effects of reducing irrigation amounts on seed cotton yield in dry, normal and wet years in the future were finally studied.

3. Results and discussions

3.1. Model evaluation

The calibrated values of cultivar and ecotype parameters and initial soil nitrate and soil moisture contents for the Halfway experimental site are shown in Table 4. Since within the season observed data such as canopy height and leaf area index (LAI) were not available, the cotton cultivar parameters were adjusted to reasonably estimate crop phenology responses and seed cotton yield over the four growing seasons. The majority of calibrated parameters were comparable to those determined previously for 'Deltapine 77,' 'Deltapine 485,' and 'Deltapine 555' cultivars in the DSSAT cotton cultivar file. The calibrated photothermal duration between plant emergence and flower appearance (EM-FL) was greater and photothermal duration between first flower and first pod (FL-SH) and photothermal duration between first flower and first seed (FL-SD) were lower than the previously determined values. The EM-FL parameter was important for accurately simulating the onset of flowering, whereas the FL-SH and FL-SD parameters were important for accurately predicting the timing of first boll and first seed, respectively. The EM-FL parameter was tested within a range of 34–44 photothermal days and a value of 42 photothermal days at which the model simulated reasonable flowering dates, was selected. Previously reported, calibrated values of EM-FL varied between 45 and 51 days depending on the geographical locations and crop management practices. For instance, Ortiz et al. (2009) reported an EM-FL value of 45 photothermal days for Deltapine 485/BG/RR cultivar at Tifton, Georgia. The calibrated value of EM-FL ranged from 46 to 51 photothermal days for cotton at Maricopa, AZ (Thorp et al., 2014). Slightly lower EM-FL value obtained in this study when compared to previous studies might have been due to the differences in weather conditions as well as crop management practices. Other cultivar parameters such as SD-PM, which was important to simulate the crop harvesting date accurately was adjusted to 42 photothermal days, and FL-LF, which was important for correctly simulating the end of the leaf growth, was adjusted to 55 days (Table 4). The LFMAX, SLAVR and SIZLF were found to be very sensitive parameters that affected the photosynthesis rate, transpiration and assimilation of carbon in the plant. The calibrated values of LFMAX, SLAVR and SIZLF were 1.1 mg CO_2 m^{-2} s^{-1}, 170 cm^2 g^{-1} and 300 cm^2, respectively. Finally, cultivar parameters which control yield such as XFRT, SFDUR, PODUR and THRSH were also adjusted during model calibration for attaining a better match between measured and simulated seed cotton yield (Table 4). Ecotype parameters such as RWDTH, RHGHT and FL-VS were very important for correctly simulating canopy width, canopy height and cessation of stem elongation, respectively. The calibrated values of RWDTH, RHGHT and FL-VS were 1, 0.9 and 40 photothermal days, respectively (Table 4).

The simulated dates of onset of various cotton development stages such as emergence, anthesis, and physiological maturity during calibration and validation over four different cotton growing seasons at Halfway, TX were within the ranges suggested

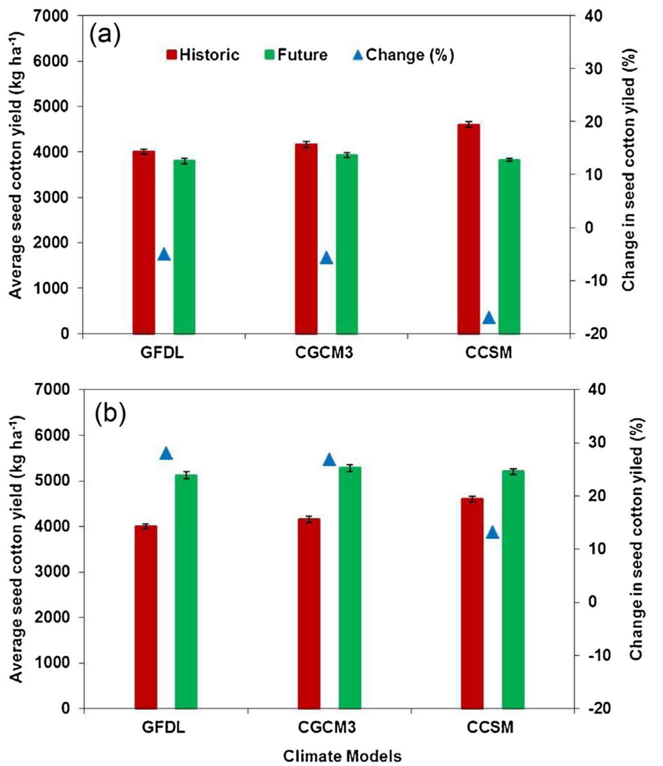

Fig. 6. A comparison of simulated historic (1971–2000) and future (2041–2070) average seed cotton yield and percentages of changes in seed cotton yield at Halfway when using climatic data projected by the RCM3-GFDL (Regional Climate Model Version3—Geophysical Fluid Dynamics Laboratory, RCM3-CGCM3 (Third Generation Coupled Global Climate Model) and CRCM-CCSM (Canadian Regional Climate Model-Community Climate System Model) climate models: (a) under a constant CO_2 concentration scenario (380 ppm), and (b) under a projected increase in CO_2 concentration according to the A2 emission scenario from 493 ppm (2041) to 635 ppm (2070)). (Vertical bars indicate the standard errors).

by Robertson et al. (2007), except on a few occasions (Table 5). Although the simulated physiological maturity dates were different among various years, they were mostly within the observed ranges for the THP region. The differences in maturity date might have been due to the differences in photothermal duration, precipitation and other weather related parameters during growing seasons. Among the four growing seasons, the duration for anthesis and physiological maturity during 2011 were shorter compared to the remaining years. For example, the date of onset of anthesis among various treatments in 2011 ranged between 61 and 63 days while in the remaining years, it ranged from 66 to 67 days. Shorter duration of anthesis and physiological maturity in 2011 was mainly because of higher air temperatures in that year (seasonal average TMAX in 2010, 2011, 2012 and 2013 was 29.1 °C, 31.8 °C, 29.9 °C and 29.6 °C, respectively; Table 1), which resulted in faster development of cotton with shorter time interval between developmental stages. A close agreement between the simulated reference ET and the reference ET calculated using REF-ET was found during all four years of experiment (2010 –2013) as indicated by a very good match between these two parameters (Fig. 4) and excellent model performance statistics (Table 6).

The CSM- CROPGRO-Cotton model predicted seed cotton yield very well during the calibration as indicated by good agreement between measured and simulated yield (Fig. 5a) and good model performance statistics (Table 6). Simulated seed cotton yield for validation treatments also matched well with the measured yield (Fig. 5b). The performance statistics r^2, d, and PE were 0.94, 0.90 and 0.1% for calibration and 0.94, 0.83 and 6.5% for validation, respectively. The calibrated model responded well to various irrigation strategies implemented in 27 treatments over 4 growing seasons with varying precipitation amounts. The average PE in seed cotton yield simulation was only 0.1% during model calibration and about 6.5% during model validation (Table 6).

3.2. Impact of climate change on seed cotton yield in the Texas High Plains

The simulated seed cotton yield at Halfway under future (2041–2070) climate scenarios projected by three climate models decreased within a range of 5–17% when compared to the historic (1971–2000) period, when the CO_2 concentration was assumed to be constant at the current level of 380 ppm (Fig. 6a). The reduction in seed cotton yield was the highest (17%) under the CRCM-CCSM model scenarios when compared to the RCM3-GFDL (5%) and RCM3-CGCM3 (5.7%) model scenarios. The reduction in seed cotton yield at Halfway under the future climate model scenarios can be attributed to the combined effect of increase in the average annual minimum and maximum temperature as well as the decrease in average annual rainfall (Figs. 2 and 3). A smaller variation in simulated seed cotton yield among different years (as indicated by small error bars) was most probably due to the implementation of automatic irrigation, which simulated non-water-limiting conditions. The simulated seed cotton yield at the remaining four study sites (Bushland, Lockney, Lubbock and Lamesa) also decreased within a range of 4–17% in the future (2041–2070) when compared to the historic (1971–2000) period as per the climate scenarios projected by three climate models when the CO_2 concentration was assumed to be constant at the current level (Table 7). The highest reduction in seed cotton yield (17%) was recorded at Lubbock in the southern part of the THP under the CRCM-CCSM projected climate scenario and the lowest reduction in seed cotton yield (4%) was recorded at Lockney under the RCM3-GFDL projected climate scenario.

When the projected increase in CO_2 concentration from 493 ppm (in year 2041) to 635 ppm (in year 2070) according to the IPCC A2 emission scenario was implemented in the CSM-CROPGRO-Cotton model, the simulated average seed cotton yield at Halfway under three climate model scenarios increased within a range of 13–28% in the future (2041–2070) when compared to the historic (1971–2000) period (Fig. 6b). A similar trend was simulated at the remaining four study sites in the THP, and the simulated average seed cotton yield increased within a range of 14–29% in the future (2041–2070) when compared to the historic (1971–2000) period under three climate model scenarios (Table 7). The highest increase in seed cotton yield (29%) was simulated under RCM3-CGCM3 projected climate at Bushland and Lamesa, and the smallest increase (14%) was simulated under CRCM-CCSM projected climate at Lubbock. Among the three climate model scenarios, the simulated seed cotton yield increase was the highest (25–29%) under the RCM3-CGCM3 projected climate scenario followed by the RCM3-GFDL (24–28%) and CRCM-CCSM (14–23%) projected climate scenarios (Table 7). These results indicate that cotton is sensitive to atmospheric CO_2 concentrations, and cotton production in the THP could potentially withstand the effects of future climate variability under moderate increases in CO_2 levels.

Simulated future seed cotton yield at Halfway under various deficit irrigation levels when using climatic data projected by the RCM3-GFDL climate model under wet, normal, and dry years are presented in Fig. 7. The CSM-CROPGRO-Cotton model responded well to the differences in irrigation amounts as indicated by proportional decrease in average seed cotton yield with the reduction in irrigation amount under both CO_2 scenarios. For example, when the irrigation amount was reduced by 40% (from 100% to 60%), the average (2041–2070) seed cotton yield decreased by 37% and 39% under the constant and increasing CO_2 concentration scenarios, respectively (Fig. 7a). On an average (2041–2070), seed cotton yield under

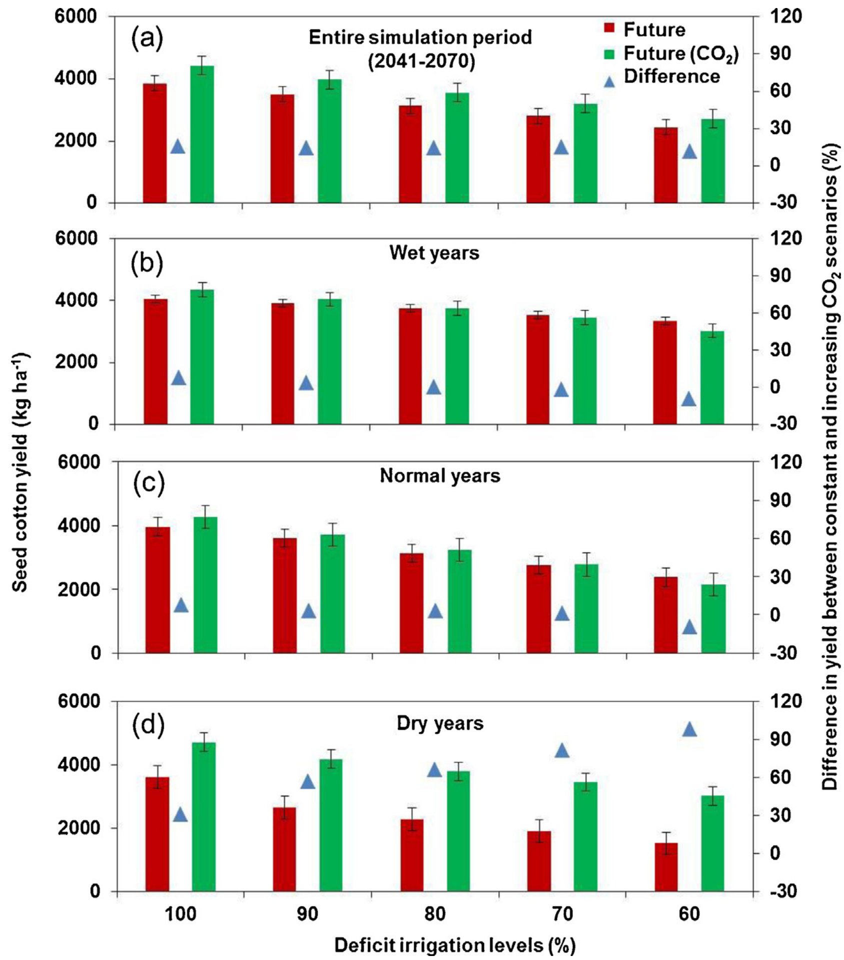

Fig. 7. Simulated future (2041–2070) average seed cotton yield under various deficit irrigation levels at Halfway when using the future climate data projected by the RCM3-GFDL (Regional Climate Model Version3—Geophysical Fluid Dynamics Laboratory) climate model under (i) a constant CO_2 concentration scenario (380 ppm), and (ii) a projected increase in CO_2 concentration according to the A2 emission scenario from 493 ppm (2041) to 635 ppm (2070) during (a) the entire simulation period (b) wet years (c) normal years and (d) dry years. (Vertical bars indicate the standard errors).

Table 7
Average seed cotton yield during historic (1971–2000) and future (2041–2070) time periods and projected future percent changes in seed cotton yield at four study locations under RCM3-GFDL (Regional Climate Model Version3—Geophysical Fluid Dynamics Laboratory, RCM3-CGCM3 (Third Generation Coupled Global Climate Model) and CRCM-CCSM (Canadian Regional Climate Model-Community Climate System Model) projected climate scenarios.

Study sites	Climate models	Seed cotton yield ($kg\,ha^{-1}$)			% Change	
		Historic (1971–2000)	Future (2041–2070)[a]	Future (2041–2070)[b]	Without considering the increase of CO_2 concentration	Considering the increase of CO_2 concentration
Bushland	RCM3-GFDL	3890 ± 42[c]	3648 ± 57	4934 ± 75	−6	27
	CRCM-CCSM	4062 ± 209	3675 ± 45	5014 ± 48	−10	23
	RCM3-CGCM3	3987 ± 66	3736 ± 46	5144 ± 47	−6	29
Lockney	RCM3-GFDL	4062 ± 41	3914 ± 65	5124 ± 76	−4	26
	CRCM-CCSM	4233 ± 145	3759 ± 46	5079 ± 39	−11	20
	RCM3-CGCM3	4221 ± 72	4033 ± 51	5280 ± 72	−5	25
Lubbock	RCM3-GFDL	4030 ± 47	3759 ± 50	5114 ± 62	−7	27
	CRCM-CCSM	4429 ± 161	3694 ± 33	5040 ± 40	−17	14
	RCM3-CGCM3	4205 ± 68	3896 ± 53	5259 ± 64	−7	25
Lamesa	RCM3-GFDL	4040 ± 43	3702 ± 57	4989 ± 52	−8	24
	CRCM-CCSM	4190 ± 214	3550 ± 33	4938 ± 46	−15	18
	RCM3-CGCM3	4040 ± 43	3831 ± 52	5204 ± 49	−5	29

[a] Simulated future (2041–2070) average seed cotton yield under a constant CO_2 concentration scenario (380 ppm).
[b] Simulated future (2041–2070) average seed cotton yield under a projected increase in CO_2 concentration according to the A2 emission scenario from 493 ppm (2041) to 635 ppm (2070).
[c] Standard error.

increasing CO_2 concentration was higher when compared to the constant CO_2 levels and the percent increase varied within a range of 11–15% among different deficit irrigation scenarios considered. However, this trend varied among wet, normal and dry years. The percentage change in average seed cotton yield from the constant CO_2 concentration scenario (380 ppm) to increasing CO_2 level from 493 ppm (2041) to 635 ppm (2070) scenario ranged between −9% (at 60% irrigation level) and 7% (at 100% irrigation level) for the wet years, −9% and 8% for the normal years, and 30% and 98% for the dry years. These results indicate that the cotton production is more sensitive to CO_2 concentration in dry years compared to normal and wet years.

The simulated increases in seed cotton yield under projected future climate scenarios were based on the effects of elevated CO_2 concentrations and increased air temperature on cotton yield, but the effects of canopy temperature on cotton yield were not considered in these simulations. This is a major limitation of the CSM-CROPGRO-Cotton model to reliably predict seed cotton yields under projected future climate change scenarios, because canopy temperature is typically lower than air temperature under well-watered conditions due to evaporative cooling but higher than air temperature when the crop experiences severe water deficit. It is estimated that the vapor pressure deficit would increase by about 5% to 6% per each °C warming (McKenney and Rosenberg, 1993) and hence crop water requirements are expected to increase under projected future climate scenarios. Insuring that canopy temperature remains cooler than air temperature in the future depends on the availability of adequate water supplies for irrigation. In the future climate simulations carried out in this study, non-water-limiting conditions were simulated due to implementation of auto irrigation. Realization of simulated increases in seed cotton yield under elevated CO_2 concentrations in the future would therefore be dependent on the availability of adequate water resources for irrigation. If limited water supplies necessitate deficit irrigation practices in the future, these simulations do not adequately characterize the effect on future cotton yield. Ability to simulate cotton canopy temperature in response to water status using energy balance methods is required to assess effects of heat and drought stress on cotton yield under future climate scenarios.

The simulated increases in future seed cotton yield under increasing CO_2 concentrations were, however, comparable to previous findings by other researchers (Smith and Tirpak, 1989; Kimball et al., 2002; Gérardeaux et al., 2013). Increasing trends of biomass and crop yield in the future were reported by Kimball et al. (2002) in the free air CO_2 enrichment (FACE) experiments conducted at Maricopa, AZ. They reported that the elevated CO_2 in the atmosphere increased photosynthesis and improved water use efficiency by decreasing stomatal conductance and transpiration, resulting in a 40% increase in seed cotton yield. Elevated CO_2 slows transpiration by inducing a partial closure of leaf stomatal guard cells (Jones and Mansfield, 1970). A 3–41% increase in seed cotton yield was also reported under different future climate change scenario experiments in California (Smith and Tirpak, 1989). Several researchers (Acock and Allen, 1985; Acock and Pasternak, 1986; Reddy et al., 1994; McRae et al., 2007; Williams et al., 2015) also stated that atmospheric CO_2 enrichment has the aerial "fertilizer effect" that benefits all plant organs. Reddy et al. (1994) conducted an experiment to observe the effects of CO_2 and temperature on cotton leaf initiation and development and found significant expansion of the mainstem leaves due to the elevated CO_2 and temperature. However, they did not find any significant effect of CO_2 on leaf initiation rates. They further reported that the effect of higher CO_2 was higher at higher temperature resulting in an increase in final leaf size, duration of expansion and rate of expansion. Attavanich and McCarl (2014) documented the impact of atmospheric CO_2 on current and future crop yield using various crop models. They reported a 51% increase in cotton yield when future increases in CO_2 were taken into consideration. Similarly, a recent study conducted in eastern Australia to quantify the effects of climate change on cotton production also reported a 5.9% increase in cotton yield by 2030 under increased CO_2 scenarios and a 17% reduction in cotton yield by 2050 under constant CO_2 concentration scenario (Williams et al., 2015).

4. Conclusions

A well calibrated CSM-CROPGRO-Cotton model was established for the THP region using measured data from field experiments on cotton water use efficiency at Halfway. The calibrated model was able to simulate seed cotton yield under varied precipitation and irrigation regimes implemented in 27 treatments over four years (2010–2013). The simulated dates of various cotton developmental stages such as emergence, anthesis and maturity were within the range of reported values for the THP region. The simulated seed cotton yield showed very good agreement with measured seed cotton yield ($r^2 = 0.94$; $d > 0.83$) for both model calibration and validation. The average *PE* in seed cotton yield prediction was negligible (0.1%) during calibration and about 6.5% during model validation. Overall, the CSM-CROPGRO-Cotton model demonstrated the potential to accurately simulate seed cotton yield under various irrigation strategies over four growing seasons with varying precipitation amounts.

On an average, simulated seed cotton yield across the THP region decreased within a range of 4–17% under projected future (2041–2070) climate scenarios when compared to the historic (1971–2000) period, when CO_2 concentration was assumed to be constant at the current level (380 ppm). In contrast, when the CO_2 concentration was assumed to increase from 493 ppm (in year 2041) to 635 ppm (in year 2070) according to the IPCC A2 emission scenario, the simulated average seed cotton yield across the THP region increased within a range of 14–29% in the future. Seed cotton yields were found to be more sensitive to CO_2 levels in dry years compared to normal and wet years, and the positive effect of CO_2 levels on seed cotton yields reduced with the reduction in irrigation amounts in normal and wet years.

These simulated increases in seed cotton yield under projected future climate scenarios were based on the effects of elevated CO_2 concentrations and increased air temperature on cotton yield, but the effects of canopy temperature on cotton yield were not considered in these simulations. Thus, impacts of increasing future air temperature on cotton yield may be less than the simulations demonstrated, which assumed water is available to maintain canopy temperature lower than air temperature. Because canopy temperature effects on future cotton yield will depend on water availability, realization of simulated increases in seed cotton yield under elevated CO_2 concentrations in the future depends on the availability of adequate water supplies for irrigation. However, the simulated increases in seed cotton yield under projected future climate scenarios were comparable to reported increases in cotton yield in the literature, which ranged from 3% to 51% under varied agro-meteorological conditions.

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