Field Crops Research 271 (2021) 108261

Contents lists available at ScienceDirect

Field Crops Research

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

Potential genotype-based climate change adaptation strategies for sustaining cotton production in the Texas High Plains: A simulation study

Kritika Kothari [a,b], Srinivasulu Ale [a,c,*], James P. Bordovsky [a,d], Clyde L. Munster [a], Vijay P. Singh [a], John Nielsen-Gammon [e], Gerrit Hoogenboom [f]

[a] Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX, 77843, United States
[b] Plant and Soil Sciences Department, University of Kentucky, Lexington, KY, 40546, United States
[c] Texas A&M AgriLife Research (Texas A&M University System), Vernon, TX, 76385, United States
[d] Texas A&M AgriLife Research (Texas A&M University System), Plainview, TX, 79072, United States
[e] Department of Atmospheric Sciences, Texas A&M University, College Station, TX, 77843, United States
[f] Institute for Sustainable Food Systems and Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, 32611, United States

ARTICLE INFO

Keywords:
Drought tolerance
DSSAT CSM CROPGRO-Cotton
Heat tolerance
High yield potential
Long maturity

ABSTRACT

The Texas High Plains (THP) is a major cotton-producing region in the United States. Sustaining cotton production under declining groundwater availability in the underlying Ogallala Aquifer and changing climate remains a key challenge for stakeholders in this region. The objectives of this study were to assess climate change impacts on cotton yield and irrigation water use, and evaluate six ideotypes for adaptation. In this study, we used the DSSAT-CSM-CROPGRO-Cotton model for simulating cotton production under 18 projected future climate scenarios and with six potential adaptation ideotypes at Bushland, Halfway and Lamesa in the northern, central, and southern parts of the THP region, respectively. Seed cotton yield and irrigation water use between baseline (1976–2005) and future periods (mid-century:2036–2065 and late-century: 2066–2095) were compared. The irrigated seed cotton yield is expected to increase by 12–21 % at cooler northern sites, and decrease by 2% at the warmer southern site, in the mid-century compared to the baseline. For the same period, seasonal irrigation water use is expected to increase by 6–11 % and dryland seed cotton yield is expected to change by +6 % to −11 % across the locations. The increases in irrigated seed cotton yield were attributed to increased vegetative growth under elevated CO_2, while the decline in dryland seed cotton yield was due to poor boll retention at high growing season temperatures. Six potential climate change adaptive ideotypes with greater drought and heat tolerances, higher yield potential, and longer maturity were designed and compared to the reference cultivar. For irrigated conditions, increasing area of full leaf and enhancing partitioning of assimilates to reproductive growth (high yield potential) were preferred, because these characteristics increased seed cotton yield substantially (by 3–9 %) with a marginal change in irrigation water use (by −1 to 3 %). For dryland production, a long maturity ideotype with longer boll filling duration was the most effective ideotype with a substantial increase in seed cotton yield by 11–45 %. The results from this study will be useful to THP cotton producers and water managers in making appropriate decisions for adapting cotton production to projected changes in future climate and groundwater availability.

1. Introduction

Cotton [*Gossypium hirsutum* L.] producers in the Texas High Plains (THP) region face challenges from the declining irrigation water supplies and changing climate. The THP region encompasses about 35 % of the total upland cotton acreage in the United States. Approximately 43 % of this area is irrigated, according to 2010–2018 annual average (USDA-NASS, 2018). Irrigating such a large area of cotton, about 0.3 million ha, may not be feasible in the future because the Ogallala Aquifer, which is the primary source of irrigation water, has been depleting rapidly (Chaudhuri and Ale, 2014). In addition, projected future increases in temperature, rainfall variability and extreme weather conditions under a changing climate (Coumou and Rahmstorf, 2012; IPCC, 2014; Wuebbles et al., 2017), could affect cotton production in the

* Corresponding author at: Texas A&M AgriLife Research (Texas A&M University System), Vernon, TX, 76385, United States.
E-mail address: sriniale@ag.tamu.edu (S. Ale).

https://doi.org/10.1016/j.fcr.2021.108261
Received 16 February 2021; Received in revised form 25 July 2021; Accepted 31 July 2021
0378-4290/© 2021 Elsevier B.V. All rights reserved.

THP. Using data from regional climate models based on the Coupled Model Intercomparison Project 3 (CMIP3) simulations, Modala et al. (2017) projected an increase in the maximum temperature (between 2.0 and 3.2 °C) and a decline in annual rainfall (between 30 and 127 mm) in a majority of the counties in the THP region in the future (2041–2070) compared to the baseline (1971–2000) period. Therefore, it has become essential to adapt cotton production to the anticipated changes in irrigation water availability and weather conditions during the growing season.

Limited literature exists on climate change adaptation strategies for cotton production. Some researchers (Gérardeaux et al., 2018; Loison et al., 2017) have used simulation models for evaluating potential cotton ideotypes for climate change adaptation; however, such efforts are lacking for the THP region. Loison et al. (2017) evaluated several crop parameters for climate change adaptation in Cameroon, Africa, using the DSSAT-CROPGRO-Cotton model. They found that ideotypes with early flowering and longer reproductive periods were best suited under climate change. Similarly, Gérardeaux et al. (2018) found that longer maturity and thicker leaves were potential traits for cotton production in Sub-Saharan Africa. Most researchers tested cotton genotypes for dryland conditions and there is little published data on potential adaptations for irrigated conditions, keeping in view both yield and irrigation water use. Farmers and planners in the THP region could benefit from better understanding of potential climate change impacts and adaptations for cotton production.

Although research on climate change adaptation for cotton is limited, many researchers have assessed climate change impacts on cotton production in controlled-environment and simulation studies (Adhikari et al., 2016; Gérardeaux et al., 2018; Kimball et al., 2002). Air temperature, rainfall, and atmospheric carbon dioxide concentration [CO_2] are key drivers of crop response to climate change (Parry et al., 2004). Cotton is a C_3 plant, which shows a substantial increase in photosynthesis rates at elevated [CO_2] level (Kimball et al., 2002). Researchers in Maricopa, AZ, reported a 43 % increase in harvestable cotton yield in a Free Air CO_2 Enrichment (FACE) experiment at ambient temperature with an elevated [CO_2] level of 550 ppm (Mauney et al., 1994). In another study in Richmond, Australia, Broughton et al. (2017) grew cotton in a greenhouse under two [CO_2] (400 ppm and 640 ppm), and two day/night temperature regimes (28/17 °C and 32/21 °C) and reported that elevated [CO_2] increased vegetative biomass at lower temperatures, but not at higher temperatures. The water use of cotton increased by 7% under elevated [CO_2] treatments for both temperature treatments. Researchers at Mississippi State University, Mississippi, used naturally lit controlled environment plant growth chambers or Soil-plant-atmosphere-research units (Reddy et al., 1995), and reported that CO_2 enrichment increased the boll count by 28 %, but it did not affect the boll weight at optimum temperatures. At higher temperatures (>35.5 °C), no bolls were produced in any [CO_2] treatment. Reddy et al. (1999) found boll retention to be the most temperature-sensitive characteristic and identified 32 °C temperature as the maximum temperature for cotton boll survival. These studies show that the positive effects of CO_2 fertilization on cotton yield depend on the air temperature. Therefore, studying interactive effects of these two parameters, [CO_2] and temperature, under a wide range of climate regimes, which is difficult to achieve in a controlled environment setting, would be beneficial in developing climate change adaptation strategies for cotton growth.

The CSM-CROPGRO-Cotton model of the Decision Support System for Agrotechnology Transfer (DSSAT) is a process-based cropping system model (Hoogenboom et al., 2019; Jones et al., 2003) and it has been widely used to simulate cotton growth under climate change. Adhikari et al. (2016) assessed the impacts of CO_2 fertilization on cotton yield in the THP region and reported a 14–29 % increase in seed cotton yield in 2041–2070 when compared to the 1971–2000 yield under non-water limiting conditions. Anapalli et al. (2016) also reported an increase in irrigated seed cotton yield under climate change in the Mississippi Delta region under moderate temperature rise; but yields decreased beyond 2050 under extreme temperature rise (2.6–4.6 °C). In contrast, in another study in Punjab, Pakistan, Rahman et al. (2018) reported a decrease in seed cotton yield by 12 % in 2030s (+1.8 °C temperature rise) and 30 % in 2060s (+3.5 °C temperature rise). All these studies, which used CSM-CROPGRO-Cotton show that this model is useful for assessing climate change impacts on cotton production, but the direction of change in the future seed cotton yield varied in those modeling studies.

The overall goal of this study was to evaluate potential climate change adaptation strategies for cotton production in the THP region. The specific objectives were to: (a) assess climate change impacts on cotton yield and irrigation water use at three locations in the THP region; and (b) evaluate six ideotypes with different genotype specific traits, for climate change adaptation at those study sites, using the CSM-CROPGRO-Cotton model.

2. Materials and methods

2.1. The DSSAT-CSM-CROPGRO-Cotton model

We used the CSM-CROPGRO-Cotton model within the DSSAT v4.6 crop modeling platform (Hoogenboom et al., 2015). The CROPGRO crop model, initially developed for grain legumes (Boote et al., 1998), computes crop growth processes based on species traits and cultivar parameters (Jones et al., 2003). Cotton was integrated into the CROPGRO model using parameterization data from the published studies (Messina et al., 2004; Pathak et al., 2007). In the CROPGRO model, crop development stages are predicted, based on temperature, photoperiod, and water deficit (Boote et al., 1998; Hoogenboom et al., 1992). If all the three conditions are optimal on any given day, it is counted as one physiological day; and once the accumulated physiological days reach the required count, the crop development phase is completed. Photosynthesis is computed using the hedgerow light interception model and leaf related parameters, with adjustments for [CO_2], row spacing, and cultivar specific photosynthesis rate (Boote and Pickering, 1994). The daily carbon assimilation rate has an asymptotic response to [CO_2]. An overview of CROPGRO model and the photosynthesis response to [CO_2] can be found in Boote et al. (1998) and Alagarswamy et al. (2006), respectively. The daily canopy assimilation response to [CO_2] is based on three species parameters: CCMP (80 ppm), which indicates canopy compensation point at which daily gross photosynthesis is zero; CCMAX (2.09) which indicates maximum daily canopy photosynthesis rate relative to the photosynthesis rate at 350 ppm [CO_2]; and CCEFF (0.0105), which represents relative efficiency of [CO_2] assimilation used to adjust canopy photosynthesis with [CO_2] (Saseendran et al., 2010). The elevated [CO_2] also affects evapotranspiration (ET) through a parameter ETRATIO, which is defined as the ratio of ET under elevated [CO_2] to the ET under base climate, which is computed using temperature, wind speed, leaf area index (LAI), and [CO_2] (B. Curry et al., 1990). In summary, the daily canopy assimilation rate increases asymptotically with increasing [CO_2], and it can be as high as 2.09 times of that at 350 ppm [CO_2]. The ETRATIO accounts for stomatal closure under elevated [CO_2] (Hoogenboom et al., 1995). The minimum inputs required for crop growth simulation include soil properties, weather data, crop management data, and initial conditions (Hoogenboom et al., 2012).

2.2. Study sites and model inputs

Three sites within the THP region were chosen for this modeling study: Bushland (35°11' N, 102°6' W, 1170 m aMSL), Halfway (34 ° 11' N, 101 ° 56' W, 1071 m aMSL), and Lamesa (32°46' N, 101 ° 56' W, 915 m aMSL). These three sites represent weather conditions in the northern, middle, and southern parts of the region (Fig. 1). There is a temperature gradient from north (cooler) to south (warmer), but the average annual

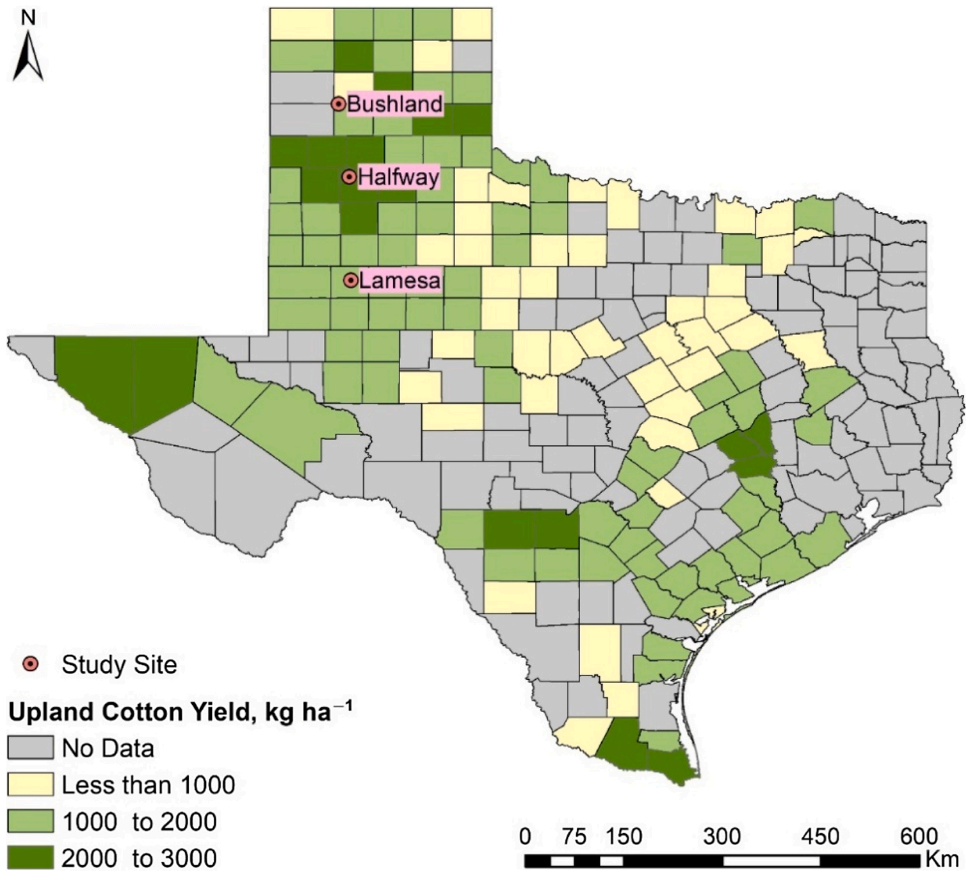

Fig. 1. Map of Texas with the study sites and county-wise average (2000–2019) cotton lint yield under dryland conditions (USDA-NASS, 2018).

rainfall is comparable at the three sites. Soils at Bushland and Halfway site are fine textured (Pullman clay loam - fine, mixed, superactive, thermic, Torrertic Paleustolls), whereas that at Lamesa site is coarser (Amarillo fine sandy loam - fine-loamy, mixed, superactive, thermic, Aridic Paleustalf). These two soil series represent the most common soils in the THP region (McMichael and Lascano, 2003). We obtained most of soil data from field measurements (Adhikari et al., 2016), and generated the remaining parameters using the SBuild tool in DSSAT. Measured soil inputs included percentages of sand and clay, pH, nitrogen and organic carbon, and cation exchange capacity. The upper 180 cm soil profile had 36 % clay and 22 % sand at Bushland, 29 % clay and 47 % sand at Halfway, and 10 % clay and 75 % sand at Lamesa.

The CSM-CROPGRO-Cotton model parameters, calibrated previously (Kothari et al., 2019b) against field data from the Halfway site, were used for performing scenario analyses at all three sites. Measured data used for calibration were obtained from field experiments conducted at Halfway over eight growing seasons and three irrigation experiments. Systematic adjustment of genotype parameters related to phenology, growth, and yield resulted in a close match between simulated and observed onset of growth stages and yield. The calibration results related to phenology and seed cotton yield were reported in Kothari et al. (2019b). We have performed additional model evaluation by comparing simulated soil water with measured volumetric soil water from the top 1.4 m soil profile reported in Bordovsky et al. (2011) from similar cotton-grain sorghum rotation experiments and similar irrigation treatments in adjacent plots under the same center pivot irrigation system. We have also compared simulated reference ET during the cotton growing season with the standardized reference ET estimated by Bushland ref-ET software (Gowda et al., 2016). The ref-ET software uses the American Society of Civil Engineers (ASCE) Standardized Reference ET equation proposed by Walter et al. (2000), and provides standard ET results that can be compared with other ET methods, as was done in previous studies (Adhikari et al., 2016; DeJonge and Thorp, 2017). These additional checks for soil water and reference ET prediction were done in this study to ensure that the simulated soil water balance and crop water use were reasonable.

Weather data projected by nine global climate models (GCMs), which were bias corrected and statistically downscaled using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown, 2012) and METDATA gridded training data (Abatzoglou, 2013), were used. The daily climate forcings from the Coupled Model Intercomparison Project 5 (CMIP5) GCMs were obtained from the MACAv2-METDATA dataset (https://climate.northwestknowledge.net/MACA/index.php). We used future climate projections from nine GCMs and two representative concentration pathways (RCPs) (Kothari et al., 2020). The GCMs used were BCC-CSM1-1, CCSM4, CSIRO-Mk3-6-0, GFDL-ESM2M, CNRM-CM5.1, IPSL-CM5A-LR, MIROC5, MRI-CGCM3, and NorESM1-M. The RCPs used were RCP 4.5 (moderate emissions scenario) and RCP 8.5 (high emissions scenario) (Van Vuuren et al., 2011). The [CO_2] was changed annually from 332 ppm in 1976 to 540 ppm and 875 ppm in 2095 under RCPs 4.5 and 8.5, respectively (IPCC, 2014). More details about the GCMs and climate change scenarios are given in Kothari et al. (2020) and Kothari et al. (2019a).

Crop management inputs were obtained from field experiments conducted at Halfway and the reported values from literature (Adhikari et al., 2016; Bordovsky et al., 2015; Bronson et al., 2009; Segarra et al., 1991). Cotton was planted on May 11th at 13 seeds m^{-2} (Bordovsky et al., 2015). Seeds were planted at a 3.8 cm depth with a row spacing of 1.02 m. Fertilizer was applied at the rate of 120 kg N ha^{-1} and 52 kg N ha^{-1} for irrigated and dryland cotton, respectively, based on average values from field experiments at Halfway (Bordovsky et al., 2011). For dryland cotton, the fertilizer amount was halved and applied at 35 and 60 days after planting (DAP), whereas for irrigated cotton, the fertilizer amount was split into three equal doses and applied at 35, 60, and 70 DAP. The fertilizer application in the case of irrigated cotton roughly corresponded to the first square, first bloom and mid bloom growth stages, respectively, as suggested by Bronson and Bowman (2009). Tillage practices included using field cultivator (on 25-Jan), bed roller (on 1-Mar) and rotary hoe (31-Mar), similar to Bordovsky et al. (2015). Irrigation was simulated using the "auto-irrigation" feature of DSSAT, assuming 90 % irrigation efficiency. Irrigation was applied to replenish plant available water content, the difference between field capacity and permanent wilting point, in the top 30 cm profile (default) to 100 % whenever it dropped to 50 %. The initial soil water was assumed as 100 % and 75 % of plant available water content for irrigated and dryland conditions, respectively. Initial soil nitrogen in the top 210 cm profile for irrigated conditions was set at 120 kg N ha^{-1}, which was close to the measured value in Lubbock, Texas (Bronson et al., 2001), and within the range of values reported at eight cotton fields across the southern THP (Bronson et al., 2009). For dryland cotton, initial soil nitrogen was assumed to be 52 kg N ha^{-1}. The simulations were initiated on January 1 each year, and the initial conditions were updated at the beginning of each year.

2.3. Adaptaion scenarios

The genotype specific parameters of the cultivar used for climate change impact assessment in this study were calibrated in a prior study (Kothari et al., 2019b), and is referred to as the 'reference cultivar'. For evaluating cultivars for climate change adaptation, some of the genotype specific parameters and species coefficients of the reference cultivar were modified, and the modified cultivars are referred to as 'ideotypes'. The adjusted values of genotype specific and species parameters were decided based on published field experiments and modeling studies. The methodology used in this study was built upon the approach used by Singh et al. (2014b) for sorghum and Loison et al. (2017) for cotton. A total of six ideotypes were evaluated in this study, including two types of drought tolerant ideotypes with modified root physical and soil hydraulic properties, two heat tolerant ideotypes with increased range of optimal temperatures for boll addition and partitioning to boll, one high yield potential ideotype with bigger leaves and greater partitioning to seed growth, and one longer maturity ideotype with earlier flowering and longer reproductive phase, relative to the 'reference cultivar'. These ideotypes are described in detail in the following sub-sections.

2.3.1. Drought tolerance I and II ideotypes

Some of the characteristics of drought tolerant cotton are efficient and vigorous root system, smaller and thicker leaves, lower transpiration, and higher photosynthetic rates than non-drought-tolerant varieties (Iqbal et al., 2013; Levi et al., 2009; Ullah et al., 2017). These characteristics were incorporated by changing relevant species and cultivar parameters. Drought tolerant I ideotype was created by increasing parameters ***RFAC1*** (root length per unit root weight, cm/g), ***RWUMX*** (Maximum Water Uptake per unit root length, constrained by soil water (cm^3[water] / cm[root]) and ***LFMAX*** (Maximum Leaf Photosynthesis rate), and decreasing ***RWUEP1*** (soil water supply to potential transpiration ratio). The ***RFAC1*** parameter was increased from 12000 (default) to 17000 (value used in a cotton root-knot nematode modeling study in Tifton, Georgia (Ortiz et al., 2009)). This is also in accordance with a field study in Pakistan (Riaz et al., 2013), where researchers reported that the most drought tolerant cotton line had the highest root length to root weight ratio, among the six lines studied. The ***RWUMX*** parameter was increased from 0.04 (default) to 0.08 (calibrated for Northern Cameroon under current climate conditions (Loison et al., 2017)). The ***LFMAX*** parameter was increased from 1.3 (calibrated) to 1.4 and the ***RWUEP1*** parameter was reduced from 1.5 (default) to 1.2 (Loison et al., 2017). Drought tolerant II ideotype was designed in the same way as drought tolerant I, except that RWMUX was decreased from 0.04 to 0.02.

2.3.2. Heat tolerance I and II ideotypes

Heat stress can negatively affect seed cotton yield by reducing boll retention and boll size (Lokhande and Reddy, 2014; Singh et al., 2007). A heat tolerant ideotype is therefore expected to have better boll retention at a higher temperature (Liu et al., 2006). In order to incorporate heat tolerance, the upper optimum and failure temperature thresholds of boll addition rate (***FNPDT***) and partitioning to boll (***YXFTEM***) were increased (Fig. S1). These thresholds were increased by 2 °C and 3 °C in Heat Tolerant I and Heat Tolerant II ideotypes, respectively. This methodology is a modified version of the approach used by Singh et al. (2014a) for chickpea.

2.3.3. High yield potential ideotype

A high yielding ideotype was designed by targeting yield related parameters. The maximum size of full leaf (***SIZLF***) was increased from 250 cm^2 to 275 cm^2; the maximum fraction of daily growth that is partitioned to seed + shell (***XFRT***) was increased from 0.8 to 0.88; and the threshing percentage ***THRSH*** (maximum ratio of (seed/(seed + shell)) at maturity) was increased from 70 to 72.

2.3.4. Long maturity ideotype

Early flowering and longer reproductive phase could optimize crop yields under climate change, as suggested by Loison et al. (2017). A long maturity ideotype was created by lengthening the crop cycle by approximately 10 % (as implemented by Singh et al. (2014a)), and inducing earlier flowering. The parameter ***EM-FL*** (the duration between emergence and first flower appearance, photothermal days) was decreased from 38 to 34; and ***SD-PM*** (the duration between first seed and physiological maturity, photothermal days) was increased from 40 to 51.

2.4. Statistical analysis

We simulated cotton growth at three locations for two RCPs, nine GCMs and three time intervals: baseline (1976–2005), mid-century (2036–2065), and late-century (2066–2095). The projections of yield and irrigation water use were visualized separately for each location, GCM, RCP, and future time intervals. This was done by averaging the model outputs of the 30-year periods for the baseline and future periods, and calculating the difference between the baseline and future yield and irrigation water use. The changes in yield/irrigation water use are further plotted against the changes in growing season temperature, rainfall, aboveground biomass, boll count at maturity, growing season length, and maximum Leaf Area Index (LAI) wherever applicable. These relationships are plotted as scatter plots with a linear regression fitted to the simulated points and the coefficient of determination (R^2) is computed to relate the pair of variables plotted. The statistical significance of the difference in the 30-year average yield/irrigation between the reference cultivar and an ideotype was tested using the two-sample *t*-test for unpaired data at 95 % confidence interval (Welch, 1938).

For evaluating ideotypes for climate change adaptation, we repeated the simulations (for three locations, two RCPs, two RCPs, nine GCMs, and two future periods) with six ideotypes comprising different genotype specific and species parameters. For evaluating the ideotypes for climate change adaptation, the difference in yield/irrigation water use between an ideotype and the reference cultivar was obtained for each year. All the differences between an ideotype and the reference cultivar for 30-years are plotted using box and whisker plots, and are shown separately for each location, RCP, GCM, and future period. To improve legibility of boxplots developed for presenting climate change adaptation results, only six out of nine GCMs are shown. Out of the six selected GCMs, three GCMs (MRI-CGCM3, CNRM-CM5.1, and GFDL-ESM2M) projected milder temperature rise and wetter growing season in the future than the baseline climate, while the other three GCMs (CCSM4, BCC-CSM1.1, and IPSL-CM5A-LR) projected greater temperature rise and drier climate than the baseline. The remaining three GCMs, which were not shown in boxplots, projected temperature and precipitation changes that were intermediate to the selected six GCMs. The relationship between the changes in yield/irrigation and the changes in key model outputs (biomass, boll count, unit boll weight, crop ET, and growing season length) are plotted for all six ideotypes to understand possible relationship between the pair of variables. To aid comparison between different scenarios, the model outputs (yield and seasonal irrigation) were averaged for 30 years within a GCM of a specific future scenario, and the differences between the 30-year average yield/irrigation under an ideotype and the reference cultivar are presented as percentage in supplementary tables.

3. Results

3.1. Model evaluation

As reported in Kothari et al. (2019b), the CROPGRO-Cotton model simulated seed cotton yield with an acceptable percent error of 3.4 % during calibration and −10.5 % during evaluation, relative root mean square error (RMSE) of 15.5 % during calibration and 25.9 % during evaluation, and index of agreement of 0.90 during calibration and 0.94 during model evaluation. Measured data from the high irrigation level, treatments were used for model calibration, while model evaluation was performed with measured data from the medium and low irrigation level treatments, all under eight environments (growing season and field). The simulated and measured volumetric soil water in the top 1.4 soil profile matched closely with mean absolute error (MAE) less than 0.01 $m^3\ m^{-3}$, and RMSE ranging from 4.4 % to 11.7 % (Fig. S2). The simulated reference crop ET during the seven cotton growing years, calculated from the planting to harvest matched closely with the reference ET obtained from the standardized ET method (Gowda et al., 2016), with MAE of 0.27–0.5 mm d^{-1} and RMSE of 6.0–8.1 % (Fig. S3). Overall, the comparison of measured and simulated phenology, seed cotton yield, and soil water under different irrigation levels indicated a fair model performance (as per RMSE < 30 % criteria suggested by Bannayan and Hoogenboom (2009)). An additional check for reference ET gave further confidence in the model for simulating crop water use and running long-term climate change scenarios. However, the model calibration did not include in-season biomass and leaf area index due to unavailability of measured data from the field experiments, and this is one of the limitations of the study.

3.2. Changes in projected cotton growing season climate

The typical growing season (May–October) rainfall at the study locations during the baseline period (1976–2005) was comparable with an average value of 345 mm. The projections from nine GCMs showed mixed trends for the future rainfall with the change in the growing season rainfall between the future and baseline periods varying from −78 to +66 mm in 2050s and from −99 to +66 mm in 2080s across locations (Fig. 2). Almost half of the selected GCMs consistently projected an increase in the rainfall, while the remaining half projected a reduction in the growing season rainfall. Based on the rainfall deviation in 2050s from the baseline period under RCP 8.5, the GCMs projecting an increase in rainfall were GFDL-ESM2M (24–64 mm increase depending on the location), CSIRO-Mk3-6-0 (9–66 mm), MIROC5 (8–33 mm), and MRI-CGCM3 (12–29 mm), and GCMs projecting rainfall reduction were IPSL-CM5A-LR (5–45 mm decrease depending on the location), CCSM4 (33–49 mm), BCC-CSM1-1 (16–26 mm), and NorESM1-M (20–25 mm). The rainfall projections differed largely among the GCMs and were similar for the three study locations and showed no specific patterns between RCPs or future periods.

The minimum/maximum temperatures during the growing season (May–October) of the baseline period varied across the three locations, Bushland (13/29 °C), Halfway (14/30 °C), and Lamesa (16/31 °C). The average growing season temperature gradient from north to south also varied from Bushland (21 °C), to Halfway (22 °C), and Lamesa (24 °C). The average growing season temperature increased under all future scenarios. The temperature rise varied among GCMs, with milder temperature increases typically projected by GFDL-ESM2M and MRI-CGCM3, and greater temperature increases projected by CSIRO-MK3.6 and IPSL-CM5A-LR (Fig. 2). Temperature rise was greater under RCP

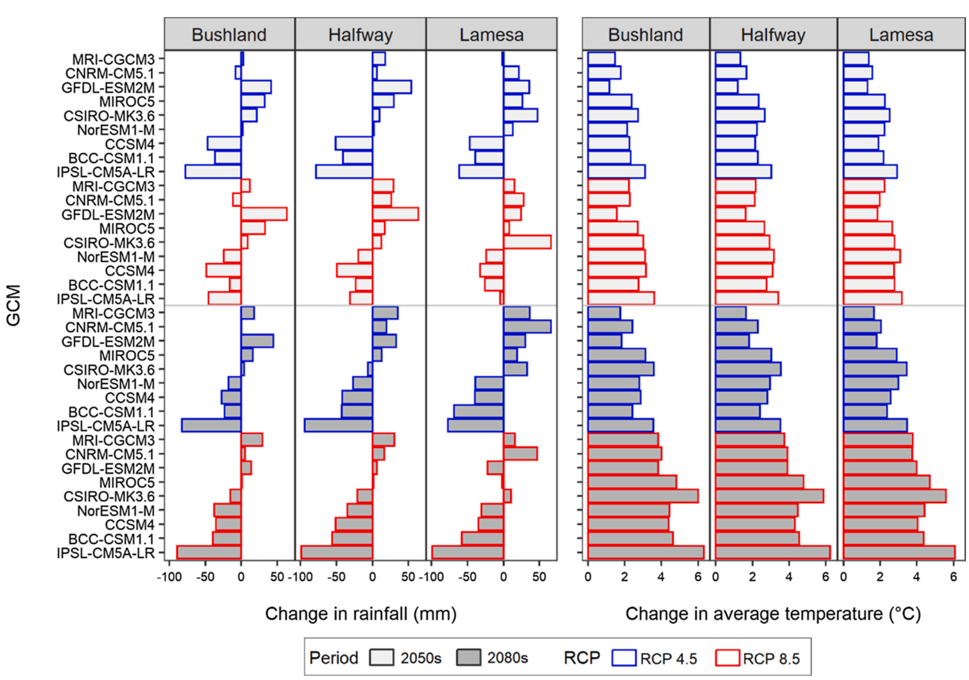

Fig. 2. Changes in cotton growing season (May–October) average temperature (ΔT) and rainfall (ΔP) at the study sites, as projected under nine GCMs for two RCPs and two future time periods 2050s (2036–2065) and 2080s (2066–2095), with respect to the baseline period (1976–2005).

8.5 than RCP 4.5, and greater in 2080s than in 2050s. The increase in temperature from the baseline period varied across the GCMs from 1.2 to 3.1 °C under RCP 4.5 to 1.6–3.6 °C under RCP 8.5 in 2050s, and from 1.7 to 3.6 °C under RCP 4.5 to 3.7–6.3 °C under RCP 8.5 in 2080s.

3.3. Climate change impact assessment

3.3.1. Changes in irrigated yield

The irrigated yield increased in all scenarios at Bushland and Halfway, but it decreased in most of the scenarios at Lamesa (Fig. 3). For example, under RCP 8.5 in 2050s, the irrigated seed cotton yield increased by 18–23 % at Bushland and 8–21 % at Halfway, while it changed by −10 % to 11 % at Lamesa. To understand the temperature rise effects on irrigated yield, the changes in irrigated yield under different scenarios were studied against the changes in growing season (planting to harvest) minimum/maximum temperature (Fig. 4). The correlation between the changes in growing season minimum and maximum temperature with yield change was weak (coefficient of determination, $R^2 < 10^{-3}$) when data for all locations were pooled together (Fig. 4a–b), but it was stronger and negative when plotted for Lamesa site alone ($R^2 = 0.42$ for minimum and 0.55 for maximum temperature). This indicated that the pattern of yield change could be related to the projected changes in growing season temperature at Lamesa but not at other two locations. The variation in growing season temperature is different at the study sites because they have different baseline temperatures. We therefore studied the correlation between absolute temperatures and yield changes for all locations together (Fig. 4c–d), which showed that the yield changes had a negative correlation with absolute growing season average temperature values ($R^2 =$ 0.49 for minimum and 0.51 for maximum temperature).

To further explore the relationship between yield and average growing season temperature, which varies from year to year, we analyzed the yield and growing season temperature data from all sites and for all simulated years, across GCMs, RCPs, and periods (Fig. 5). The yield-average temperature relationship appeared to be quadratic with an increase in yield with increasing temperature up to an optimal temperature followed by a decline in seed cotton yield. The temperature response curves in DSSAT-CROPGRO-Cotton also follow a similar trend with an optimal temperature range for boll addition rate as 28.2–30 °C, and that for partitioning to boll as 17–26 °C (Fig. S1).

Possible reasons behind the differences in yield responses across the sites and among GCMs were further studied by analyzing additional model outputs such as the aboveground biomass, boll count at maturity, and growing season length (Fig. S4). Under RCP 8.5 in 2080s, the aboveground biomass at maturity increased by 37–50 % at Bushland, 30–35 % at Halfway, and 15–26 % at Lamesa, depending on the GCM (Fig. S4a). The changes in biomass were correlated reasonably well with the changes in seed cotton yield ($R^2 = 0.51$), but the correlation between seed cotton yield and boll count was much better ($R^2 = 0.84$) (Fig. S4b). Under RCP 8.5 in 2080s, the boll count at maturity deviated from the baseline period by 5%–24% at Bushland, −6% to 5 % at Halfway, and −21 % to −2 % at Lamesa, depending on the GCM (Fig. S4b). The growing season length was shortened under climate change since a warmer temperature hastened development and reduced the growing period (Reddy et al., 2002). The changes in irrigated yield and growing season length showed a weaker and negative correlation ($R^2 = 0.21$) when plotted for all three sites together, but the pattern for Lamesa alone showed a stronger and positive correlation ($R^2 = 0.48$, Fig. S4c).

3.3.2. Changes in dryland yield

Dryland seed cotton yield showed a mixed response across the nine GCMs, with a reduction in dryland yield simulated in 70 out of 108 future scenarios (Fig. 3). Under RCP 8.5 in 2050s, the dryland seed cotton yield deviated from baseline by −30 % to 40 % at Bushland, −35 % to 57 % at Halfway, and −41 % to 19 % at Lamesa. Based on the dryland yield deviation in 2050s from the baseline under RCP 8.5, the GCMs projecting yield increase were GFDL-ESM2M (19–57 % increase depending on the location), and CSIRO-Mk3-6-0 (5–8 %); and the GCMs projecting yield reduction were IPSL-CM5A-LR (6–16 % decrease depending on the location), CCSM4 (28–35 %), BCC-CSM1-1 (18–41 %), and NorESM1-M (5–23 %). Typically, the GCMs that projected milder temperature increase and wetter future tended to project an increase in dryland yield, while the GCMs that projected warmer and drier future tended to project a decline in dryland yield.

To understand the dryland yield changes with respect to other key variables, we compared the changes in dryland yield with the changes in growing season temperature, rainfall, biomass, boll count at maturity, and growing season length (Figs. 6 and S5). The change in dryland yield

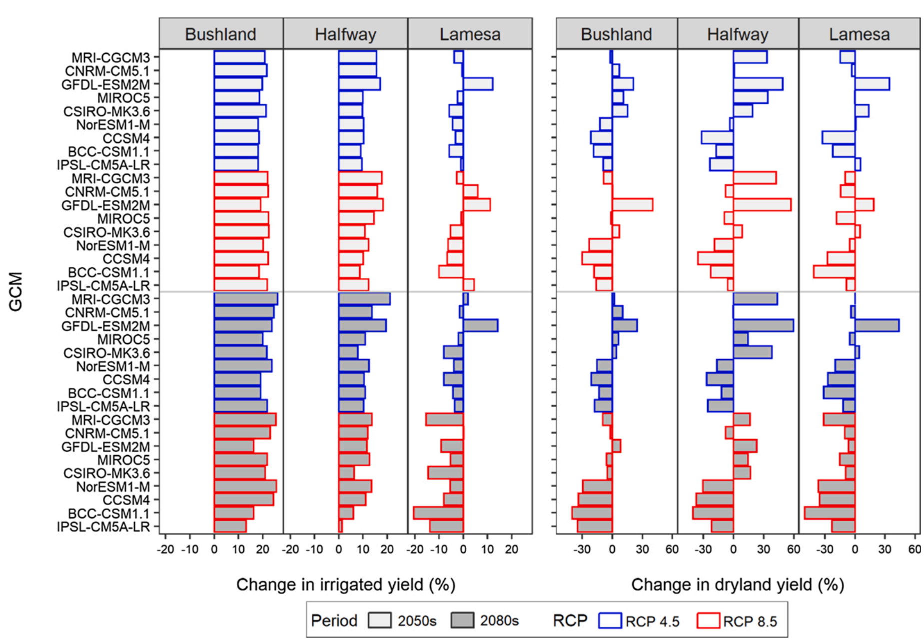

Fig. 3. Changes in irrigated and dryland seed cotton yield in 2050s and 2080s compared to the baseline historic period (1976–2005) under nine GCMs at the study sites.

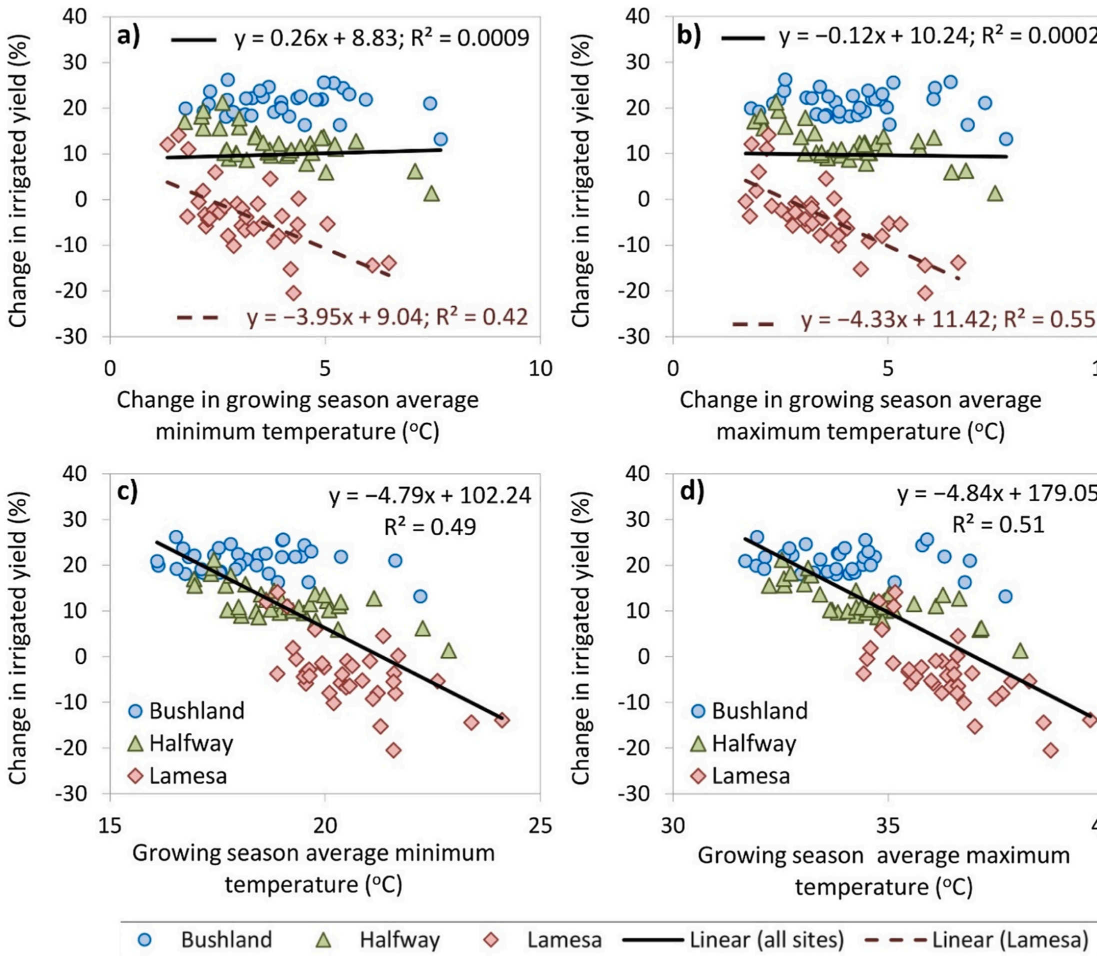

Fig. 4. Relationship between the changes in 30-year average **irrigated seed cotton yield** with changes in growing season (planting-harvest) temperature, simulated across 108 scenarios (3 locations, 2 RCPs, 2 future periods and 9 GCMs).

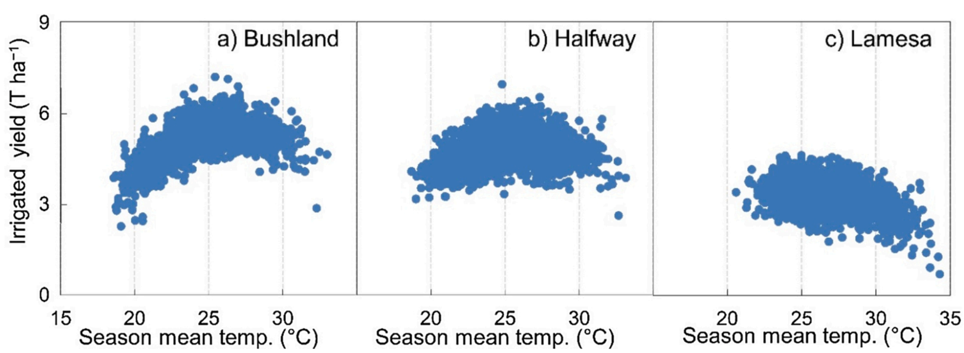

Fig. 5. The effect of average growing season (planting–harvest) temperature on irrigated seed cotton yield, presented across all simulations for the three locations, two RCPs, nine GCMs, and 150 years including historic and future years (1950–2099).

had a negative correlation with the changes in the growing season minimum/maximum temperature (Fig. S5a–b) and the average growing season temperature (Fig. S5c–d). The correlation of change in dryland yield was slightly higher with the maximum temperature ($R^2 = 0.25$) than with the minimum temperature ($R^2 = 0.13$) during the growing season. Overall, the dryland yield changes were better explained by the changes in growing season rainfall ($R^2 = 0.53$, Fig. 6a) than the temperature. The correlation between the changes in the dryland yield and the growing season length was weak when plotted for all locations together ($R^2 = 0.08$), but increased substantially when plotted for one location at a time, for example for Lamesa ($R^2 = 0.39$, Fig. 6b). Like the trends in irrigated yield, the changes in dryland yield closely followed the change in boll count at maturity ($R^2 = 0.81$, Fig. 6d), and the change in the total aboveground biomass ($R^2 = 0.54$, Fig. 6c).

3.3.3. Changes in irrigation water use

Seasonal irrigation increased under most climate change scenarios, 85 cases out of 108 scenarios (Fig. 7). Under the baseline 30-year simulations, the average seasonal irrigation varied across locations: Bushland (372 mm), Halfway (423 mm), and Lamesa (399 mm). Under RCP 8.5 in 2050s, the irrigation water use among GCMs changed by −11 % to 36 % at Bushland, −9% to 24 % at Halfway, and −2% to 23 % at Lamesa.

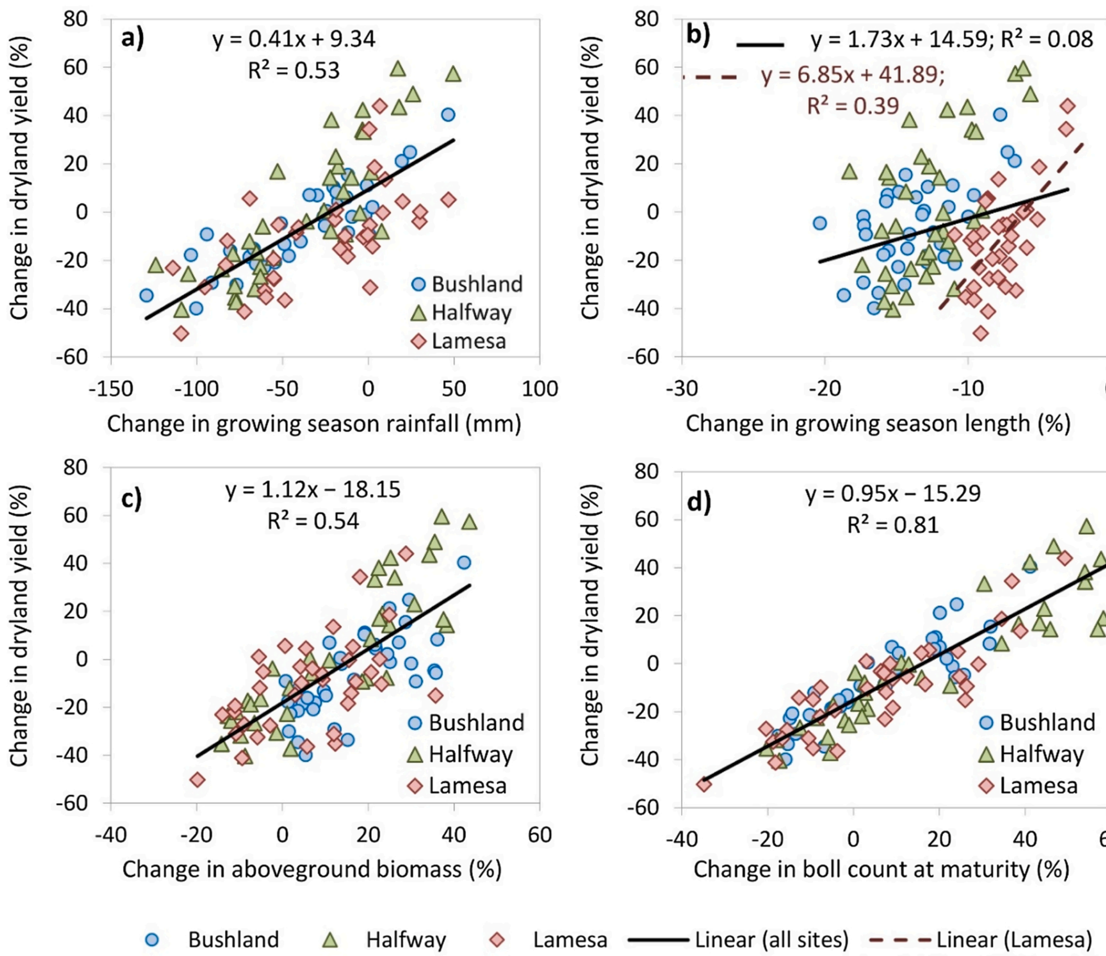

Fig. 6. Relationship between the changes in 30-year average **dryland seed cotton yield** with changes in other key model outputs, simulated across 108 scenarios (3 locations, 2 RCPs, 2 future periods and 9 GCMs).

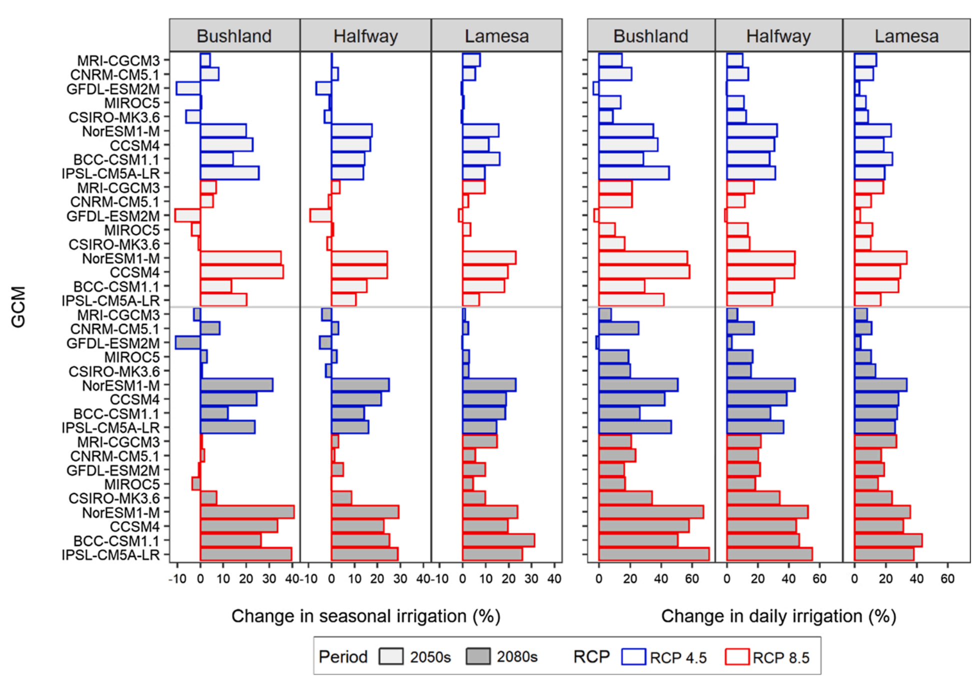

Fig. 7. Changes in seasonal (planting to harvest) daily irrigation water use in 2050s and 2080s compared to the baseline historic period (1976-2005) under nine GCMs at the study sites.

Most of the scenarios that projected a reduction in seasonal irrigation water use in the future (Fig. 7) corresponded to the GCMs that had projected an increase in May–October precipitation (Fig. 2). Based on the seasonal irrigation water use deviation in 2050s from the baseline under RCP 8.5, the GCMs projecting reduction or modest increase in seasonal irrigation were GFDL-ESM2M (−11 to −2% change depending on the location), CSIRO-Mk3−6-0 (−2 to 0 %), and MIROC5 (−4 to +4 %), and GCMs projecting a substantial increase in seasonal irrigation were IPSL-CM5A-LR (7–20 % increase depending on the location), CCSM4 (20–36 %), BCC-CSM1-1 (14–18 %), and NorESM1-M (23–35 %). The changes in seasonal irrigation were strongly correlated with the changes in growing season rainfall ($R^2 = 0.69$, Fig. 8e), and somewhat correlated with the changes in growing season maximum temperature ($R^2 = 0.34$, Fig. 8c), but the correlations between seasonal irrigation water use and other factors (biomass, maximum LAI, season length, and minimum temperature, Fig. S6) were small ($R^2 < 0.14$).

We further analyzed the effect of climate change on daily irrigation water use, estimated by dividing the seasonal irrigation water use with the growing season length (Fig. 7). Unlike the mixed response of seasonal irrigation water use across GCMs, the daily irrigation water use was projected to increase in most future scenarios (103 out of 108 scenarios). The daily irrigation water use increased by a greater extent in case of drier GCMs (IPSL-CM5A-LR, BCC-CSM1.1, CCSM4, and NorESM1-M) than the wetter GCMs (GFDL-ESM2M, CNRM-CM5.1, CSIRO-Mk3-6-0, and MIROC5), by a greater extent in 2080s than in 2050s, and by a slightly greater extent at Bushland than Halfway and Lamesa (Fig. 7). The daily irrigation water use was comparable for the three locations under baseline period: Bushland (2.3 mm), Halfway (2.7

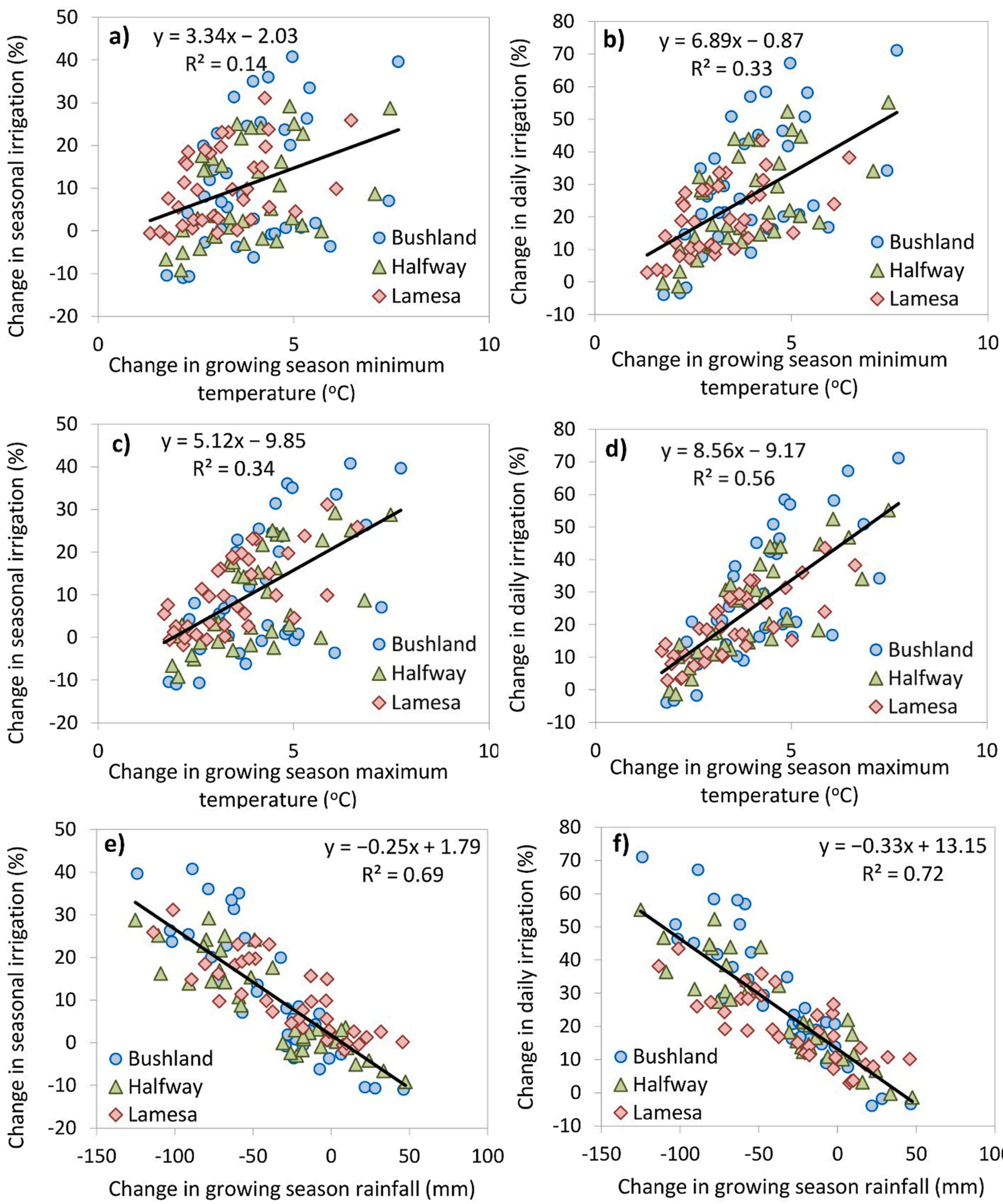

Fig. 8. Relationship between the changes in 30-year average **daily and seasonal irrigation water use** with changes in growing season (planting-harvest) temperature and rainfall, simulated across 108 scenarios (3 locations, 2 RCPs, 2 future periods and 9 GCMs).

mm), and Lamesa (2.8 mm). Under RCP 8.5 in 2050s, the daily irrigation water use among GCMs changed by −3% to 58 % at Bushland, −1% to 44 % at Halfway, and 4%–34% at Lamesa. The changes in daily irrigation water use were strongly correlated with the changes in growing season rainfall (R^2 = 0.72, Fig. 8f) and maximum temperature (R^2 = 0.56, Fig. 8d), and partially related with the minimum temperature (R^2 = 0.33, Fig. 8b) and growing season length (R^2 = 0.32, Fig. S6b). There was generally a positive trend of increasing daily irrigation water use with increasing vegetative growth (biomass and maximum LAI), but the correlation was not strong (R^2 = 0.16), most likely because of the variable seasonal irrigation water use responses among GCMs (Fig. S6).

3.4. Climate change adaptation

3.4.1. Irrigated production

Under the drought tolerant I ideotype, the yield deviation from the reference cultivar was almost similar during the future 30-year periods at Bushland, slightly variable at Halfway, and varied greatly at Lamesa (Fig. 9). For example, under RCP 4.5 in 2050s, considering all GCMs, the yield deviation between the reference cultivar and this ideotype over the 30 years varied by 2–12 % at Bushland, −2% to 18 % at Halfway, and −10 % to 27 % at Lamesa. When averaged over 30 years, there was an overall yield gain from using the drought tolerant I ideotype as compared to the reference cultivar and this was generally not affected by RCP or future period or study location (Table S1). These results suggest that by using drought tolerant I ideotype, the seed cotton yield would increase by almost the same extent across RCPs, future periods, and GCMs (5–7% in Bushland and 5–10 % yield gain in Halfway and Lamesa, Table S1), but the inter-annual variability in yield response depended on the location as shown in Fig. 9. The yield benefits could also be attributed to increased vegetative growth as seen through the increased aboveground biomass and maximum LAI, and increased crop ET (Fig. S7).

The drought tolerant II ideotype that had the same properties as the drought tolerant I ideotype, except a lower maximum water uptake per unit root length, showed similar patterns across locations in terms of inter-annual yield responses, which were stable at Bushland and varied greatly depending on the year at Lamesa (Fig. 9). As an example of the inter-annual variability, under RCP 8.5 in 2050s considering all GCMs, the yield deviation between reference cultivar and this ideotype varied by 0–7% at Bushland, −8% to 9% at Halfway, and −10 % to 23 % at Lamesa. When averaged over the 30 years, there was a marginal yield gain from using the drought tolerant II ideotype than using the reference cultivar and this was generally not affected by RCP or future period (Table S1). Like drought tolerant I ideotype, the yield gains could be attributed to increased biomass and seasonal crop ET (Fig. S7), but the yield gains were smaller with drought tolerant II than the drought tolerant I ideotype.

Under the heat tolerant I ideotype, the irrigated seed cotton yield was higher than the reference cultivar, the inter-annual variability in yield response tended to be higher for the warmest scenarios. For example, the yield deviation between the reference cultivar and this ideotype at Bushland over 30 years under RCP 8.5 in 2050s ranged from −3% to 18 % and this range expanded to −9% to 54 % in 2080s at Bushland (Fig. 9).

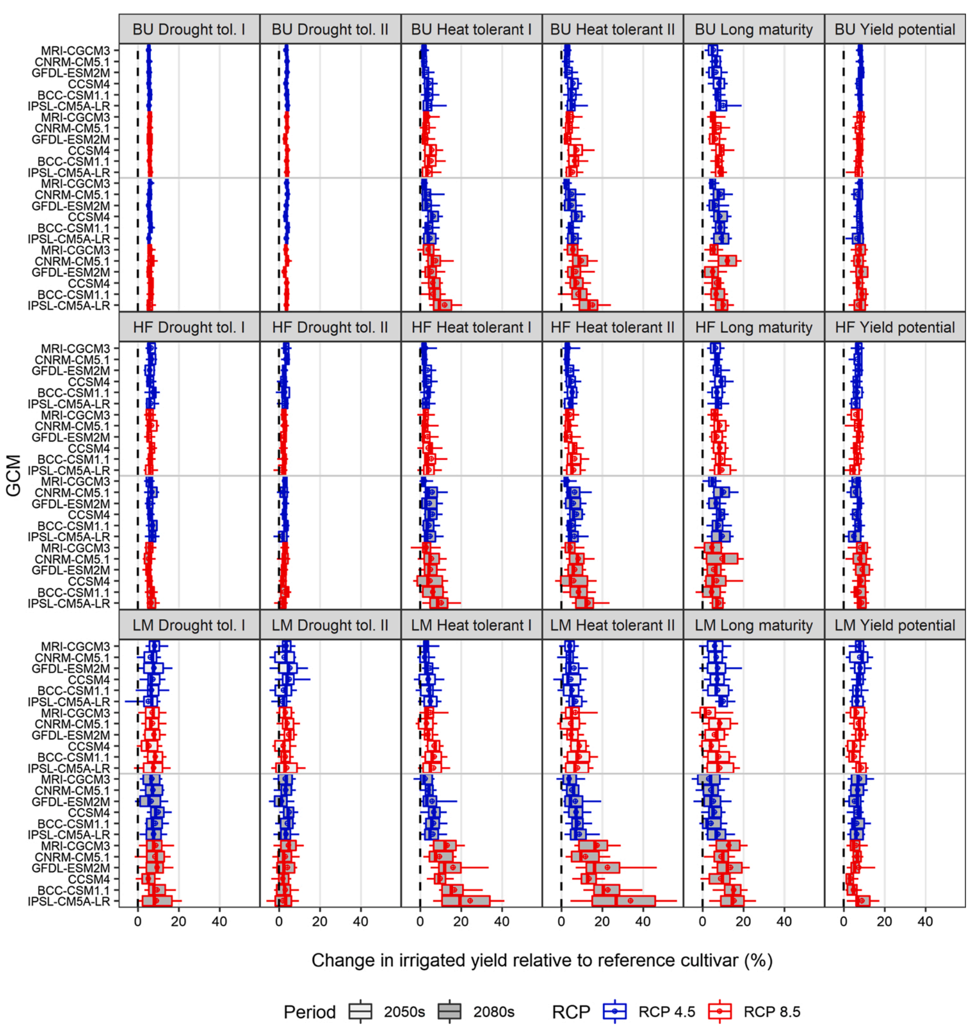

Fig. 9. Difference in **irrigated seed cotton yield** between a potential ideotype and the reference cultivar, during the future periods of 2050s and 2080s, under two RCPs, and six ideotypes, across three locations: Bushland (BU), Halfway (HF), and Lamesa (LM). The boxplots show the yield differences over 30 years. To improve legibility, results are shown only for six GCMs instead of nine. The boxplot bounds show 25 and 75 percentiles, whiskers extend to 10 and 90 percentiles, the bold line within the box is the median while the circle shows the mean of the 30 years.

The 30-year average yield values also showed a similar trend; an overall yield gain from using the heat tolerant I ideotype than using the reference cultivar and the yield benefits were higher for warmer scenarios (Table S1). These results suggest that by using heat tolerant I ideotype, the seed cotton yield would increase depending on the heat stress under the simulated scenario, with greater benefits under the warmest scenarios than in a scenario with milder temperature rise. Heat tolerant II ideotype showed similar irrigated yield response as the heat tolerant I ideotype, except that the yield benefits were greater with type II (Fig. 9), and the overall yield benefits shifted towards a 1–3% increase at Bushland and Halfway, and a 1–7% increase at Lamesa (Table S1). The yield benefits under heat tolerant I and II ideotypes were associated with an improved reproductive growth as seen from an increase in boll number at maturity (Fig S7).

The long maturity ideotype simulated greater yield than the reference cultivar in most scenarios (Fig. 9). Under RCP 8.5 in 2080s, the yield deviation across all GCMs between the reference cultivar and this ideotype varied from 5% to 12 % at Bushland, 5%–10% at Halfway, and 7%–14% at Lamesa (Table S1). On an average, there was a yield gain from using the long maturity ideotype than using the reference cultivar and this was generally not affected by RCP or future period, except for Lamesa where yield benefits tended to be greater under RCP 8.5 in 2080s (Fig. 9). The yield benefits of long maturity ideotype could be associated primarily with increased boll count at maturity, which was due to a longer reproductive phase (Fig. S7). The vegetative growth, however, showed mixed response likely due to advancing the flowering, which might have shortened the period of vegetative growth.

The high yield potential ideotype simulated yield gains across all scenarios (Fig. 9). The yield deviation considering all GCMs over 30 years for the RCP 8.5 at Lamesa ranged from −2% to 21 % in 2050s and −11 % to 31 % in 2080s. Overall, there was a yield gain from using the high yield potential ideotype than using the reference cultivar and this was generally not affected by RCP or future period or location (Fig. 9 and Table S1). The differences between the 30-year average yields of the high yield potential ideotype and the reference cultivar varied between 6% and 9% among the GCMs at Bushland, 5–9% at Halfway, and 3–8% at Lamesa considering all RCPs and future periods (Table S1). These results suggest that the RCPs, GCMs, and future periods had minor effect on the yield response of high yield potential traits. The yield benefits of high yield potential ideotypes could reach up to 31 % in a year and 30-year average yield benefits with this ideotype ranged from 3% to 9%. The yield benefits due to high yield potential ideotype could be associated partly with the increased unit weight of boll at maturity and increased boll count at maturity (Fig. S7).

3.4.2. Dryland production

The highest advantage in dryland seed cotton yield among the simulated ideotypes was found with the long maturity ideotype followed by heat tolerant ideotypes (Fig. 10 and Table S2). Under the drought tolerant I ideotype, the dryland seed cotton yield showed mixed response across locations, typically decreasing at Bushland and Lamesa and increasing at Halfway (Fig. 10 and Table S2). Under RCP 4.5 in 2050s, the difference between 30-year average yield of drought tolerant I ideotype and the reference cultivar varied from −11 % to −1% among

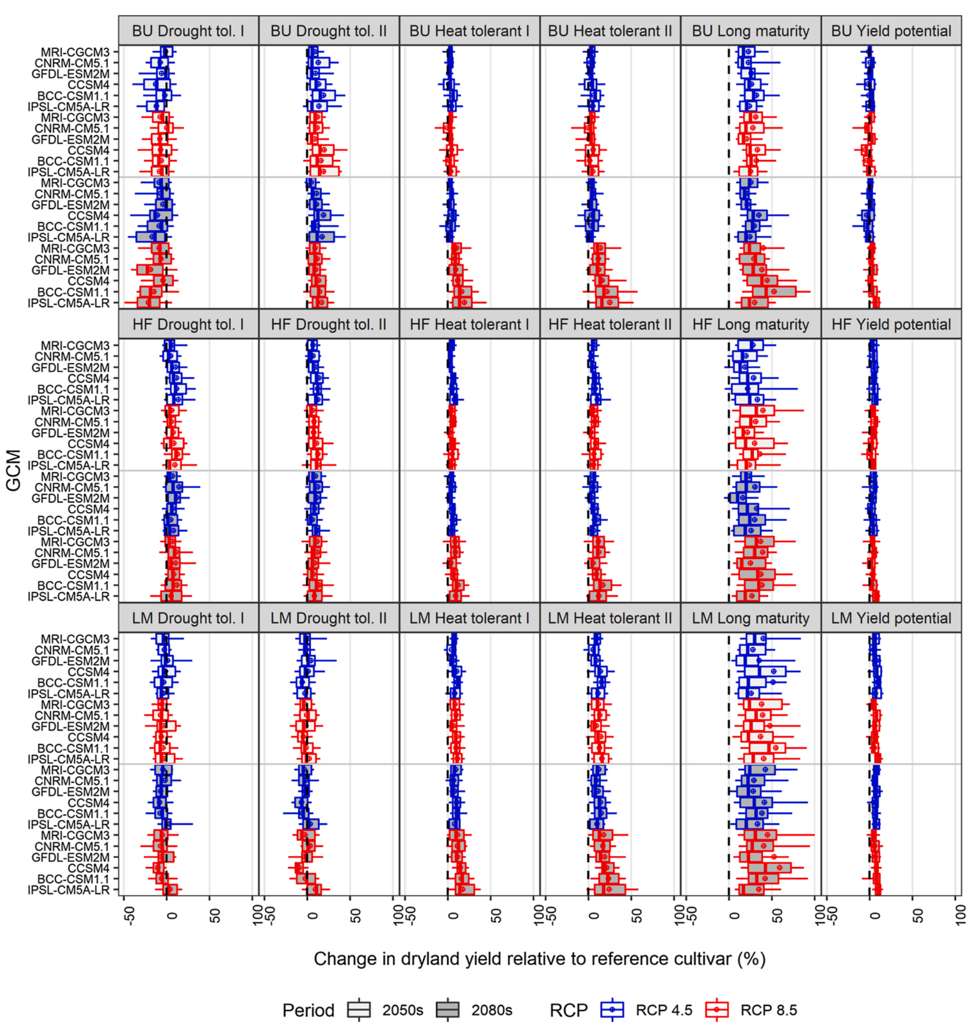

Fig. 10. Difference in **dryland seed cotton yield** between a potential ideotype and the reference cultivar, during the future periods of 2050s and 2080s, under two RCPs, and six ideotypes, across three locations: Bushland (BU), Halfway (HF), and Lamesa (LM). The boxplots show the yield differences over 30 years. To improve legibility, results are shown only for six GCMs instead of nine. The boxplot bounds show 25 and 75 percentiles, whiskers extend to 10 and 90 percentiles, the bold line within the box is the median while the circle shows the mean of the 30 years.

the GCMs at Bushland, 2%–9% at Halfway, and −5% to 0% at Lamesa (Table S2). The reduction in dryland yield with altered root properties was likely due to higher root water uptake and faster exhaustion of stored soil water earlier in the season. The reduced availability of water later in the season especially during reproductive stages likely led to the reduced seed cotton yield. This is indicated by the increased vegetative growth or biomass in all scenarios and locations, but mixed response of boll count at Bushland and Lamesa (Fig. S8).

Under the drought tolerant II ideotype, the dryland seed cotton yield showed mixed response across locations, typically decreasing at Lamesa, and increasing at Bushland and Halfway (Fig. 10). For example, the drought tolerant II ideotype increased yield on average (of 30 years) by 5–14 % at Bushland, 4–9% at Halfway, but it decreased yield by 0–5% at Lamesa for the RCP 8.5 scenario in 2050s (Table S2). Under both drought tolerant ideotypes, vegetative biomass and crop ET increased while boll count at maturity and yield showed mixed responses (Fig. S8). While Bushland suffered yield loss with drought tolerant I ideotype, yield gains were simulated with drought tolerant II ideotype. At Lamesa, which has the lowest soil water holding capacity, neither of the two drought tolerant ideotypes showed yield gains. These results suggest that care should be taken while designing ideotypes for dryland production based on root hydraulic properties.

The dryland seed cotton yield generally increased with heat tolerant ideotypes at all locations (Fig. 10). Overall, 30-year average dryland yield increased with the heat tolerant I ideotype as compared to the reference cultivar under all scenarios at all locations, and the yield benefits were generally greater for warmer scenarios (RCP 8.5 in 2080s) and warmer location (Lamesa) (Fig. 10). The yield benefits for Bushland ranged from 2% to 7% in 2050s, which increased to 7–14 % in 2080s under RCP 8.5 (Table S2). The yield benefits could be associated with increased resource allocation for the reproductive growth as seen from the increased boll count at maturity (Fig. S8).

Under the heat tolerant II ideotype, the dryland seed cotton yield showed similar response as heat tolerant I ideotype, except that the inter-annual variability was greater and the overall yield benefits were slightly higher under type II (Fig. 10). Under RCP 8.5, the yield increased by 2–8% at Bushland, and by 8–16 % at Lamesa in 2050s, and by 12–24 % at Lamesa in 2080s (Table S2). Like the heat tolerant I ideotype, the yield benefits were associated with enhanced reproductive growth under higher temperatures that increased boll count at maturity (Fig. S8).

The dryland seed cotton yield increased under all scenarios across locations with the long maturity ideotype (Fig. 10). Considering the RCP 4.5 in 2080s, the dryland yield increased by 17–30 % at Bushland, 11–24 % at Halfway and 19–31 % at Lamesa (Table S2). These trends were generally not affected by RCP or future period (Fig. 10). The yield benefits were associated with increased growing season length, which led to greater vegetative and reproductive growth (Fig. S8).

The dryland seed cotton yield trends with the high yield potential ideotype showed mixed responses across locations and among GCMs at Bushland (Fig. 10). Overall, based on the 30-year average seed cotton yields, the high yield potential ideotype simulated yield gains. For example, under RCP 8.5 in 2080s, the yield was projected to increase by 0–5% at Bushland, by 3–8% at Halfway, and by 6–10 % at Lamesa

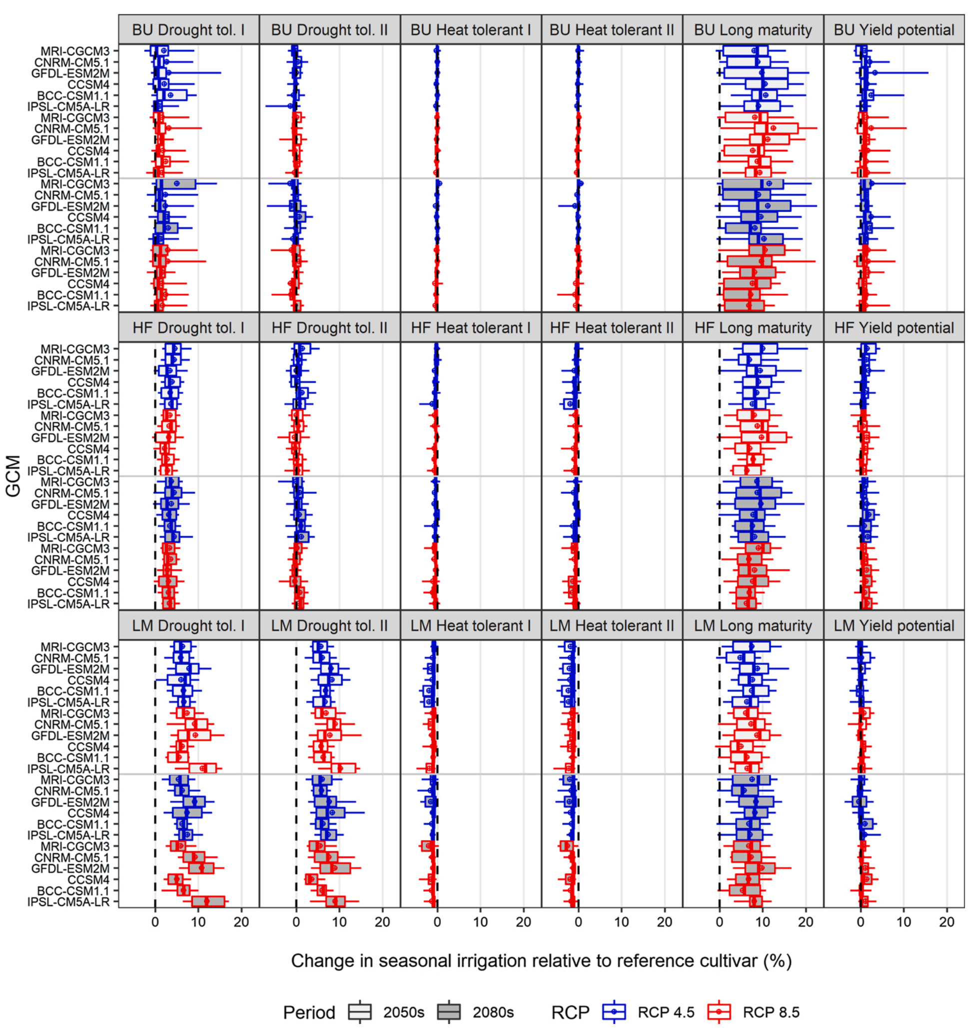

Fig. 11. Difference in **seasonal irrigation water use** between a potential ideotype and the reference cultivar, during the future periods of 2050s and 2080s, under two RCPs, and six ideotypes, across three locations: Bushland (BU), Halfway (HF), and Lamesa (LM). The boxplots show the yield differences over 30 years. To improve legibility, results are shown only for six GCMs instead of nine. The boxplot bounds show 25 and 75 percentiles, whiskers extend to 10 and 90 percentiles, the bold line within the box is the median while the circle shows the mean of the 30 years.

(Table S2). This was most likely due to simultaneous modification of boll count and boll weight related parameters (Fig. S8). In future research, it is recommended to test one parameter at a time to tease apart the effect of greater partitioning to, or increasing potential weight of, cotton bolls.

3.4.3. Irrigation water requirement

Under the drought tolerant I ideotype, the seasonal irrigation increased under most scenarios (Fig. 11 and Table S3). On an average, there was an overall increase in seasonal irrigation water use from using the drought tolerant I ideotype than using the reference cultivar and this was greater for Lamesa followed by Halfway (Table S3). The results suggest that seasonal irrigation water use could increase from 1% to 12 % depending on the location and GCM. Under RCP 8.5 in 2080s, the (30-year) average seasonal irrigation water use was simulated to increase by 1–3% at Bushland, 3–4% at Halfway, and 5–12 % at Lamesa (Table S3). The increase in seasonal irrigation water use was associated with increased vegetative growth (Fig. S9) which led to higher crop ET (Fig. S9).

The seasonal irrigation water use under drought tolerant II ideotype showed mixed responses at Bushland and Halfway, while at Lamesa, it showed an increasing trend in most years (Fig. 11). When averaged over 30 years within a GCM, the seasonal irrigation water use changed marginally at Bushland (−2% to +1%) and Halfway (−1% to +5%), and increased by a greater extent at Lamesa (4–10 %) (Table S3). The increase in seasonal irrigation water use was once again due to an increased vegetative growth similar to drought tolerant I ideotype (Fig. S9). The reduction in seasonal irrigation water use in some cases, which occurred on more instances at Bushland could be due to constraining the maximum water uptake per unit root length. However, this trait did not prove to be a limiting factor at Lamesa where seasonal irrigation water use and vegetative biomass increased by a greater extent than at the other two sites.

The seasonal irrigation water use under heat tolerant I and II ideotypes was almost the same as that under the reference cultivar under all scenarios and years at Bushland and Halfway (Fig. 11 and Table S3), and it slightly reduced at Lamesa. The change in seasonal irrigation water use between the reference cultivar and the heat tolerant I ideotype varied from −1% to 0% at Bushland and Halfway; and from −2% to −1% at Lamesa, considering 30-year average across all GCMs, RCPs, and future periods (Table S3). The response was similar for the heat tolerant II ideotype with 30-year average seasonal irrigation water use being reduced at most by 3% (Lamesa in 2080s). Negligible changes or minor reductions in seasonal irrigation water use with the heat tolerant I and II ideotypes could be due to enhanced partitioning to reproductive growth as seen in the increased number of bolls (Fig. S9), which suppressed vegetative growth to some extent (Fig. S9) and thereby reduced the crop ET demand (Fig. S9).

Under the long maturity ideotype, the seasonal irrigation water use increased substantially and showed high inter-annual variability for all locations and scenarios (Fig. 11). These results suggest that the use of long maturity ideotypes could alter the seasonal irrigation water use between 5% and 12 % across future climate scenarios and locations. The increase in seasonal water use was mainly due to increased length of the growing season for which higher amount of irrigation water was required (Fig. S9).

The seasonal irrigation water use under high yield potential ideotype showed a mixed, but generally increasing tendency under most scenarios (Fig. 11). The difference between 30-year average seasonal irrigation water use of high yield potential ideotype and the reference cultivar varied by 1–3% at Bushland, 0–2% at Halfway, and −1% to 1% at Lamesa among GCMs under both RCPs and future periods (Table S3). These results suggest that on using high yield potential ideotype, the 30-year average seasonal irrigation water use could change between −1% and 3% across future climate scenarios and locations. Relatively minor change in projected seasonal water use with the high yielding ideotype as compared to other ideotypes could be because the high yield potential ideotype was designed by targeting the reproductive growth (seed and shell partitioning and size) and thus the response of this ideotype for biomass, boll count and ET was mixed (Fig. S9).

4. Discussion

4.1. Climate change impacts on irrigated cotton production

Future irrigated seed cotton yield showed a mixed trend across the study sites (Fig. 3), with a projected yield increase of 12–21 % at Bushland and Halfway, and a yield decrease of 2% at Lamesa, in the mid-century compared to the baseline. Based on the correlations between the growing season temperature and yield change under climate change scenarios (Fig. 4) and from the optimal temperature ranges set in the model for boll addition and partitioning to reproductive growth (Fig. S1), it seemed plausible that the growing season temperature at Lamesa under future climate scenarios fell outside the optimal range, which negatively impacted the reproductive growth. For other two sites, the growing season temperature generally remained within the optimal ranges and therefore the CROPGRO-Cotton model did not project any reduction in yield. This is consistent with Hatfield et al. (2011), who reviewed multiple studies and identified the optimal temperature for cotton reproductive growth to vary between 25 °C and 26 °C. Previously, Reddy et al. (1999) had also reported that boll retention was severely reduced when the average seasonal temperature was greater than 26 °C, when they grew cotton in naturally lit plant growth chambers at elevated temperatures in the mid-South U.S.

Interestingly, aboveground biomass increased under all scenarios at all three locations (Fig. S4), unlike the projections for seed cotton yield or boll count at maturity. This could be because the optimal temperature range for cotton vegetative growth (28–30 °C) is typically higher than that for the reproductive growth (Hatfield et al., 2011), which explains why in our study the biomass increased under all scenarios while boll count and seed cotton yield decreased for the warmer site (Lamesa). The increase in yield at the cooler sites and biomass at all sites could be attributed to the "CO_2 fertilization" effect, which has been shown to increase cotton biomass by 34–37 % and yield by 44–46 % when [CO_2] was elevated from ~350 to 550 ppm in FACE studies (Mauney et al., 1994). Lastly, with decreasing growing season length the irrigated yield decreased at Lamesa, but the relation was weak for the other two locations (Fig. S4). This could be due to confounding effect of CO_2 fertilization that resulted in yield gains despite a shorter growing season at Bushland and Halfway.

Our results suggest that irrigated cotton yield could benefit from elevated CO_2 under climate change if the growing season temperature remains below the optimal range for reproductive growth. Similar to our results, in a recent simulation study using DSSAT, Ayankojo et al. (2020) found a reduction in irrigated seed cotton yield in Maricopa, Arizona by at least 40 % in the mid- and 51 % in the late-century periods, compared to the baseline. The greater reduction in seed cotton yield in their study compared to our results was primarily due to much higher growing season temperature (30 °C) at Maricopa, Arizona. Like our results, they reported a slight increase in the biomass and significant reduction in boll count at maturity. Our results also agree with most of the results of Adhikari et al. (2016) who reported an increase in seed cotton yield in the THP. They found that the yield would increase at all sites in the THP, northern and southern; however, in our study the yield decreased at the southern site (Lamesa). It is worth noting that Adhikari et al. (2016) used future climate forcings from three CMIP3-GCMs, while we used climate forcings from nine CMIP5-GCMs. Their future data extended up to year 2070, while our simulations were extended to year 2095. The future [CO_2] in their study was higher than the [CO_2] level of RCP 4.5 but comparable to [CO_2] of RCP 8.5 used in our study.

Overall, our results suggest that seasonal irrigation water use showed mixed response to climate change, mostly due to variable future rainfall projections across GCMs. On average, under RCP 8.5, the seasonal irrigation water use was projected to increase when averaged across GCMs, between 7% (Halfway) to 11 % (Bushland) by mid-century and from 14 % (Halfway) to 16 % (Bushland and Lamesa) by late-century. These results are comparable to the results of Ayankojo et al. (2020), who projected that seasonal irrigation water use at Maricopa, Arizona, would increase by 10–13 % by mid-century and 14–24 % by late-century. The daily irrigation water use was projected to increase under most climate change scenarios partly due to increased growing season maximum temperature and reduced growing season length, and the extent of change depended on the future rainfall projections.

4.2. Climate change impacts on dryland cotton production

Dryland seed cotton yield showed mixed trend across GCMs in all three locations (Fig. 3). Considering all the future scenarios, the yield could change between +6% (average of GCMs at Halfway) to −11 % (at Lamesa) by mid-century compared to the baseline. Overall, our results suggest that dryland seed cotton yield is expected to decrease under climate change, which could be partly explained by an increase in growing season temperature and reduction in rainfall in the future in case of some GCMs, and shorter growing season length (but this effect was site-specific). However, under the GCMs that projected wetter growing season in the future and temperature increases below the optimal range of cotton reproductive growth, CROPGRO-Cotton model projected increases in dryland yield at all three locations. It was interesting to note that irrigated yield at Bushland and Halfway increased under climate change for all GCMs, but it decreased under rainfed conditions in case of some GCMs, this suggests that the beneficial effects of elevated [CO_2] were greater than the negative effects of temperature increase under irrigated conditions, but the beneficial effects of elevated [CO_2] were suppressed due to water stress under rainfed conditions. Our results are consistent with the findings of Gray et al. (2016), who analyzed eight years of data from an open-air FACE facility in Champaign, IL, USA and found that the yield gains for soybean, another C3 crop, diminished when drought was intensified.

4.3. Irrigated cotton production – climate change adaptation

Overall, irrigated seed cotton yield increased under all six simulated ideotypes. Based on the yield change relative to the reference cultivar, considering 30-year average yields across all locations, GCMs, RCPs, and future periods (Table S1), the high yield potential (with 3–9% yield gain), long maturity (3–14 %), and heat tolerant II (3–26 %) ideotypes were found to be more effective. On the other hand, the drought tolerant II ideotype (with 1–5% yield gain) was found to be the least effective ideotype. The seasonal irrigation water use increased under the long maturity ideotype, remained relatively less affected under heat tolerant and high yield potential ideotypes, and showed mixed responses under drought tolerant ideotypes depending on the location. Based on the seasonal irrigation water use change relative to the reference cultivar, considering 30-year average yields across all locations, GCMs, RCPs, and future periods (Table S3), the heat tolerant I and II ideotypes (with no change to 3% reduction in seasonal irrigation water use), and the high yield potential ideotype (with small (-1%) reduction to minor increase (3%)) were found to be among the more effective ideotypes. In contrast, the long maturity (with 5–12 % increase in seasonal irrigation) and drought tolerant I (with 1–12 % increase) ideotypes were found to be the least effective ideotypes. Considering the seed cotton yield and seasonal irrigation water use together, the high yield potential ideotype was found to be the most desirable ideotype for the irrigated cotton production in the THP region, since it resulted in a substantial increase in irrigated yield without much increase in water requirements for irrigation. The heat tolerant ideotypes also found beneficial under most scenarios. With a substantial increase in yield and marginal reduction in water requirement, the heat tolerant ideotypes were found to be more effective under warmer conditions. The drought tolerant ideotypes showed mixed responses across locations, depending on the type of soil, with a substantial increase in irrigation water use in case of low soil water holding capacity soils at Lamesa. Although the longer maturity trait resulted in substantial yield gains, it is not advisable due to the substantial increase in water requirements for irrigation.

Both the high yield potential and heat tolerant ideotypes that were found to be the most desirable ideotypes in our study for irrigated production were effective for the similar reason: increased dry matter allocation to reproductive growth (Fig. S7). The high yield potential ideotype was designed by increasing maximum size of full leaf and seed size, and enhancing partitioning to seed and shell. These changes resulted in an increase of either boll count or boll weight while decreasing aboveground biomass and increasing or decreasing maximum LAI. In a recent field study comprising of three cotton cultivars in China, Nie et al. (2020) showed that the highest yielding cultivar partitioned significantly greater proportion of photosynthate to inner bolls and fiber than the lower yielding cultivars and thus this trait could be useful in screening for high yielding ideotypes. Apart from selecting a suitable ideotype, the partitioning of photosynthate to bolls could also be maximized by adopting appropriate management practices such as adjustment of sowing date to ensure optimal condition during boll growth (Yeates et al., 2010). These field studies, which were conducted under current climate conditions confirm that enhanced partitioning to bolls is an important factor in deciding the final seed cotton yield. Our results suggest that this trait could be effective in increasing cotton yield under climate change as well, and with the similar efficacy across all locations, GCMs and RCPs.

Similarly, the second most desirable ideotype in our study, the heat tolerant ideotypes were designed by increasing optimal temperature thresholds for boll addition and partitioning to bolls, which resulted in a substantial increase in boll count at maturity (Fig. S7). With a temperature rise of 1.6–3.6 °C as projected under RCP 8.5 in 2050s, the heat tolerant ideotypes produced up to 10 % greater yield than the reference cultivar under the future climate. Simulated seed cotton yield benefits in our study are comparable with 13 % yield benefits of heat tolerant ideotype simulated for chickpea at Nandyal, India (Singh et al., 2014a) and slightly lower than that the 17 % yield benefits simulated for pearl millet at Bikaner, India (Singh et al., 2017). In addition, like our study, above studies reported no to marginal benefits of heat tolerant ideotypes in cooler sites and under cooler climate scenarios. The heat tolerant ideotype would thus provide greater benefit in the hotter southern THP sites than the cooler northern THP site, and the yield benefits would increase as the temperature rises for all sites under climate change (Fig. 9). Our results suggest that the ideotypes that can retain cotton boll under higher temperature would play a key role in sustaining cotton production in the THP region under climate change. Cotton breeders have used the boll retention percentage as an indicator for identifying heat-tolerant genotypes (Abro et al., 2015), as reported in a recent review study (Azhar et al., 2020).

The drought tolerant ideotypes were found unsuitable because either yield benefits were marginal (in case of drought tolerant II ideotype), or the seasonal irrigation water use increased (in case of type I ideotype). For the site with lowest soil water retention properties (Lamesa), both drought tolerant ideotypes resulted in substantial increase (up to 12 %) in seasonal irrigation water use. The drought tolerant ideotypes were designed by increasing the photosynthetic capacity, root length per unit root weight, and raising the threshold before which the water stress is imposed on leaf expansive growth (through RWUEP1 as described in Saseendran et al. (2015)). These modifications increased aboveground biomass and crop ET in almost all years (Fig. S9). These results suggest that cultivars with higher photosynthetic capacity and capability to maintain leaf expansion under water stress could help in increasing seed cotton yield through increased vegetative growth, but they could also lead to higher irrigation water use than the reference cultivar. In addition to these modifications, the drought tolerant I ideotype had a greater capacity to take water per unit root length than the reference cultivar, which could also partly explain the increase in seasonal irrigation water use. In summary, greater photosynthetic capacity, capability to maintain leaf expansion despite water stress, and increased root water uptake per unit length could serve as appropriate adaptation strategies in the regions where irrigation water supply is not a limiting factor. However, in the THP region, there are restrictions on the groundwater withdrawals for irrigation (HPWD, 2015), and therefore ideotypes with greater seasonal irrigation water use than the reference cultivar would not be advisable.

4.4. Dryland cotton production – climate change adaptation

Overall, the dryland seed cotton yield increased under long maturity and heat tolerant ideotypes while drought tolerant and high yield potential ideotypes simulated mixed responses depending on the location. Based on the yield change relative to the reference cultivar, considering 30-year average yields across all locations, GCMs, RCPs, and future periods (Table S2), the long maturity (with 11–45 % yield gain) and heat tolerant II (2–24 %) ideotypes were found to be among the more effective ideotypes. On the other hand, the drought tolerant I ideotype (with 2–9% yield gain at Halfway, but up to 17 % yield loss at Bushland, and up to 8% yield loss at Lamesa) was found to be the least effective ideotype. The high yield potential ideotype was found to be not suitable for dryland production because the yield benefits (up to 10 % yield gains at Halfway and Lamesa, and yield loss up to 3% at Bushland) were lower than those for other ideotypes (long maturity and heat tolerant). The longer maturity ideotype, which was considered as the most effective ideotype for dryland cotton production, was characterized by earlier flowering and longer reproductive phase than the reference cultivar. These traits are similar to the traits of best yielding cotton ideotypes under climate change in Northern Cameroon in Sub-Saharan Africa (Gérardeaux et al., 2018; Loison et al., 2017). The effectiveness of heat tolerant ideotypes was similar under rainfed conditions as in the irrigated conditions, with similar yield gains due to greater boll retention at higher temperatures.

4.5. Drought tolerant ideotypes

The performance of drought tolerant ideotypes was highly dependent on the location and therefore ideotype selection for drought tolerance under dryland conditions needs to be examined carefully based on soil water retention properties and rainfall patterns of the location, similar to the findings of Singh et al. (2017) for pearl millet. Despite an overall yield gain when averaged across 30 years, there were some years with lower yield with the drought tolerant ideotypes than the reference cultivar, and the number of years with yield loss was greater for the drought tolerant II ideotype than the type I ideotype. The lower benefits and higher probability of yield loss under type II ideotype was due to constraining the maximum water uptake from the roots, which likely led to inefficient use of auto-irrigation and thus the drought tolerant type II ideotype is not recommended for irrigated production.

Another interesting point was that seed cotton yield slightly increased with drought tolerant I cultivar under irrigated conditions, but it decreased under rainfed conditions at Bushland. This was likely because the biomass and leaf area or vegetative growth increased with drought tolerant I ideotype under rainfed conditions, but the boll count reduced (Fig. S8). The increased vegetative growth and suppressed reproductive growth could be due to earlier exhaustion of stored soil water under rainfed conditions. This is further confirmed by increased dry matter productivity and reduced seed cotton yield productivity per unit water used under drought tolerant I ideotype at Bushland (Fig. S10). The soil water extractable at maturity also reduced by a greater extent under ideotype I, which further attests the hypothesis about reduced water availability during reproductive growth (Fig. S10).

5. Conclusions

We simulated cotton growth and yield under irrigated and dryland conditions at three locations in the THP region, under 18 future climate scenarios (two RCPs and nine GCMs). Our results showed that under projected climate change, irrigated seed cotton yield could increase due to CO_2 fertilization if growing season temperatures remain below the optimal limits. Seasonal irrigation water use was projected to increase under most GCMs depending on the rainfall projections. Under the dryland conditions, the beneficial effects of CO_2 fertilization were not only suppressed by temperature stress but also by water stress. We tested six ideotypes for their resilience to climate change based on their yield and seasonal irrigation water use relative to the reference cultivar. The high yielding ideotype, which is characterized by higher potential leaf size and increased partitioning to seed plus shell, was found to be desirable for irrigated cotton production; while long maturity ideotype, with earlier flowering and longer reproductive duration, was found suitable for dryland cotton production. Heat tolerant ideotype would be another safe choice, especially for the warmer southern THP region.

CRediT authorship contribution statement

Kritika Kothari: Conceptualization, Methodology, Formal analysis, Visualization, Data curation, Writing - original draft, Writing - review & editing. **Srinivasulu Ale:** Funding acquisition, Methodology, Supervision, Resources, Writing - review & editing, Project administration. **James P. Bordovsky:** Investigation, Writing - review & editing. **Clyde L. Munster:** Funding acquisition, Supervision, Resources, Writing - review & editing. **Vijay P. Singh:** Writing - review & editing. **John Nielsen-Gammon:** Writing - review & editing. **Gerrit Hoogenboom:** Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Funding support for this research was provided by the College of Agriculture and Life Sciences (COALS), Texas A&M University, and the Ogallala Aquifer Program (OAP), a consortium between USDA Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University. Partial support for this research was also provided by Cotton Incorporated.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2021.108261.

References

Abatzoglou, J.T., 2013. Development of gridded surface meteorological data for ecological applications and modelling. Int. J. Climatol. 33 (1), 121–131. https://doi.org/10.1002/joc.3413.

Abatzoglou, J.T., Brown, T.J., 2012. A comparison of statistical downscaling methods suited for wildfire applications. Int. J. Climatol. 32 (5), 772–780. https://doi.org/10.1002/joc.2312.

Abro, S., Rajput, M.T., Khan, M.A., Sial, M.A., Tahir, S.S., 2015. Screening of cotton (Gossypium hirsutum L.) genotypes for heat tolerance. Pak. J. Bot. 47 (6), 2085–2091.

Adhikari, P., Ale, S., Bordovsky, J.P., Thorp, K.R., Modala, N.R., Rajan, N., Barnes, E.M., 2016. Simulating future climate change impacts on seed cotton yield in the Texas High Plains using the CSM-CROPGRO-Cotton model. Agric. Water Manag. 164, 317–330. https://doi.org/10.1016/j.agwat.2015.10.011.

Alagarswamy, G., Boote, K., Allen, L., Jones, J., 2006. Evaluating the CROPGRO–Soybean model ability to simulate photosynthesis response to carbon dioxide levels. Agron. J. 98 (1), 34–42. https://doi.org/10.2134/agronj2004-0298.

Anapalli, S.S., Fisher, K.D., Reddy, N.K., Pettigrew, T.W., Sui, R., Ahuja, R.L., 2016. Vulnerabilities and adapting irrigated and rainfed cotton to climate change in the Lower Mississippi Delta region. Climate 4 (4). https://doi.org/10.3390/cli4040055.

Ayankojo, I.T., Thorp, K.R., Morgan, K.T., Kothari, K., Ale, S., 2020. Assessing the impacts of future climate on cotton production in the Arizona low desert. Trans. ASABE.

Azhar, M.T., Wani, S.H., Chaudhary, M.T., Jameel, T., Kaur, P., Du, X., 2020. Heat tolerance in cotton. In: Wani, S.H., Kumar, V. (Eds.), Heat Stress Tolerance in Plants: Physiological, Molecular and Genetic Perspectives. John Wiley & Sons, Inc., Hoboken, NJ, USA, pp. 1–22.

Bannayan, M., Hoogenboom, G., 2009. Using pattern recognition for estimating cultivar coefficients of a crop simulation model. Field Crops Res. 111 (3), 290–302. https://doi.org/10.1016/j.fcr.2009.01.007.

Boote, K., Pickering, N., 1994. Modeling photosynthesis of row crop canopies. HortScience 29 (12), 1423–1434.

Boote, K.J., Jones, J.W., Hoogenboom, G., 1998. Simulation of crop growth: CROPGRO model. In: Peart, R.M., Curry, R.B. (Eds.), Agricultural Systems Modeling and Simulation. Marcel Dekker, New York, pp. 651–692.

Bordovsky, J.P., Mustian, J., Cranmer, A., Emerson, C., 2011. Cotton-grain sorghum rotation under extreme deficit irrigation conditions. Appl. Eng. Agric. 27 (3), 359.

Bordovsky, J.P., Mustian, J.T., Ritchie, G.L., Lewis, K.L., 2015. Cotton irrigation timing with variable seasonal irrigation capacities in the Texas south plains. Appl. Eng. Agric. 31 (6), 883–897.

Bronson, K., Bowman, R., 2009. Nutrient Management for Texas High Plains Cotton Production. Retrieved from. . Texas AgriLife Research and Extension, College Station, TX, USA. http://lubbock.tamu.edu/files/2011/10/nutrmgmtforcot.pdf.

Bronson, K., Onken, A., Keeling, J., Booker, J., Torbert, H., 2001. Nitrogen response in cotton as affected by tillage system and irrigation level. Soil Sci. Soc. Am. J. 65 (4), 1153–1163.

Bronson, K., Malapati, A., Booker, J., Scanlon, B., Hudnall, W., Schubert, A., 2009. Residual soil nitrate in irrigated Southern High Plains cotton fields and Ogallala groundwater nitrate. J. Soil Water Conserv. 64 (2), 98–104.

Broughton, K.J., Smith, R.A., Duursma, R.A., Tan, D.K., Payton, P., Bange, M.P., Tissue, D.T., 2017. Warming alters the positive impact of elevated CO2 concentration on cotton growth and physiology during soil water deficit. Funct. Plant Biol. 44 (2), 267–278. https://doi.org/10.1071/FP16189.

Chaudhuri, S., Ale, S., 2014. Long-term (1930–2010) trends in groundwater levels in Texas: influences of soils, landcover and water use. Sci. Total Environ. 490, 379–390. https://doi.org/10.1016/j.scitotenv.2014.05.013.

Coumou, D., Rahmstorf, S., 2012. A decade of weather extremes. Nat. Clim. Chang. 2, 491. https://doi.org/10.1038/nclimate1452.

Curry, R.B., Peart, R.M., Jones, J.W., Boote, K.J., Allen Jr., L.H., 1990. Simulation as a tool for analyzing crop response to climate change. Trans. ASAE 33 (3), 981–0990. https://doi.org/10.13031/2013.31427.

DeJonge, K.C., Thorp, K.R., 2017. Implementing standardized reference evapotranspiration and dual crop coefficient approach in the DSSAT cropping system model. Trans. ASABE 60 (6), 1965–1981.

Gérardeaux, E., Loison, R., Palaï, O., Sultan, B., 2018. Adaptation strategies to climate change using cotton (Gossypium hirsutum L.) ideotypes in rainfed tropical cropping systems in Sub-Saharan Africa. A modeling approach. Field Crops Res. 226, 38–47. https://doi.org/10.1016/j.fcr.2018.07.007.

Gowda, P.H., Howell, T.A., Baumhardt, R.L., Porter, D.O., Marek, T.H., Nangia, V., 2016. A user-friendly interactive tool for estimating reference ET using ASCE standardized Penman-Monteith equation. Appl. Eng. Agric. 32 (3), 383–390. https://doi.org/10.13031/aea.32.11673.

Gray, S.B., Dermody, O., Klein, S.P., Locke, A.M., McGrath, J.M., Paul, R.E., Rosenthal, D. M., Ruiz-Vera, U.M., Siebers, M.H., Strellner, R., Ainsworth, E.A., Bernacchi, C.J., Long, S.P., Ort, D.R., Leakey, A.D.B., 2016. Intensifying drought eliminates the expected benefits of elevated carbon dioxide for soybean. Nat. Plants 2 (9), 16132. https://doi.org/10.1038/nplants.2016.132.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A.M., Wolfe, D., 2011. Climate impacts on agriculture: implications for crop production. Agron. J 103 (2), 351–370. https://doi.org/10.2134/agronj2010.0303.

Hoogenboom, G., Jones, J.W., Boote, K.J., 1992. Modeling growth, development, and yield of grain legumes using SOYGRO, PNUTGRO, and BEANGRO: a Review. Trans. ASAE 35 (6), 2043–2056. https://doi.org/10.13031/2013.28833.

Hoogenboom, G., Tsuji, G.Y., Pickering, N.B., Curry, R.B., Jones, J.W., Singh, U., Godwin, D.C., 1995. Decision Support System to Study Climate Change Impacts on Crop Production, Climate Change and Agriculture: Analysis of Potential International Impacts, pp. 51–75.

Hoogenboom, G., Jones, J.W., Traore, P.C., Boote, K.J., et al., 2012. Experiments and data for model evaluation and application. In: Kihara, J. (Ed.), Improving Soil Fertility Recommendations in Africa Using the Decision Support System for Agrotechnology Transfer (DSSAT). Springer, Dordrecht, the Netherlands, pp. 9–18.

Hoogenboom, G., Jones, J.W., Wilkens, P.W., Porter, C.H., Boote, K.J., Hunt, L.A., Singh, U., Lizaso, J.I., White, J.W., Uryasev, O., Ogoshi, R., Koo, J., Shelia, V., Tsuji, G.Y., 2015. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.6. DSSAT Foundation, Prosser, Washington. www.DSSAT.net.

Hoogenboom, G., Porter, C.H., Boote, K.J., Shelia, V., Wilkens, P.W., Singh, U., White, J. W., Asseng, S., Lizaso, J.I., Moreno, L.P., Pavan, W., Ogoshi, R., Hunt, L.A., Tsuji, G. Y., Jones, J.W., 2019. The DSSAT crop modeling ecosystem. In: Boote, K.J. (Ed.), Advances in Crop Modelling for a Sustainable Agriculture. Burleigh Dodds Science Publishing, Cambridge, UK.

HPWD, 2015. Rules of the High Plains Underground Water Conservation District No. 1. Retrieved from. http://www.hpwd.org/rules/.

IPCC, 2014. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

Iqbal, M., Khan, M.A., Naeem, M., Aziz, U., Afzal, J., Latif, M., 2013. Inducing drought tolerance in upland cotton (Gossypium hirsutum L.), accomplishments and future prospects. World Appl. Sci. J. 21 (7), 1062–1069. https://doi.org/10.5829/idosi.wasj.2013.21.7.222.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18 (3–4), 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7.

Kimball, B.A., Kobayashi, K., Bindi, M., 2002. Responses of agricultural crops to free-air CO_2 enrichment. In: Sparks, D.L. (Ed.), Advances in Agronomy. Academic Press, San Diego, California, USA, pp. 293–368.

Kothari, K., Ale, S., Attia, A., Rajan, N., Xue, Q., Munster, C.L., 2019a. Potential climate change adaptation strategies for winter wheat production in the Texas High Plains. Agric. Water Manag. 225, 105764 https://doi.org/10.1016/j.agwat.2019.105764.

Kothari, K., Ale, S., Bordovsky, J.P., Thorp, K.R., Porter, D.O., Munster, C.L., 2019b. Simulation of efficient irrigation management strategies for grain sorghum production over different climate variability classes. Agric. Syst. 170, 49–62. https://doi.org/10.1016/j.agsy.2018.12.011.

Kothari, K., Ale, S., Bordovsky, J.P., Porter, D.O., Munster, C.L., Hoogenboom, G., 2020. Potential benefits of genotype-based adaptation strategies for grain sorghum production in the Texas High Plains under climate change. Eur. J. Agron. 117, 126037 https://doi.org/10.1016/j.eja.2020.126037.

Levi, A., Paterson, A.H., Barak, V., Yakir, D., Wang, B., Chee, P.W., Saranga, Y., 2009. Field evaluation of cotton near-isogenic lines introgressed with QTLs for productivity and drought related traits. Mol. Breed. 23 (2), 179–195. https://doi.org/10.1007/s11032-008-9224-0.

Liu, Z., Yuan, Y.-L., Liu, S.-Q., Yu, X.-N., Rao, L.-Q., 2006. Screening for high-temperature tolerant cotton cultivars by testing in vitro pollen germination, pollen tube growth and boll retention. J. Integr. Plant Biol. 48 (6), 706–714. https://doi.org/10.1111/j.1744-7909.2006.00276.x.

Loison, R., Audebert, A., Debaeke, P., Hoogenboom, G., Leroux, L., Oumarou, P., Gérardeaux, E., 2017. Designing cotton ideotypes for the future: reducing risk of crop failure for low input rainfed conditions in Northern Cameroon. Eur. J. Agron. 90, 162–173. https://doi.org/10.1016/j.eja.2017.08.003.

Lokhande, S., Reddy, K.R., 2014. Quantifying temperature effects on cotton reproductive efficiency and fiber quality. Agron. J. 106 (4), 1275–1282.

Mauney, J.R., Kimball, B.A., Pinter, P.J., LaMorte, R.L., Lewin, K.F., Nagy, J., Hendrey, G.R., 1994. Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment. Agric. For. Meteorol. 70 (1), 49–67. https://doi.org/10.1016/0168-1923(94)90047-7.

McMichael, B., Lascano, R.J., 2003. Laboratory evaluation of a commercial dielectric soil water sensor. Vadose Zone J. 2 (4), 650–654. https://doi.org/10.2136/vzj2003.6500.

Messina, C., Ritchie, J., Jones, J., Boote, K., Hoogenboom, G., Whalen, V., 2004. A simulation model of cotton growth and development for CSM. Proc. Biological Systems Simulation Group (BSSG) Conference 54–55.

Modala, N.R., Ale, S., Goldberg, D.W., Olivares, M., Munster, C.L., Rajan, N., Feagin, R. A., 2017. Climate change projections for the Texas High Plains and rolling plains. Theor. Appl. Climatol. 129 (1), 263–280. https://doi.org/10.1007/s00704-016-1773-2.

Nie, J., Qin, D., Mao, L., Liu, Y., Dong, H., Song, X., Sun, X., 2020. Genotypic variance in 13C-photosynthate partitioning and within-plant boll distribution in cotton. J. Cotton Res. 3 (1), 15. https://doi.org/10.1186/s42397-020-00055-3.

Ortiz, B., Hoogenboom, G., Vellidis, G., Boote, K., Davis, R., Perry, C., 2009. Adapting the CROPGRO-Cotton model to simulate cotton biomass and yield under southern root-knot nematode parasitism. Trans. ASABE 52 (6), 2129–2140.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob. Environ. Chang. 14 (1), 53–67. https://doi.org/10.1016/j.gloenvcha.2003.10.008.

Pathak, T., Fraisse, C., Jones, J., Messina, C., Hoogenboom, G., 2007. Use of global sensitivity analysis for CROPGRO cotton model development. Trans. ASABE 50 (6), 2295–2302.

Rahman, M.H.u., Ahmad, A., Wang, X., Wajid, A., Nasim, W., Hussain, M., Ahmad, B., Ahmad, I., Ali, Z., Ishaque, W., Awais, M., Shelia, V., Ahmad, S., Fahd, S., Alam, M., Ullah, H., Hoogenboom, G., 2018. Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. Agric. For. Meteorol. 253–254, 94–113. https://doi.org/10.1016/j.agrformet.2018.02.008.

Reddy, K.R., Hodges, H.F., McKinion, J.M., 1995. Carbon dioxide and temperature effects on pima cotton growth. Agric. Ecosyst. Environ. 54 (1), 17–29. https://doi.org/10.1016/0167-8809(95)00593-H.

Reddy, K.R., Davidonis, G.H., Johnson, A.S., Vinyard, B.T., 1999. Temperature regime and carbon dioxide enrichment alter cotton boll development and fiber properties contribution from the Dep. of Plant and Soil Sciences, Mississippi State Univ., and the USDA-ARS Southern Regional Res. Ctr., New Orleans, LA. Mississippi Agric. and Forestry Exp. Stn. Paper no. J9391. Agron. J. 91 (5), 851–858. https://doi.org/10.2134/agronj1999.915851x.

Reddy, K.R., Prashant, R.D., Linda, O.M., Mariquita, Y.L.B., Harry, F.H., Alec, G.R., Vijaya Gopal, K., 2002. Simulating the impacts of climate change on cotton production in the Mississippi Delta. Clim. Res. 22 (3), 271–281.

Riaz, M., Farooq, J., Sakhawat, G., Mahmood, A., Sadiq, M., Yaseen, M., 2013. Genotypic variability for root/shoot parameters under water stress in some advanced lines of cotton (Gossypium hirsutum L.). Genet. Mol. Res. 12 (1), 552–561. https://doi.org/10.4238/2013.February.27.4.

Saseendran, S.A., Nielsen, D.C., Ma, L., Ahuja, L.R., 2010. Adapting CROPGRO for simulating spring canola growth with both RZWQM2 and DSSAT 4.0. Agron. J. 102 (6), 1606–1621. https://doi.org/10.2134/agronj2010.0277.

Saseendran, S.A., Trout, T.J., Ahuja, L.R., Ma, L., McMaster, G.S., Nielsen, D.C., Andales, A.A., Chávez, J.L., Ham, J., 2015. Quantifying crop water stress factors from soil water measurements in a limited irrigation experiment. Agric. Syst. 137, 191–205. https://doi.org/10.1016/j.agsy.2014.11.005.

Segarra, E., Keeling, J.W., Abernathy, J.R., 1991. Tillage and cropping system effects on cotton yield and profitability on the Texas southern high plains. J. Prod. Agric. 4 (4), 566–571.

Singh, R.P., Prasad, P.V.V., Sunita, K., Giri, S.N., Reddy, K.R., 2007. Influence of high temperature and breeding for heat tolerance in cotton: a review. In: Sparks, D.L. (Ed.), Advances in Agronomy. Academic Press, pp. 313–385.

Singh, P., Nedumaran, S., Boote, K.J., Gaur, P.M., Srinivas, K., Bantilan, M.C.S., 2014a. Climate change impacts and potential benefits of drought and heat tolerance in chickpea in South Asia and East Africa. Eur. J. Agron. 52, 123–137. https://doi.org/10.1016/j.eja.2013.09.018.

Singh, P., Nedumaran, S., Traore, P., Boote, K., Rattunde, H., Prasad, P.V., Singh, N., Srinivas, K., Bantilan, M., 2014b. Quantifying potential benefits of drought and heat tolerance in rainy season sorghum for adapting to climate change. Agric. For. Meteorol. 185, 37–48. https://doi.org/10.1016/j.agrformet.2013.10.012.

Singh, P., Boote, K.J., Kadiyala, M.D.M., Nedumaran, S., Gupta, S.K., Srinivas, K., Bantilan, M.C.S., 2017. An assessment of yield gains under climate change due to genetic modification of pearl millet. Sci. Total Environ. 601–602, 1226–1237. https://doi.org/10.1016/j.scitotenv.2017.06.002.

Ullah, A., Sun, H., Yang, X., Zhang, X., 2017. Drought coping strategies in cotton: increased crop per drop. Plant Biotechnol. J. 15 (3), 271–284. https://doi.org/10.1111/pbi.12688.

USDA-NASS, 2018. Quick Stats-Crops. available at https://quickstats.nass.usda.gov/, verified 10/28/2018.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., 2011. The representative concentration pathways: an overview. Clim. Change 109 (1–2), 5.

Walter, I.A., Allen, R.G., Elliott, R., Jensen, M., Itenfisu, D., Mecham, B., Howell, T., Snyder, R., Brown, P., Echings, S., 2000. ASCE's standardized reference evapotranspiration equation. Watershed Management and Operations Management 2000, pp. 1–11.

Welch, B.L., 1938. The significance of the difference between two means when the population variances are unequal. Biometrika 29 (3–4), 350–362. https://doi.org/10.1093/biomet/29.3-4.350.

Wuebbles, D., Fahey, D., Hibbard, K., Dokken, D., Stewart, B., Maycock, T., 2017. Climate Science Special Report: Fourth National Climate Assessment, Vol. I. Washington, DC.

Yeates, S.J., Constable, G.A., McCumstie, T., 2010. Irrigated cotton in the tropical dry season. II: biomass accumulation, partitioning and RUE. Field Crops Res. 116 (3), 290–299. https://doi.org/10.1016/j.fcr.2010.01.007.